

Late-Early to Middle Pleistocene vegetation and climate history of the Highland Valley, British
Columbia, Canada

by

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B.Sc.(Psychology), University of Calgary, 2011

B.Sc.(Biological Sciences), University of Calgary, 2011

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of the Requirements for the Degree of

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The climate and vegetation history of the Middle Pleistocene transition in the interior of British Columbia (BC) is poorly understood due largely to the lack of records. Sediments from the overburden of the Teck Highland Valley Copper mine (HVC) of British Columbia straddle the Brunhes-Matuyama paleomagnetic transition, providing an opportunity to study this critical Pleistocene interval. The stratigraphy was described and sampled for paleomagnetic and pollen/spore analysis at reconnaissance scale. The HVC sediments consist mainly of (from bottom to top) a lower glacial drift, >50 m of lakebed sediments, ~50 m of gravel fan deposits, and a >60 m thick drift of mostly glacial till. These units were deposited by a valley glacier, lake, fluvial/debris flow events, and an ice sheet, respectively. Pollen and spore analyses reveal at least 11 climate-vegetation intervals (9 zones, 2 more possible ones). These are broadly classified as either warm *Pinus-Picea* parkland and forest, cold *Selaginella*-rich steppe or arid *Artemisia*-Poaceae steppe. These intervals suggest a long paleo-environmental record at HVC and indicate fluctuations between glacial and interglacial climates which can tentatively be placed with Marine Isotope Stages 23 through 16 and younger. The HVC record is a unique sequence with the potential to reveal a much more detailed history of this critical time in Earth's past. Implications of these findings are discussed.

Table of contents

Supervisory Committee.....	ii
Abstract.....	iii
Table of contents.....	iv
List of tables.....	vi
List of figures.....	vii
Acknowledgements.....	x
Dedication.....	xi
Chapter 1: Introduction.....	1
Chapter 2: Background.....	5
2.1 Bedrock Geology.....	5
2.2 Physiography.....	7
2.3 Climate.....	9
2.4 Vegetation and soils.....	11
2.5 Quaternary geology.....	16
2.6 The Highland Valley Copper study site.....	19
Chapter 3: Methods.....	22
3.1 Field work, sampling and dating.....	22
3.2 Palynology.....	26
3.3 Pollen identification, counting and analysis.....	28
Chapter 4: Stratigraphy and geochronology.....	31
4.1 Stratigraphy.....	31
4.1.1 Bedrock.....	33
4.1.2 Unit 1 – Partially cemented red conglomerates and fine sands.....	35
4.1.3 Unit 2 – Lower diamicton.....	38
4.1.5 Unit 4 – Sandy silts and clays.....	40
4.1.6 Unit 5 – Fine grained rhythmites.....	40
4.1.7 Unit 6 – Inclined sands and gravels.....	46
4.1.8 Unit 7 – Upper diamicton.....	49
4.1.9 Units 8a and 8b – Red-brown clayey silts/sands and peats/marls.....	51
4.2 Interpretation.....	53
4.2.1 Bedrock and Unit 1: Pre-glacial deposition.....	53
4.2.2 Units 2-4: Lower drift.....	55
4.2.3 Units 5 and 5a: Lacustrine deposits.....	56
4.2.4 Units 6 and 6a.....	57
4.2.5 Unit 7.....	61
4.2.6 Units 8a, 8b.....	62
Chapter 5. Palynology and Paleontology Results.....	63
5.1 Edge reversed sequence (ER).....	64
5.1.1 Zone ER-1: <i>Pinus-Picea</i> (8 to 10.3 m).....	67
5.1.2 Zone ER-2: <i>Selaginella-Poaceae</i> (10.3 to 15.5 m).....	68
5.1.3 Zone ER-3: <i>Pinus-Picea</i> and <i>Artemisia-Poaceae</i> (15.5 to 19 m).....	71
5.2 Main sequence (M).....	72
5.2.1 Zone M-1: <i>Pinus-Picea</i> (0 to 4.5 m).....	75
5.2.2 Zone M-2: <i>Artemisia-Poaceae</i> (4.5 to 13 m).....	76
5.2.3 Zone M-3: <i>Poaceae-Artemisia</i> (13 to 20.25 m).....	77
5.2.4 Zone M-4: <i>Poaceae-Artemisia-Polemonium-Forb</i> (20.25 to 29 m).....	78
5.3 Edge-normal Sequence (EN).....	79

5.3.1 Zone EN-1: <i>Pinus-Picea</i> (0 to 9 m).....	80
5.3.2 Zone EN-2: <i>Artemisia-Poaceae</i> (9 to 23 m).....	83
5.3.3 Zone EN-3: <i>Artemisia-Poaceae</i> (23 to 29 m).....	83
5.4 HVC-4/HVC-12.....	84
5.5 Taphonomy.....	85
5.6 Pollen zone correlation.....	86
Chapter 6. Interpretation and Discussion.....	89
6.1 Vegetation history and inferred paleoclimate of Highland Valley.....	89
6.1.1 Pine-Spruce forest and parkland.....	93
6.1.2 <i>Selaginella</i> steppe.....	98
6.1.3 <i>Artemisia-Poaceae</i> steppe.....	100
6.1.4 HVC-12/4.....	102
6.1.5 Climate and vegetation summary.....	103
6.2 Correlation with the marine isotope stage (MIS) record.....	107
6.3 Discussion.....	109
6.3.1 Early Pleistocene glaciation in the Highland Valley.....	110
6.3.2 A unique pollen and spore record.....	112
6.3.3 Plant communities of the late Early-Middle Pleistocene BC interior.....	115
6.3.4 Two glaciations at Highland Valley.....	116
6.4 - Conclusions and future work.....	118
References.....	121

List of tables

Table 2.1. Modern biogeoclimatic zones around the Highland Valley Copper locality based on descriptions offered in Meidinger and Pojar (1991).....	15
Table 2.2. Early Pleistocene glacial records from British Columbia prior to this study.....	17
Table 2.3. Previously described stratigraphic units and ages within the overburden at HVC. All data from Bobrowsky et al. (1993) unless otherwise indicated.....	20
Table 3.1. Table of localities at HVC.....	23
Table 3.2. List of R libraries and their usage as used in pollen analysis and the presentation of data...	29
Table 5.1. Pollen and spore concentrations from Edge reversed sequence samples per gram of sediment. Values were determined by calculating the total added <i>Lycopodium</i> spores by weight and multiplying that value by the ratio of pollen and spores to counted <i>Lycopodium</i> spores (added type only).....	66
Table 5.2. Pollen and spore concentrations from Main sequence samples per gram of sediment. Values were determined by calculating the total added <i>Lycopodium</i> spores by weight and multiplying that value by the ratio of pollen and spores to counted <i>Lycopodium</i> spores (added type only).....	72
Table 5.3. Pollen and spore concentrations from Edge normal sequence samples per gram of sediment. Values were determined by calculating the total added <i>Lycopodium</i> spores by weight and multiplying that value by the ratio of pollen and spores to counted <i>Lycopodium</i> spores (added type only).....	78
Table 5.4. Selected palynomorph percentages from samples from locality HVC-12 by local height and lab ID. Stated local heights are relative to the base of Unit 7a (sands and peats) with Unit 7 (gravels). All values are in percentages except height and the ratio of Poaceae to <i>Artemisia</i>	83
Table 6.1. Summary of the pollen and spore zones and macrofossil record exposed at the Highland Valley Copper Valley Pit. Zones listed in stratigraphic order from youngest to oldest. Dominant pollen and spores are listed from highest to lowest abundance.....	89
Table 6.2. Guide for interpretation of pollen and spore zones on the BC interior after recommendations in Hebda (1982).....	91
Table 6.3. Interpretation of pollen and spore zone data at HVC.....	103
Table 6.4. Early Pleistocene glacial records from British Columbia prior to this study.....	110
Table 6.5. Terrestrial pollen and spore records of the Middle Pleistocene Transition of North America.	113

List of figures

Figure 1.1. Hillshade map showing location of the Highland Valley Copper Valley Pit (HVC). Converted from Shuttle Radar Topography Mission data (SRTM DEM; NASA: http://dds.cr.usgs.gov/srtm/) in QGIS (software).....	2
Figure 2.1. Topographic map of part of southern British Columbia showing the location of the HVC Valley Pit, the geographic extent of the Thompson Plateau and nearby physiographic regions. Elevation data from from the Shuttle Radar Topography Mission (NASA: http://dds.cr.usgs.gov/srtm/). Physiographic regions after Holland (1976; digitized version by Mihalynuk 2009).....	8
Figure 2.2. Normal climate conditions for four nearest sites to the Highland Valley locality. Data here were compiled from the Government of Canada climate data archives (http://climate.weather.gc.ca/climate_normals/station_select_1981_2010_e.html).....	10
Figure 2.3. Biogeoclimatic subzones around Highland Valley, British Columbia. Data for this map was sourced from the British Columbia Ministry of Forests, Lands and Natural Resource Operations (2016b).....	14
Figure 2.4. Map of the study region showing the Highland Valley Copper location and elevation.....	18
Figure 3.1. Sieving apparatus designed by Vera Pospelova (University of Victoria) for palynological application. Nylon sieves are attached to the open bottom of the plastic food containers as shown, and stacked with the coarser sieve on top. A stirring rod on the lower sieve is spun by a magnetic stirrer. Water and fine sediment is collected in the reservoir which is allowed to drain. RO water is fed into the system gradually until the water coming out of the lower sieve is clean and the material on that sieve is retained.....	26
Figure 4.1. Schematic view of the sedimentary exposure at the HVC Valley Pit facing north-northeast.	31
Figure 4.2. Bedrock contacts (dashed lines) with sediment at HVC. a - Unit 1 contact with bedrock at HVC-11a. Note the clast angularity and composition of basal Unit 1 material; examples indicated with arrows. Also note rusty red color in the upper part of Unit 1. b - Unit 2 contact with bedrock at HVC- 10. c - Unit 4 contact with Bedrock at HVC-11. Arrows in Figures b and c show examples of weathered bedrock observed at the contact.....	33
Figure 4.3. a - Exposures of units 1, 3, and 4 atop bedrock at HVC-11a. Note rusty red colour in upper part of Unit 1 and the boulder lag at the Unit 1-3 contact (arrow). b and c - Debris on road below exposure likely derived from Unit 1. Note the heavy oxidation on a and thick weathering rind on b. Photos a and c courtesy Richard Hebda, used with permission.....	35
Figure 4.4. a - sedimentary exposure at HVC-10. b - close-up view of Unit 2 diamict at HVC-10 showing variety of clasts. Note the bullet shape and faceting present on several clasts. Note also the relatively uniform clast composition compared to Unit 7 (discussed later in this chapter).....	36
Figure 4.5. Units 3 and 4 at HVC-11. Note scattered imbrication in Unit 3 and disrupted bedding in Unit 4. Arrow indicates rip-up clast from what was likely Unit 1 material.....	38
Figure 4.6. a - closeup of bedding at HVC-1. b - Charcoal rich part of organic debris layer found at HVC-1 (arrow), similar to one found at HVC-10. Photo credit for a and b: Richard Hebda, used with permission.....	41
Figure 4.7. Unit 5a and associated features. a - View of 5a in context with other units at HVC. Arrows label location of features pictured in Figures b and c (labelled with figure letter). Photo credit: Richard Hebda, used with permission. b - Example of tectonic folding and faulting observed at HVC-2. c - Folding and rip-up clasts at HVC-3d. Arrow indicates thick tephra discussed in text.....	42
Figure 4.8. Unit 5 and 5a at HVC-3b. a - Exposure of Unit 5a at southern end of lens showing the unit pinching out toward the south. b - Close up view of Unit 5a gravels.....	43

Figure 4.9. a - Exposure at HVC-3f. Arrow indicates thick tephra used to correlate section with other sections. Note continuity of beds well below the tephra bed. b - Close up view of coarse beds encountered more frequently towards the transition into Unit 6.....	44
Figure 4.10. a - Exposure at HVC-4a at the base of Unit 6. Arrows show examples of thin rhythmite beds interbedded with the gravels of Unit 6. b - Close up view of coarse material within Unit 6. Note the poor sorting and angularity of the grains. Also note the light patchy rusty colour.....	46
Figure 4.11. a - Exposure at HVC-4/12 at the top of Unit 6. Note the deformation of the gravel beds..	47
b - View of same locality from about 10 m south showing where Unit 6a is exposed.....	47
Figure 4.12. a - Exposure at HVC-9 looking toward HVC-5. Arrows show dropstones and stratified sand beds. b - Stratified sand and diamict at HVC-9 showing normal faulting. c - Diamict at HVC-5. Note faceted clasts of a multitude of rock types. Arrows show stratification.....	49
Figure 4.13. a - Cleaned surface of Unit 8a material at HVC-14. Note lenticular fracture and slickenside. b - Unit 8b beds at HVC-8.....	51
Figure 4.14. Grus sample from Colorado (left; collected by Kendrick Marr (Royal BC Museum)) compared to a bulk sample from the base of Unit 6.....	57
Figure 4.15. Example of grus development in the alpine of northern British Columbia. Photo illustrates progression of parent granite (left) to gravel sized grus particles (right) in an environment relatively devoid of other macro-scale biological activity. Taken at 1734 m asl east of Hook Creek (59° 43.321' N, 131° 16.002' W). Photo credit: Richard Hebda, used with permission.....	58
Figure 5.1. Pollen and spore diagram from the edge-normal sequence (HVC-10). Open bars show 10x the percentage for selected palynomorphs. Occurrence of a palynomorph at 1% or less in an assemblage is indicated by a plus sign (+). Height is stratigraphic height relative to bedrock at HVC-10 (see Table 3.1 for locality position). The cluster analysis tree (CONISS) is also shown with the interpreted numbered pollen and spore zones. These zones correspond to those referred to in the text.	64
Figure 5.2. Percent arboreal pollen (%AP) and the ratio of Poaceae to <i>Artemisia</i> pollen for pollen and spore samples of the edge-reversed sequence. Blue annotations are the suggested interpretation scheme from Hebda (1982) and used later in this thesis for interpretation.....	65
Figure 5.3. Light microscope photographs of indicator pollen types from the ER-2 zone at HVC. (a-d) <i>Selaginella sibirica</i> -type. (e-h) <i>Polemonium pulcherrimum</i> -type.....	69
Figure 5.4. Pollen and spore diagram from the main sequence. Open bars show 10x the percentage for selected palynomorphs. Occurrence of a palynomorph at 1% or less in an assemblage is indicated by a plus sign (+). Height is stratigraphic height relative to the 1050 m asl roadcut at HVC-1(see Table 3.1 for locality position). The cluster analysis tree (CONISS) is also shown with the interpreted numbered pollen and spore zones. These zones correspond to those referred to in the text.....	73
Figure 5.5. Percent arboreal pollen (%AP) and the ratio of Poaceae to <i>Artemisia</i> pollen for pollen and spore assemblages of the main sequence. Blue annotations are the suggested interpretation scheme from Hebda (1982) and used later in this thesis for interpretation.....	74
Figure 5.6. Pollen and spore diagram from the edge-normal sequence. Open bars show 10x the percentage for selected palynomorphs. Occurrence of a palynomorph at 1% or less in an assemblage is indicated by a plus sign (+). Height is stratigraphic height relative to the "thick felsic tephra" at HVC-3f (see Table 3.1 for locality position and text for further information). The cluster analysis tree (CONISS) is also shown with the interpreted numbered pollen and spore zones. These zones correspond to those referred to in the text.....	80
Figure 5.7. Percent arboreal pollen (%AP) and the ratio of Poaceae to <i>Artemisia</i> pollen for pollen and spore samples of the edge-normal sequence. Blue annotations are the suggested interpretation scheme from Hebda (1982) and used later in this thesis for interpretation.....	81
Figure 5.8. Proposed correlation of zones at HVC between the three defined sequences. See text for explanation.....	85
Figure 6.1. Percent arboreal pollen and Poaceae: <i>Artemisia</i> ratios for samples counted at HVC for the present study. Refer to Fig. 4.1 and the text for locations and groupings of each sequence.	

Interpretations of general landscape are after Hebda (1982) are indicated by blue dashed lines and blue text (see Table 6.1 for cutoff values).....93

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Dedication

To the many I consider family, both natural and chosen.

And to nature, may it continue to surprise and inspire us.

Chapter 1: Introduction

The mid-Pleistocene transition (MPT) marked a substantial change in global climate. In particular, there was an increase in the extent and thickness of glaciers during longer cold phases as the first Cenozoic ‘continental-scale’ ice sheets formed (Head & Gibbard 2005). This transition occurred between roughly 1.2 Ma and 500 ka when the cyclicity of Earth’s global climate began to change from ~41 thousand year to ~100 thousand year cycles (Head & Gibbard 2005). This interval of major climatic change has attracted a substantial amount of attention by numerous researchers such as anthropologists, paleobiologists, climatologists, and Quaternary geologists. The general questions asked by these investigators aims to understand what changes occurred and how those changes impacted their respective subjects of study (Head & Gibbard 2005).

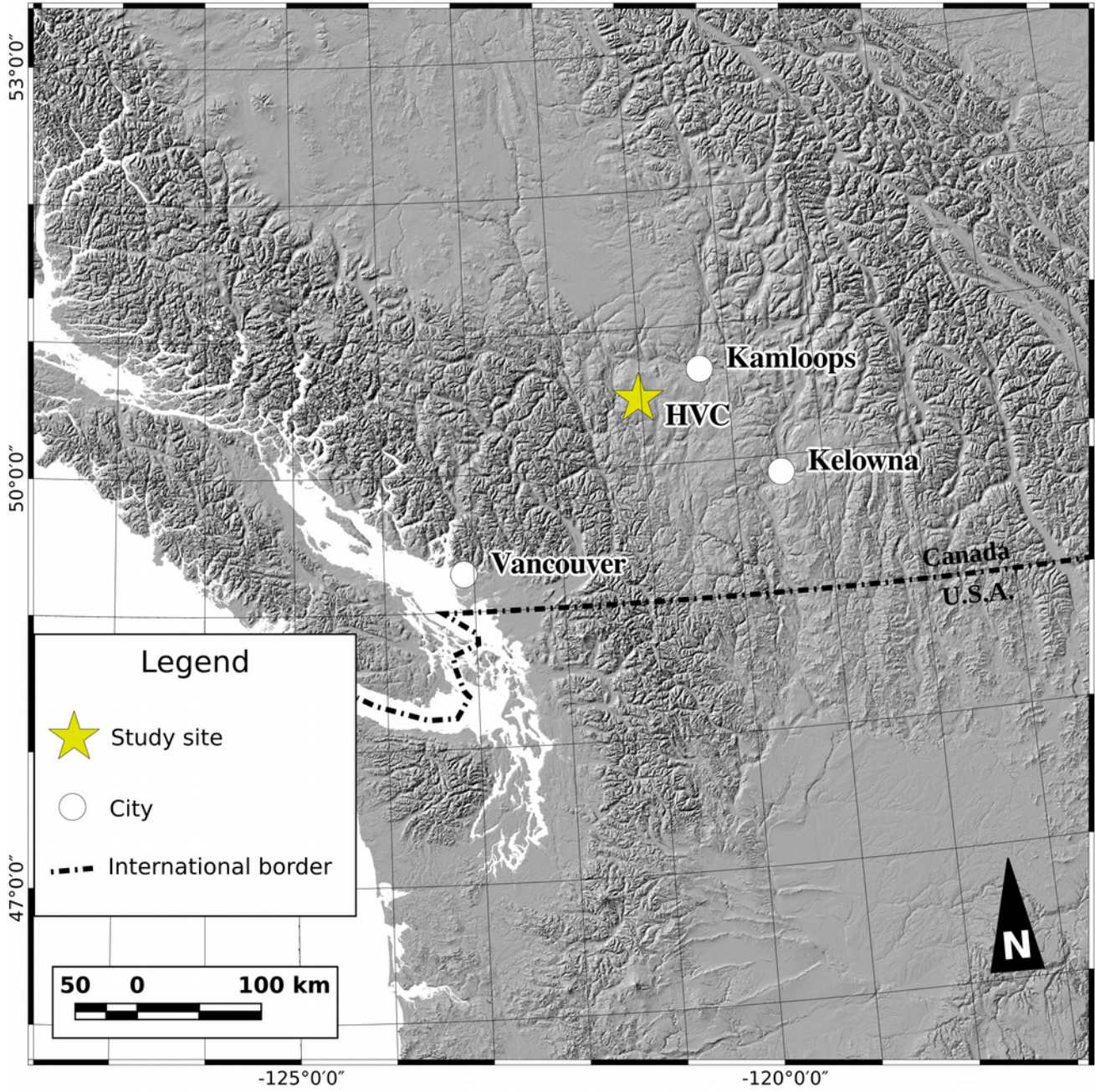


Figure 1.1. Hillshade map showing location of the Highland Valley Copper Valley Pit (HVC).

Converted from Shuttle Radar Topography Mission data (SRTM DEM; NASA:

<http://dds.cr.usgs.gov/srtm/>) in QGIS (software).

Quality sedimentary records representing this interval are rare in British Columbia mainly due to the erosion and burial of earlier unconsolidated Quaternary sediments by subsequent continental-scale glaciations. Recent paleomagnetic data from the Highland Valley Copper Valley Pit (HVC) ~50 km west southwest of Kamloops, BC (Fig. 1.1) indicate that fossiliferous lakebeds straddle the most recent reversal (Jonsson et al. 2016). This horizon is currently dated to ~781 ka (radiometric (^{40}Ar - ^{39}Ar) and marine isotope records; e.g. Shackleton et al. 1990, Spell & McDougall 1992, Tauxe et al. 1996) and currently defines the Early/Middle-Pleistocene boundary (Richmond 1996, Gibbard & Cohen 2008) thus indicating that sediments of the MPT interval are preserved at HVC. This excellent exposure provides an exceptional target for study of a key time in Earth's history.

Prior work on the sediments at HVC has been conducted on a partial exposure (~150m) of the material (Bobrowsky et al. 1993, Fulton 1995). Available data from previous work includes preliminary stratigraphy, sedimentology, geochemistry, radiocarbon dating, bulk sample palynology and macrofossil content (Bobrowsky et al. 1993, Fulton 1995). Robert Fulton (unpublished data) also undertook early reconnaissance paleomagnetic analysis. Previous work on these beds placed little emphasis on paleobiology.

The previous work yielded little data to suggest sediments in Highland Valley are older than Late Pleistocene in age. Earlier interpretations of the pre-Holocene depositional setting include a proglacial lake overtopped by an ice advance (Bobrowsky et al. 1993) and later two glacial tills separated by a pre-Fraser Glaciation non-glacial lake (Fulton 1995). Organics (wood) recovered below the uppermost till at this site consistently generated radiocarbon ages beyond the limit of radiocarbon dating (Bobrowsky 1995, Fulton 1995, McNeely 2005; see Section 2.6) and the sediments found at the base of the earlier exposed sediments were normally magnetized (Robert Fulton, unpublished data). The uppermost till was originally correlated with the Kamloops Drift (Bobrowsky et al. 1993, Fulton 1995) which is assigned to the Fraser Glaciation (regionally ~19.1 ka BP to ~10.5 ka BP; Fulton 1978). This

is the typical assignment for most surficial tills in the region. The age of the lower till and intermediate material remained uncertain (Fulton 1995, McNeely 2005).

Reconfiguration of the Valley Pit in 2009 and 2010 (Piteau Associates Engineering Ltd. 2010) yielded an additional ~130m of sediments below the sequence described previously. This provides an opportunity to improve upon prior stratigraphic and chronologic work at HVC, as well as more abundant and stratigraphically better constrained macro- and microfossil material for study. This study takes advantage of this opportunity to improve the stratigraphy and chronology at HVC, and to investigate the nature of the paleoclimate and paleoenvironment during the MPT in British Columbia. It is intended that by working towards this goal, this work will improve the general understanding of the characteristics associated with this key interval and strengthen knowledge of its character in North America.

Considering the large extent of the exposure at the Valley Pit a reconnaissance-scale evaluation paleobiological study was undertaken. Three main of this thesis are to:

- Describe the stratigraphy of the Quaternary sediments in Highland Valley and offer an interpretation of local geologic events based on lithological data.
- Use palynological analysis and macrofossils to describe paleoclimate and paleoenvironment intervals within the inter-till lake sediments.
- Estimate the chronological extent of the record and associate local events to global ones.

Chapter 2: Background

This chapter discusses the geology, physiography, and biogeoclimate setting of the southern British Columbia interior and focuses specifically on the region around study site in Highland Valley. The immediate region around Highland Valley is known as the Thompson Plateau (Fig. 2.1, Holland 1964) so is of special focus. The discussion in this chapter begins with a description of bedrock geology then focuses on the physiography, climate and vegetation of the region. A separate discussion of regional Quaternary Geology is given extra treatment and follows. Lastly, an account of the study site itself follows this regional background with more specific information about the local conditions.

2.1 Bedrock Geology

The geologic history of the British Columbia (BC) portion of the North American Cordillera - an extensive series of mountain ranges along the western edge of the North American continent - is covered in detail elsewhere (e.g. Colpron et al. 2007, Mihalynuk, Nelson & Diakow 1994). This cordillera was formed gradually by the accumulation of numerous terranes tectonically wedged against the west edge of the North American continent (Coney et al. 1980). Numerous basalt flows (Ewing 1981a, 1981b, Monger, 1989a, 1989b, Church 1973) and depositional basins (Mustoe 2005, Cockfield 1948, Ewing 1981b, Rouse & Mathews 1961) later formed throughout the intermontane region during the Cenozoic. As a result the bedrock of the Cordillera is composed of a diverse mixture of allochthonous rocks with numerous intrusive bodies, lava flows and sedimentary units (e.g. Colpron et al. 2007, Mihalynuk, Nelson & Diakow 1994).

The latest Triassic-earliest Jurassic Guichon Creek Batholith makes up the basement rock at HVC. This body belongs to the Quesnel Terrane (Wheeler et al. 1991) and is presently interpreted to be comagmatic with other intermontane volcanic rocks of BC of the same age (McMillan, 1976). These

volcanics formed as part of an exotic volcanic arc during the upper Triassic to early Jurassic and eventually accreted onto the western edge of North America as part of the Intermontane Superterrane during the Middle Jurassic (Mihalynuk et al. 1994, Colpron et al 2007). The Guichon Creek Batholith consists of several phases which are differentiated by their varieties of quartz diorite and granodiorite (Northcote 1969). The ages of these phases are nearly identical resolving to the end Triassic to the earliest Jurassic Period in age (200 +/- 5 Ma (K-Ar; White et al. 1967), 198 +/- 8 Ma (K-Ar; Northcote 1969)).

During the Cenozoic Era the BC interior experienced lava flows and deposition of numerous lacustrine sedimentary sequences. The extensive Cenozoic lava flows include those of the Eocene Kamloops Group which can be found just south of 50°N to almost 52°N in the interior and occur on the Thompson Plateau (Ewing 1981a, 1981b). Other notable flows of the same age include the Princeton Group which together discontinuously extend from just north of Merritt to near the Canada-USA border (Monger, 1989a, 1989b) and the Penticton Group which is exposed north of Kelowna and south to almost 48°N (Church 1973). Notable fossiliferous sedimentary beds of Eocene age have also been found in the southern interior. These include the McAbee beds near Cache Creek (Mustoe 2005, Dillhoff et al. 2005), the Coldwater/Quilchena beds near Merritt (Cockfield 1948, Ewing 1981b, Mathews et al. 2016) and the Princeton Chert near Princeton (Rouse & Mathews 1961, Mustoe 2011).

The younger Oligocene to Late Pleistocene Chilcotin Group Basalts of the Nechako, Chilcotin, Cariboo and Thompson plateaus lie north-northwest of Kamloops and form the most recent episode of volcanism in the interior (Bevier 1983, Mathews 1989) including flows from the Early and Middle Pleistocene (Church 1980). Chilcotin group sediments have been described in several localities and include Pleistocene aged sediments such as at Dog Creek (Mathews & Rouse 1986) and in the Okanagan Valley (Roed et al. 2014). These Pleistocene deposits are treated in greater detail in Section 2.5.

2.2 Physiography

The Physiographic regions of British Columbia (BC) were defined by Holland (1976) where the landscapes of BC were divided into a diverse set of regions. Of interest is the description of the Thompson Plateau in particular where the study area is located. The Thompson Plateau is the southernmost part of the Interior Plateau which is a region circled by the Coast and Cascade Mountains to the west, Skeena and Omineca Mountains to the north, and the Rocky and Columbia Mountains to the east and southeast (Holland 1976). The Thompson Plateau is bordered on the west and south by a number of defined mountain ranges and on the east by the Okanagan and Shushwap Highlands (see Fig. 2.1, Holland 1976). The northern boundary of the Thompson Plateau is determined by the transition into largely undissected late Miocene to Pliocene basalt flows which cover a large part of the Fraser Plateau to the north (Holland 1976).

Overall the Thompson Plateau is a gently rolling upland plateau with low relief and elevations typically between ~1200-1500 m above sea level (m asl) with peaks as high as 2247 m asl (Holland 1976). The plateau is further dissected by the Thompson, Similkameen and Okanagan Rivers and their tributaries which result in many valleys only a few hundred meters above sea level at their base. The Thompson and Okanagan valleys are particularly deep and are far deeper than any of the other valleys on the Thompson Plateau having been dissected by both fluvial and glacial processes (note light blue valleys in Fig. 2.1).

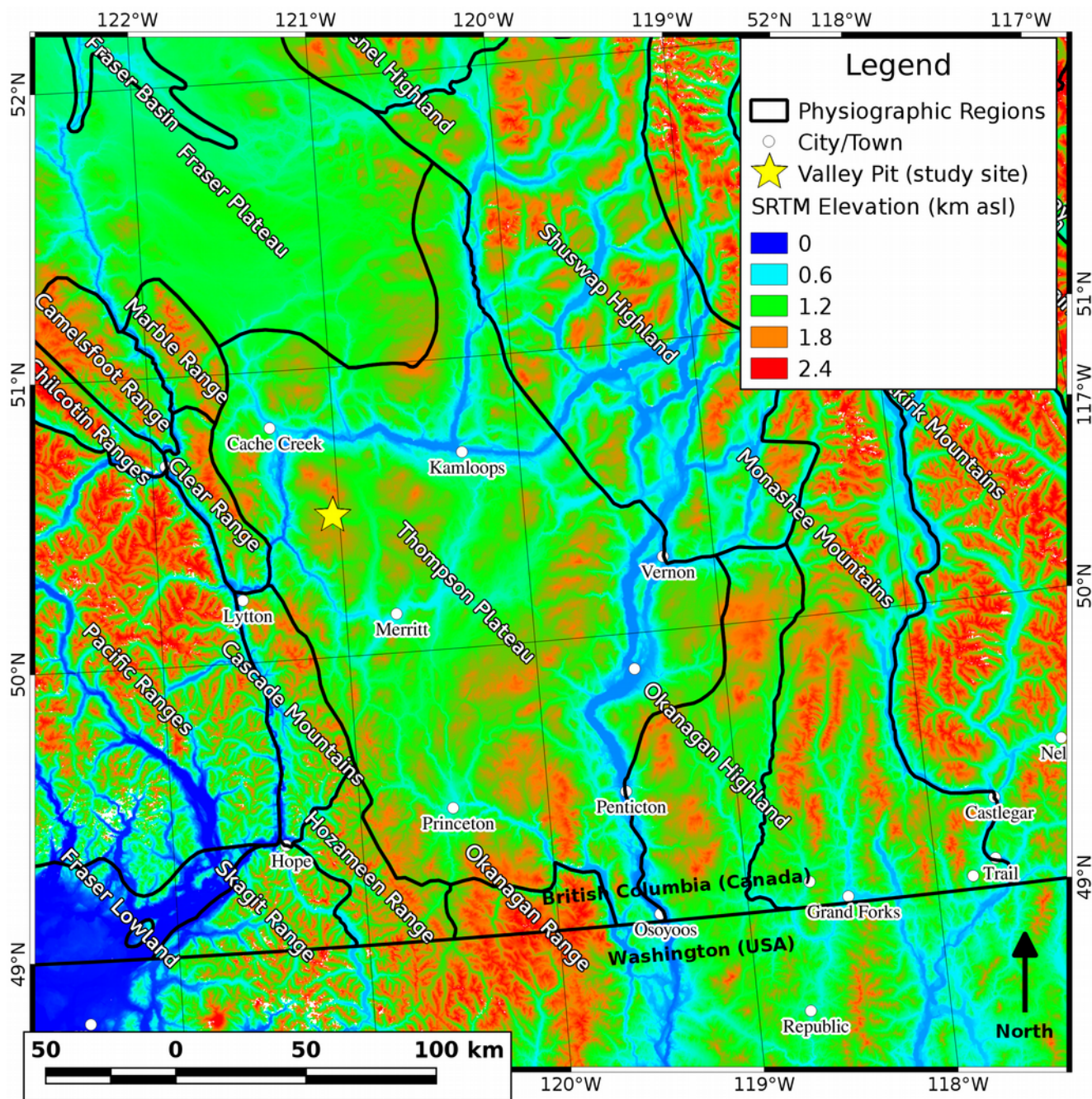


Figure 2.1. Topographic map of part of southern British Columbia showing the location of the HVC Valley Pit, the geographic extent of the Thompson Plateau and nearby physiographic regions. Elevation data from from the Shuttle Radar Topography Mission (NASA: <http://dds.cr.usgs.gov/srtm/>). Physiographic regions after Holland (1976; digitized version by Mihalynuk 2009).

The Thompson Plateau also represents an area of low terrain in the BC Cordillera relative to most of the surrounding terrain. The region is surrounded mostly by high mountain ranges and highlands to the west, east and south with the only adjacent relatively low region, the Fraser Plateau to the north (see Fig 2.1). As discussed later, this feature has strong implications for the overall climate, as the surrounding topography restricts airflow and moisture across the Plateau (see Valentine et al. 1978 for instance). In addition to this, the deep valleys amid rolling uplands further promote substantial local-scale climate and vegetation gradients within the region (Meidinger & Pojar 1991).

2.3 Climate

The southern interior of BC consists of a widely diverse landscape with a climate driven by both the proximity to the Pacific Ocean and long bordering mountain belts. These high elevation belts tend to starve moisture from the interior of BC from westerly air moving over the Coast and Cascade Ranges. In addition, the interior is largely protected from arctic continental winter air masses by the Rocky Mountains to the east (Valentine et al. 1978). The resulting climate is semiarid with temperatures moderate to warm overall, a pattern which is reflected by the regional vegetation (Pojar & Meidinger 1991).

The rain shadow effect from the Coast and Cascade range results in low precipitation in the southern interior ranges, mostly between 225 and 750 mm year⁻¹ (Environment Canada 2015, Fig. 2.2). Some of the driest conditions within this region occur generally south of 53°N only becoming moister south of Princeton where the Okanagan Range modifies the amount of descending air and hence results in less removal of moisture. Highland Valley itself is situated at roughly 50.5°N within this area of extreme dry lowlands but on elevated, slightly moister and cooler uplands than the extremely dry valleys below.

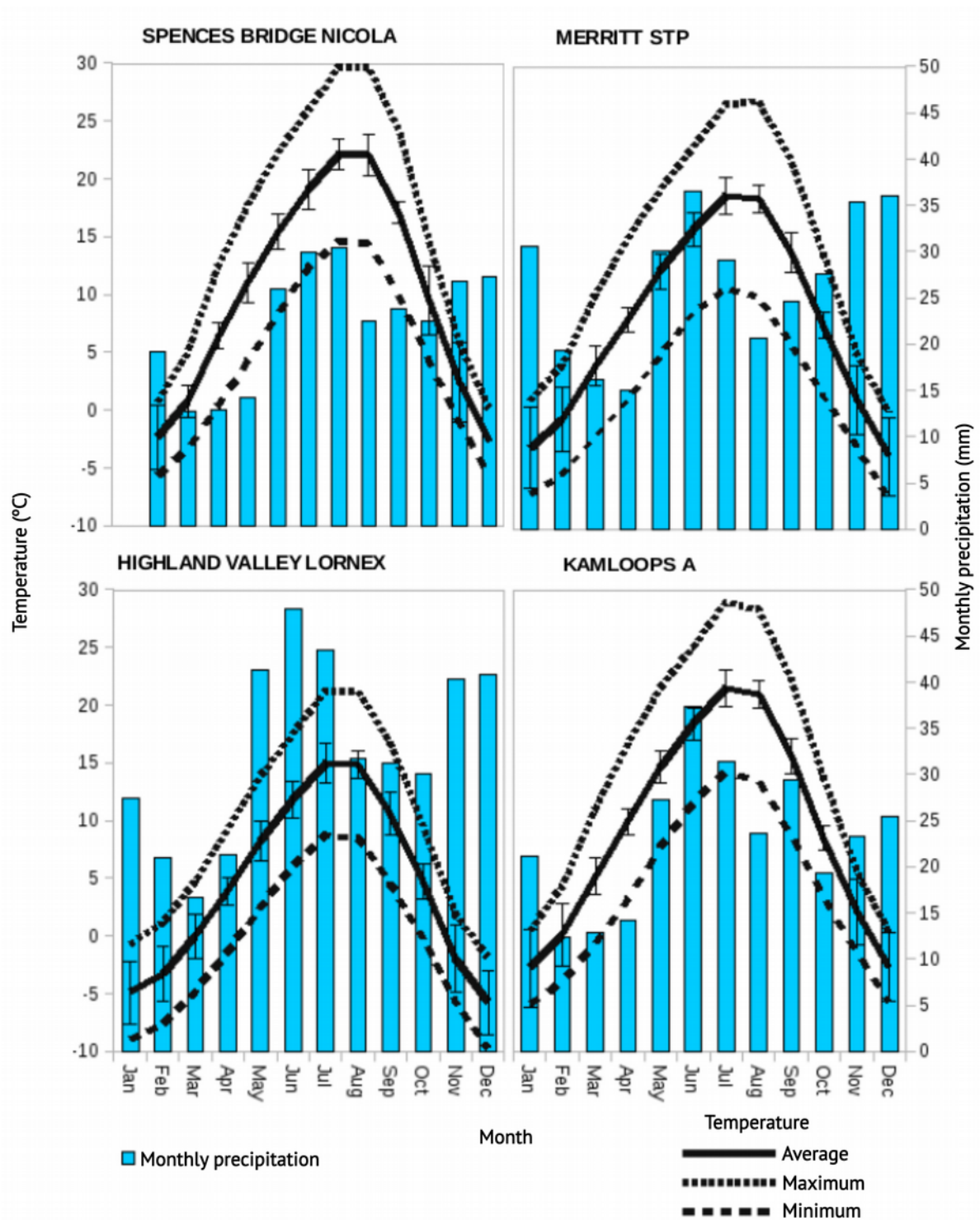


Figure 2.2. Normal climate conditions for four nearest sites to the Highland Valley locality. Data here were compiled from the Government of Canada climate data archives (http://climate.weather.gc.ca/climate_normals/station_select_1981_2010_e.html).

Air temperature trends in the region follow the local topography and are highly variable but systematic trends varying mostly as a function of elevation. The highest mean annual temperatures (MATs) in the region are found in the deepest valleys, where they range between 5 to 10°C, comparable to the warm coastal regions of the province (Environment Canada 2015). MATs in the southern interior decreases with elevation reaching as low as 2 to 5°C at higher altitudes (Environment Canada 2015).

Winter temperatures (December through February) in the lower elevations of the Southern Interior (Stations KAMLOOPS A, MERRITT STP and SPENCES BRIDGE NICOLA in Table 2.1 for examples) are typically no colder than about -5.8°C with rare extremes (Fig. 2.2; Environment Canada 2015). At slightly higher elevations in Highland Valley, average temperatures in the coldest month, December, are around -7°C (Fig. 2.2; Environment Canada 2015). In contrast, summer temperatures (June through August) in the interior valleys tend to be about 20°C on average whereas average summer temperatures in Highland Valley are typically around 5°C cooler (Fig. 2.2; Environment Canada 2015).

2.4 Vegetation and soils

Owing to its complex geography and climate, British Columbia consists of numerous biogeoclimatic (BGC) zones (Meidinger & Pojar 1991). The sixteen general zones defined for the province are broadly distributed throughout, varying by latitude, elevation and distance from the Pacific coast. Boreal and sub-boreal spruce zones (Boreal White and Black Spruce and Sub-boreal Spruce) dominate the northern half of the province north of 52°N, while warmer types of BGC zones make up most of the communities in the southern half (Ministry of Forests, Lands and Natural Resource Operations 2016a). The Coastal western hemlock (CWH) BGC zone occurs along the coastal regions (Ministry of Forests, Lands and Natural Resource Operations 2016a) under higher

precipitation and mild temperatures associated with adiabatic forcing along the Coast Range (Ministry of Forests, Lands and Natural Resource Operations 2016a). The resulting rain shadow on the lee side of the Coast Range, particularly in the southern BC interior, supports the Interior Douglas-fir (IDF) BGC zone which makes up the dominant forest type in the BC interior south of 52°N.

The southern interior of BC in the vicinity of the study area is characterized by a variety of dry to mesic types of biogeoclimatic zones (summarized in Table 2.3). Low elevation valleys typically support steppe vegetation of the Bunchgrass (BG) BGC zone. At slightly lower temperatures and with increased precipitation the Ponderosa pine (PP) BGC Zone parkland and forest are found adjacent to the IDF BGC zone at moderate elevations (~1 km asl). The scattered high elevation parts of the region (>~1.4 km asl) support the Montane Spruce (MS) zone, which transitions into the Engelmann Spruce-Subalpine Fir (ESSF) BGC zone at the highest elevations.

A further breakdown to BGC subzone around the northern Thompson Plateau yields more insight into the climate and vegetation that characterizes the area around the study site. The Highland Valley around the Thompson Plateau contains seven specific subzones of interest in this study (Table 2.1). Lower elevations contain steppe communities of either Nicola Very Dry Warm (BGxw1) or Thompson Very Dry Hot (BGxh2) subzones (Fig. 2.3). The BG zones are characterized by ~60% widely spaced Bunchgrasses (*Agropyron spicatum*) with a cryptogam crust (Nicholson et al. 1991). The BGxh2 subzone is distinguished from BGxw1 by the additional abundant presence of *Artemisia tridentata* (Nicholson et al. 1991). Owing to the aridity of these deep valleys this zone is commonly associated with chernozemic soils in the Thompson River and east Nicola valleys, and the eutric brunisols of the southern Thompson River and west Nicola valleys (Nicholson et al. 1991, Lord & Valentine 1978).

At ~ 550 m asl, the BG zone transitions into the Ponderosa Pine Thompson Very Dry Hot subzone (PPxh2; Fig 2.3). This zone is the warmest and driest forested zone in BC, and is dominated by

Ponderosa pine (*Pinus ponderosa*) with a Bunchgrass understory (Hope et al. 1991a). The PPxh2 subzone contains abundant Rocky mountain fescue (*Festuca saximontana*), Idaho fescue (*Festuca idahoensis*) and has other differences in the forb assemblage. It is the driest variant of this particular BGC zone (Hope et al. 1991a). Like the BG zone, chernozemic and eutric brunisols are the primary soils developed in these zones (Hope et al. 1991a, Lord & Valentine 1978) reflecting the very dry conditions. This zone grades into the IDF zone at around 1250 m asl.

The IDF zone in the HVC area consists of two subzones, the Thompson Very Dry Hot (IDFxh2) and Thompson Dry Cool (IDFdk1) subzones (Fig. 2.3). Subzones IDFxh and IDFdk can be differentiated by the abundant presence of either *Pinus ponderosa* or *Pinus contorta*, respectively (Hope et al. 1991b). The latter zone occupies lower slopes of the Thompson Plateau whereas the former occupies elevations between ~1250 to ~1450 m asl which is coincident with the elevation of the Highland Valley, the immediate landscape around HVC and most of the Thompson Plateau (Fig. 2.3). Soil on the Thompson Plateau consists mainly of eutric brunisol and gray luvisol (Valentine & Dawson 1978, Hope et al. 1991b); in contrast with the chernozems of the valleys. The gray luvisols are the most extensive soil type in the Interior Plateau occurring where medium- to coarse-grained surface till lies over the surface (Valentine & Dawson 1978). These soils are alkaline reflecting the parent volcanics and limestone bedrock sources worked into, and deposited as, surficial till (Valentine & Dawson 1978).

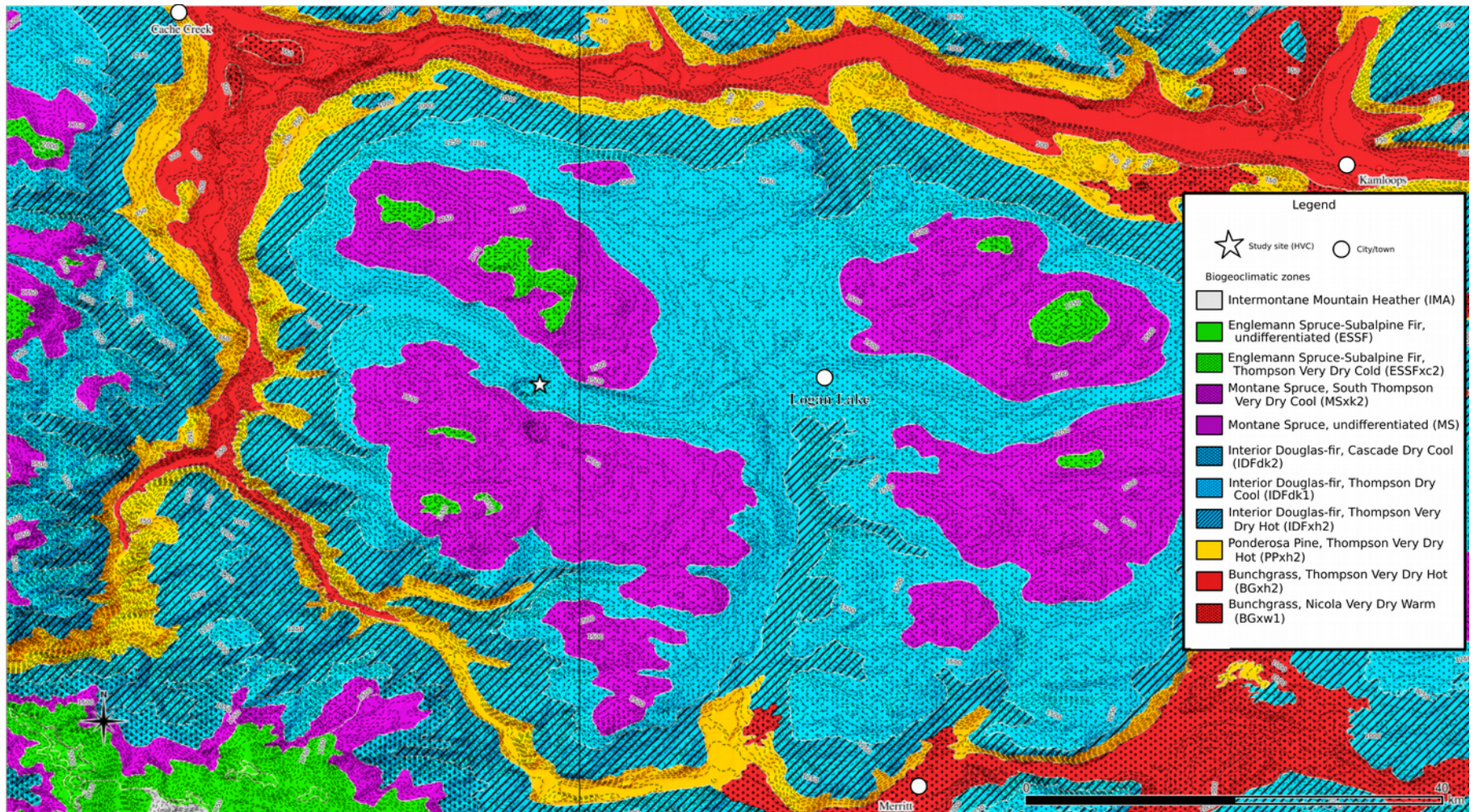


Figure 2.3. Biogeoclimatic subzones around Highland Valley, British Columbia. Data for this map was sourced from the British Columbia Ministry of Forests, Lands and Natural Resource Operations (2016b).

Table 2.1. Modern biogeoclimatic zones around the Highland Valley Copper locality based on descriptions offered in Meidinger and Pojar (1991).

Biogeoclimatic classification		Approx. elevation (m)		dominant vegetation ¹	
zone	variant and subzone ²	Lower ecotone	Upper ecotone	common to subzones	characteristic of subzone
Bunchgrass (BG)	Thompson very dry hot (xh2)	< 335	~600	BG	AT
	Nicola very dry warm (xw1)	< 335	800-920		mixed forbs
Ponderosa Pine (PP)	Thompson very dry hot (xh2)	~550	900-1000		PP BG RIF
Interior Douglas Fir (IDF)	Thompson very dry hot (xh2)	800-900	~1250	DF WS PG	PP
	Thompson dry cool (dk1)	~1250	1400-1500		LP RF
Montane Spruce (MS) ²	South Thompson very dry cold (xk2) ²	1400-1500	1600-1800		LP ² hWS ² GB ² PG ²
Engelmann Engelmann Spruce - Subalpine Fir (ESSF)	Thompson very dry cold (xc2)	1600-1800	>1800		GB SF ES FB

1 - List of vegetation from highest to lowest abundance and limited to enough types to differentiate the zone/subzone. Listed taxa >10%. Abbreviations used: BG - Bunchgrass (*Agropyron spicatum*), AT - Big sagebrush (*Artemisia tridentata*), DF - Douglas-fir (*Pseudotsuga menziesii*), PP - Ponderosa pine (*Pinus ponderosa*), LP - Lodgepole Pine (*Pinus contorta*), PG - Pinegrass (*Calamagrostis rubiscens*), WS - White spirea (*Spiraea betulifolia*), RF - Red-stemmed feathermoss (*Pleurozium schreberi*), RIF - Rough or Idaho fescue (*Festuca scabrella/idahoensis*), GB - Grouseberry (*Vaccinium scoparium*), SF - Subalpine fir (*Abies lassiocarpa*), ES - Engelmann spruce (*Picea engelmannii*), hWS - Hybrid white spruce (*Picea engelmannii* x *glauca*), FB - Five-leaved bramble (*Rubus pedatus*). 2 - Classification based on current table of subzones in British Columbia Ministry of Forests and Range (2008). 3 - Described under MSxk in Lloyd et al. (1990) where specific vegetation data for MSxh2 was taken from for this table.

The local IDFdk1 subzone transitions into the MS South Thompson Very Dry Cool subzone (MSxk2) above ~1400-1500 m asl and then into the ESSF Thompson Very Dry Cold subzone (ESSFxc2) at around 1600-1800 m asl (Fig. 2.3). Several major tree species in the MS zone include

Lodgepole pine, Subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*), as well as Douglas-fir in some variants (Hope et al. 1991c). The ESSFxc2 subzone in contrast contains a limited assemblage of tree species, consisting of mostly Subalpine fir and Engelmann spruce with an underbrush of mostly Grouseberry (*Vaccinium scoparium*) and Five-leafed bramble (*Rubus pedatus*) as well as several minor species (Coupé et al. 1991).

2.5 Quaternary geology

The Quaternary stratigraphic and chronologic framework of the southern interior of BC is largely based on early work by Fulton and Smith (1978). Four major units were defined (Fulton & Smith 1978): the Westwold Sediments, the Okanagan Centre Drift, the Bessette Sediments and the Kamloops Drift. The latter two of these units have been assigned to the Olympia Interglaciation (or interstadial; see Hebda et al. 2016; ~60-22 ka) and the Fraser Glaciation (~22-10ka). These were assigned on the basis of radiometric ages (~19-31ka) from the Bessette Sediments near Lumby, BC with the Westwold Sediments and the Okanagan Centre Drift inferred to correlate with the early and mid-Wisconsinan North American stages (Fulton & Smith 1978). These units have been correlated throughout the deeply incised valleys of the southern interior of BC (Fulton & Smith 1978).

Most of the Quaternary work in the BC interior since then has correlated the uppermost drift and interglacial units to this particular schema. Drift deposits cover the majority of the BC interior (e.g. Plouffe & Ferbey 2015) and are typically interpreted to correlate with the Kamloops Drift (e.g. Fulton et al. 1991, Lian et al. 1999, Roed et al. 2014) despite the absence of good chronological control, especially for the underlying units correlated with Bessette Sediments (Fulton & Smith 1978).

Outside of the Lumby area there are few reliable dates available for deposits correlated with the Bessette Sediments. Near Kamloops data have yielded mixed ages for preglacial late Wisconsinan sediments. In a pit 8 km west of Kamloops both finite (25.2 +/- 0.46 ka BP; shells; GSC-79; Dyck &

Fyles 1963 and 24.2 +/- 0.29 ka BP; shells; GSC-79-2; Lowdon et al. 1967 [both the same sample]) and 'infinite' (>35.5 ka BP; shells; GSC-413; Dyck et al. 1966) ages have been reported. At Peterson Creek in Kamloops, an infinite date is reported on preglacial material below till (>32.7 ka BP; wood; GSC-275; Dyck et al. 1966). In the former case, the infinite age is stratigraphically higher than the finite one, which likely indicates contamination of the former. Re-examination of these ages is also needed as recently acquired data from preglacial material is lacking. The age of the Bessette-correlated sediment candidates in the Kamloops region thus should be regarded as unresolved. In the absence of these constraints on the Bessette Sediments outside the Lumby area, the age of the overlying strata must also be considered uncertain.

The remaining two units - Westwold Sediments and the Okanagan Drift - have ages that are speculative at best since they are beyond the limit of radiocarbon dating (Fulton & Smith 1978).

Table 2.2. Early Pleistocene glacial records from British Columbia prior to this study.

	Age	Supported by	Name	Location
Mathews & Rouse 1986	1-1.4 Ma	Basal (>1.4 Ma) and capping basalt dates (>1-1.2 Ma)	Dog Creek Formation	Dog Creek Valley
Fulton et al. 1992	Matuyama	Magnetically reversed	Sub-Coutlee Silts Coldwater Silts	Merritt
Lian et al. 1999	Matuyama	Magnetically reversed over normal sediment	"unit 47-4"	Marble Range
Roed et al. 2014	Jaramillo	Capping basalt dates (>0.97+/-0.03Ma) Magnetically normal	Westbank First Nations Till	West Kelowna, Okanagan Valley

Numerous studies have suggested that multiple glaciations occurred throughout the BC interior prior to the Late Pleistocene (e.g.s Fulton & Smith 1978, Fulton et al. 1992, Lian et al. 1999, Nichol et al. 2015). In this context whether or not Middle Pleistocene strata occur more broadly in the BC interior is largely unknown.

Several investigations have unambiguously identified Early Pleistocene deposits in BC, largely owing to the application of paleomagnetic analysis (Table 2.2). These Early Pleistocene sites can be grouped into three periods of glacial advance. Collectively, these represent two to four cold events. It is possible the Dog Creek 1-1.4 Ma (Mathews & Rouse 1986) and Westbank First Nations Till (Roed et al. 2014) are from the same cooling event as the Jaramillo subchron occurs within the same constraining age as the former. The other two could also be related or unrelated as multiple cooling events occur within the same chron (Lisiecki & Ramo 2005). Unfortunately, these sites contain discontinuous records which make this determination difficult.

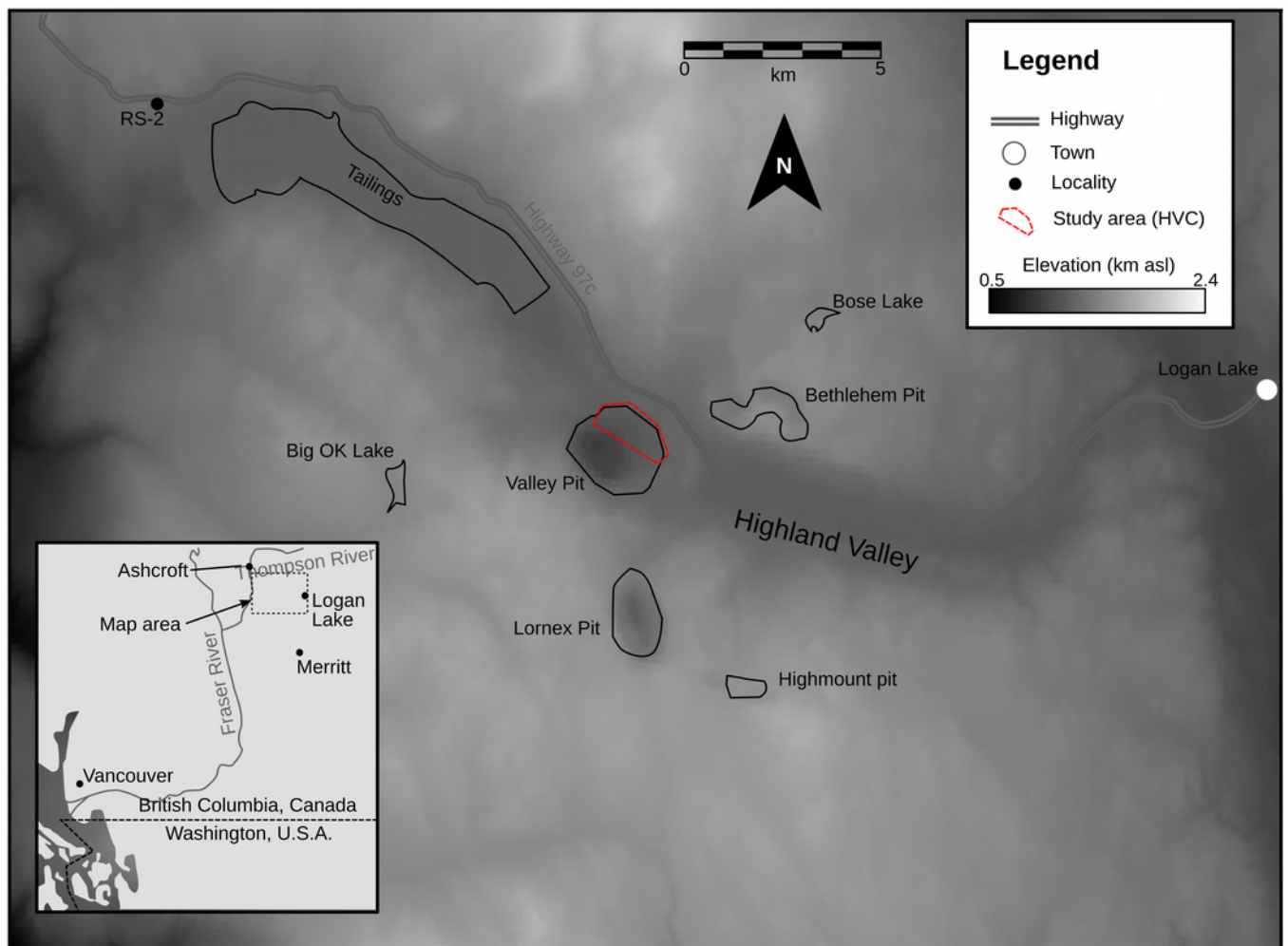


Figure 2.4. Map of the study region showing the Highland Valley Copper location and elevation.

2.6 The Highland Valley Copper study site

The Highland Valley Copper Valley Pit (HVC) site is situated ~15 km west of Logan Lake, British Columbia along Highway 97c within Highland Valley on the Thompson Plateau (Fig. 2.4). The Highland Valley is an east-west oriented valley bounded on the north by the Glossy Upland, and on the south by the Gnawed Upland rising ~600-700 m above the valley. The Highland Valley terminates with the Guichon Valley to the East and the western mouth of the Highland Valley opens into the deeply incised Thompson River Valley which wraps around the northwest corner of the local uplands.

The Valley Pit is cut into the Bethsaida (quartz monzonite) and Bethlehem (granodiorite) phases of the Guichon Creek Batholith (McMillan 1969, Piteau Associates Engineering Ltd. 2010). The former of these phases is found west, and latter east of the Lornex fault (McMillan 1969, Piteau Associates Engineering Ltd. 2010). Cenozoic lava flows (andesite and dacite mostly) overlie the felsic bedrock in places both below the overburden at HVC (McMillan 1976) and in parts of the surrounding uplands (Scharizza et al. 1994, Scharizza & Church 1996). Overburden is primarily concentrated on the northeast edge of the pit as the Valley Pit itself cuts into the rocky side of the valley. This overburden was studied previously when it was less well exposed, and was limited to material above 1100 m asl (Bobrowsky et al. 1993, Fulton 1995).

Table 2.3. Previously described stratigraphic units and ages within the overburden at HVC. All data from Bobrowsky et al. (1993) unless otherwise indicated.

Unit	Approximate elevation (m asl)	Description, ages	Interpretation
	~1210	Remnant McNaughton lake beds. 7.08 +/- 0.1 ka BP (GSC-4054) ^a , 7.58 +/- 0.08 ka BP (GSC-4050) ^a , 8.13 +/- 0.1 ka BP (GSC-4061) ^a and 8.33 +/- 0.1 ka BP (GSC-4046) ^a .	Holocene lake deposit
IX	1205 - 1210	Remnant Quiltanton Lake (drained) beds. Sand, marl, and peat with shells. 9.6 +/- 0.07 ka BP (TO-215) at base.	Holocene lake deposit
VIII	1200 - 1210	~ 6m thick stratified sand, gravel and diamicton. Sharp erosive contact at base.	Braided stream deposits from <i>in-situ</i> ice decay
VII	1220 -1260	33 m thick, stratified sand, gravel and diamicton.	Supraglacial depositional facies
VI	1200 - 1220	25 m thick, diamicton with lenses of stratified coarse sand and pebbly gravels.	Basal till
V	1186 - 1202	10 m thick, discontinuous, sands and gravels. Includes stratified sandy silt, silty sand and diamicton lenses.	Subglacial outwash
IV	1150 - 1200	55 m thick, poorly stratified matrix supported and clast supported diamicton (granules to boulders). Gravels, sand lenses and dropstones.	Proglacial/subglacial outwash
III	1130 - 1155	Up to 25 m thick, steeply inclined sand and sandy gravels. Includes wood. Discontinuous diamicton, and dropstones interbedded with increasing frequency with height. >48 ka BP (GSC-5838; wood) ^b .	Foreset beds
II	1100 - 1130	35 m thick, grey silty clay and clayey silt rhythmite. >44.45 ka BP (Beta-47216; <i>Picea</i>), >45.07 ka BP (Beta-48735; <i>Picea</i>), >39 ka BP (GSC-5531; wood) ^b , >47 ka BP (GSC-6013; wood) ^b . Magnetically normal.	Glaciolacustrine or non-glacial lacustrine ^c
I	1100 - 1120	6-10 m thick, oxidized silty sand and sandy gravel. Thin unit in contact with bedrock.	colluvium or till ^c

a - McNeely & McCuaig (1991)

b - McNeely (2005)

c - Fulton (1995)

Notes:

- Three further unpublished ages are included in Fulton (1995), however, their position in this stratigraphy is uncertain: >42.19 ka BP, >42.07 ka BP and 41.12 +/- 3.390 ka BP (all AECV-1734C).

Bobrowsky et al. (1993) originally described nine units (Table 2.3). Most of which were cautiously attributed to the Wisconsinan Glaciation (Bobrowsky et al. 1993). The lack of finite ages from pre-Holocene materials at HVC remains a problem with this reconstruction (Bobrowsky et al. 1993, Fulton 1995). The single finite age (see notes in Table 2.3) is too close to the radiocarbon limit to be considered reliable, hence all the presently known ages below the latest drift deposits (Units IV-IX in Table 2.3) should be considered beyond the radiocarbon limit (Fulton 1995). Earlier work prior to the expansion of the pit also indicated that basal sediments prior to expansion had a normal magnetic polarity (Fulton 1995).

Little work on the paleontological data available at the site has been published being limited to brief mention in Bobrowsky et al. (1993) and Fulton (1995). These include the presence of *Picea* wood pieces, freshwater gastropod and bivalve fragments, a bulk pollen spectrum (Jetté in Bobrowsky et al. 1993) and cones of *Pinus* and *Picea* from the lacustrine unit (Fulton 1995). The single count bulk pollen spectrum reported in Bobrowsky et al. (1993) consists of mostly *Artemisia*, *Pinus* and *Picea* pollen with some grasses and small numbers of other types. This is apparently similar to another pollen spectrum of Bessette Sediments found at Meadow Creek (Bobrowsky et al. 1993, Alley et al. 1986).

Chapter 3: Methods

The majority of the work undertaken in this study involved collecting and compiling stratigraphic data followed by palynological sampling and analysis. Conventional approaches were used, however due to challenges such as accessibility to some parts of the exposures meant field sampling was suboptimal. This was also due to safety considerations while collecting. Generally, the methods used were suitable for reconnaissance-level investigation of the HVC material.

3.1 Field work, sampling and dating

Stratigraphic data collection and sampling from the northeast side of the HVC Valley Pit was conducted over the course of two field seasons (2014, 2015) under the safety and logistic constraints of working in an active open pit mine. Specific field sampling sites (Table 3.1) were chosen in the field where there was safe access and such that most of the exposed record was represented. Access was facilitated by benched terraces sculpted from the overburden and in the bedrock. Each bench is engineered and maintained to be at a precise elevation, which aided in the reconstruction of the sedimentary sequence. Sampling of a few sections was not possible because of mining activities and pit engineering limitations. For example, debris aprons at most sites and some broad, angled road cuts which obscured the stratigraphy presented challenges. As a consequence, direct correlation between sites of some specific beds was not immediately possible.

Table 3.1. Table of localities at HVC.

Site	GPS coordinates	Elevation (m asl)*	Site	GPS coordinates	Elevation (m asl)*
HVC-1	50°29.38'N 121°2.040'W	1050	HVC-5	50°29.70'N 121°2.074'W	1160
HVC-1a	50°29.39'N 121°2.053'W	1050	HVC-5b	50°29.68'N 121°2.035'W	1154
HVC-1b	50°29.37'N 121°1.972'W	1059	HVC-6	50°29.78'N 121°2.155'W	1183
HVC-2	50°29.53'N 121°2.186'W	1067	HVC-7	50°29.40'N 121°1.564'W	1218
HVC-2a	50°29.49'N 121°2.138'W	1066	HVC-8	50°29.17'N 121°1.542'W	1206 ^e , 1219 ^f
HVC-3	50°29.40'N 121°1.984'W	1070	HVC-9	50°29.53'N 121°1.841'W	1145
HVC-3b	50°29.32'N 121°1.901'W	1070	HVC-9b	50°29.49'N 121°1.750'W	1163
HVC-3c	50°29.29'N 121°1.898'W	1070	HVC-10	50°29.62'N 121°2.747'W ^g	1074
HVC-3d	50°29.45'N 121°2.014'W	1083 +/- 4 ^a		50°29.64'N 121°2.731'W ^h	1077
HVC-3e	50°29.52'N 121°2.115'W	1083	HVC-11	50°29.46'N 121°2.338'W	980
HVC-3f	50°29.67'N 121°2.641'W ^b	1081	HVC-11a	50°29.53'N 121°2.541'W	980
	50°29.69'N 121°2.584'W ^c	1092	HVC-12	50°29.64'N 121°2.052'W	1138
	50°29.69'N 121°2.529'W ^d	1094	HVC-13	50°29.39'N 121°2.181'W	1000
HVC-4	50°29.65'N 121°2.063'W	1139	HVC-14	50°29.56'N 121°1.728'W	1197
HVC-4a	50°29.72'N 121°2.598'W	1097			

* - +/- 1m, corrected using a topographic map. (a) GPS reading within exposure face on topographic map, uncorrected values reported. (b) at “thick tephra”, (c) start of sampling transect and (d) end of sampling transect above 1085 bench. (e) Base of peats and marls (f) Base of exposure. (g) At diamict exposure and (h) sandy charcoal bed.

Lithological characteristics were examined in a continuous sequence at each site (Table 3.1) and in photographs. Further observations of sediment characteristics were made in the lab during palynological processing. Stratigraphic units and sampling positions were directly measured using a tape measure and thicknesses of units with reference to photographs and and further verified by the precise schematic maps provided by mine staff.

Sediment samples were removed from cleaned exposure faces for pollen and spore extraction using a clean shovel blade and then placed in plastic bags which were then sealed in the field. Care was taken

to carefully clean each sample to minimize potential contamination from modern atmospheric sources. With the intention of obtaining an evenly distributed temporal resolution, local sampling was based primarily on the character and rate of change in the lithology. For instance, dark organic sediments were sampled at a higher resolution than lighter mineral-rich ones. Pairs of samples were extracted immediately above and below sharp changes in sediment character. The stratigraphic thickness of each sample is estimated to be less than 5 cm thick. Samples which lacked substantial fine-grained material were not processed or analyzed for palynological purposes as these sediments rarely preserve pollen and spores.

Paleomagnetic sampling was done in parallel with the other sampling for analysis at the University of Lethbridge by Rene Barendregt. Samples were collected using plastic cylinders with their in-situ orientation recorded after Barendregt et al. (2010). These samples were obtained within wet fine-grained (up to very fine sand) units or from within matrix material where possible. Fine grains were chosen because fine-grained magnetic minerals orient more readily to the Earth's magnetic field and wet sediments were chosen since they have better cohesion than dry sediment, preventing sampling from disturbing mineral orientation during sampling and transport (Rene Barendregt, personal communication). Sediments containing occasional pebbles were avoided if possible as these clasts tend to orient randomly rather than with the natural magnetic field (Barendregt et al. 2010, Barendregt et al. 1991). Beds which showed indications of post-depositional disruption were purposefully avoided and care was taken to avoid placing paleomagnetic sediment samples near strong magnetic fields to reduce post-depositional influences on grain orientation.

Samples from suspected tephra beds were examined under a microscope for the presence of glass shards. From these samples, a subsample from one bed was sent to the Microbeam Lab at the Washington State University where it was examined for composition and compared to a database of known tephtras. A further six were subsampled into conical tubes and were submitted for ^{40}Ar - ^{39}Ar

dating at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia. At the time of writing results from only three of these later six subsamples are available.

Macrofossils found at the locality were collected carefully and packaged in bubble wrap or foam and then placed in rigid plastic totes for transport. Macrofossils recovered in the course of this study have been deposited at the Royal British Columbia Museum (RBCM) in Victoria, British Columbia, Canada. Current accession numbers for this collection start with RBCM.EH2015.001 and include the macrofossils discussed in this paper.

3.2 Palynology

In total, 95 samples were processed from HVC for the purpose of this study. Samples were prepared in pre-weighed 50 ml Nalgene centrifuge test tubes. Where possible, intact blocks of sediment were used and cleaned by scraping off the outer rind. Loose sediment samples where this was not possible the sediment was placed directly in the test tubes. The weight of the sediment was measured after the tubes containing sediment were initially allowed to dry in an oven at 40°C ~ 1-3 days after which a dry weight was obtained. Dried samples were rehydrated with reverse osmosis (RO) water then treated with diluted (10%) hydrochloric acid until reaction was completed. *Lycopodium clavatum* spore tablets (Lund University batch no. 177745; 18 584 *L. clavatum* spores per tablet) were added and stirred into the samples at this point to determine pollen concentrations after Stockmarr (1971). Prior to the application of *Lycopodium* spores, some samples were counted to ensure large amounts of *Lycopodium* did not make up the natural assemblage. In general, two to four *L. clavatum* tablets were added to samples with suspected high organic content, but only one or two tablets were added to high silicate samples. Samples were washed twice with RO water after this step.

The post-HCl residue was sieved through a 120 μm nylon mesh onto a 10 μm nylon mesh using a sieving apparatus (see Fig. 3.1) with a magnetic stirring rod to keep particles suspended. This type of screening with mechanical stirring is a cost-effective method to isolate pollen and reduce the required chemical treatment in low pollen density sediment (Heusser & Stock 1984). The choice of mesh size was expected to isolate most 10-120 μm particles which include the vast majority of temperate pollen and spores. Ten μm meshes have been used in studies which examined southern interior pollen before (e.g. Britnell 2012) and 120 μm is larger than the maximum diameter of the largest native pollen types such as *Pseudotsuga* (74-93 μm ; Owens & Simpson 1986) and *Picea* (81-109 μm ; Owens & Simpson 1986). The upper coarse fraction was set aside for future work such as a survey of



Figure 3.1. Sieving apparatus designed by Vera Pospelova (University of Victoria) for palynological application. Nylon sieves are attached to the open bottom of the plastic food containers as shown, and stacked with the coarser sieve on top. A stirring rod on the lower sieve is spun by a magnetic stirrer. Water and fine sediment is collected in the reservoir which is allowed to drain. RO water is fed into the system gradually until the water coming out of the lower sieve is clean and the material on that sieve is retained.

coarse organics in the samples while the 120-10 μm fraction was returned to the test tubes for further processing.

Concentrated HF (48-70%) was applied to the filtrate to remove the silica fraction. Due to the larger volume and slow reactivity of some of the samples they were processed in Nalgene beakers overnight and decanted the next day after all visible sediment had settled to the bottom. Samples were placed back in 50 ml test tubes and washed in RO water. Remaining silicofluorides were removed with an additional treatment with 10% hydrochloric acid and two more RO water washes.

A second sieving using only 10 μm nylon mesh ensured most of the remaining fine silica fraction and other debris were removed. Organic aggregates, which often formed at this step, were broken up using sonication as required for no more than one minute. The remaining residue was mounted on slides in glycerine jelly. A minimum of three slides were made per sample, with extra slides made in the event they were needed (when slides dried out for instance). Macrofossil samples and pollen and spore slides used in this study will be deposited in the collections of the Royal British Columbia Museum, Victoria, British Columbia.

3.3 Pollen identification, counting and analysis

A total of 85 samples were counted with the initial rejection of 10 samples due to unsuitable material for counting resulting after processing (n=8), or errors in labelling or field notes (n=2). A further two were in ambiguous stratigraphic positions so not included in the analysis (slumped block and event bed material; n=2). Pollen and spores were inspected along alternating side-to-side transects, taking care to leave a buffer between transect fields of view in order to avoid double counting grains. Pollen and spores were identified at 400x magnification resorting to 1000x or 2500x (oil) as necessary.

The pollen and spores were identified mostly to family or genus level and rarely to species level. Numerous resources were used to identify the palynomorphs including a reference collection at the Royal BC Museum, illustrated (Moore et al. 1994, Kapp 2000, Bassett et al. 1978) and a non-

illustrated (R. Hebda et al. unpublished key to pollen and spores of British Columbia) dichotomous keys as well as internet resources (e.g. Davis 2001).

Identification to species level or within a group of species was possible with two particular palynomorphs: *Polemonium pulcherrimum*-type and *Selaginella sibirica*. This was accomplished by both comparison with images and descriptions in literature (e.g. Reeve 1935, Heusser and Peteet 1988), and specific dichotomous keys for regional species (Heusser and Peteet 1988, Mathewes 1979). The specific reasoning for this identification is discussed in the results (Chapter 5).

To account for frequent breakage of bisaccate conifer grains, the bladders of these palynomorphs were treated as half a grain each to avoid over or under-representing these taxa.

For each processed sample (with the exception of samples with less than 30 grains per slide), counts were conducted until either all three (sometimes four) slides were examined or a total of at least 300 fossil pollen and spores were observed. Counts were entered into a spreadsheet, and exported in ‘csv’ (comma separated values) format as this is a human readable format also compatible with a wide variety of programs and is suitable for archiving. The exported pollen data were imported into and analyzed using the open source statistical program R (R Core Team 2016) and a number of libraries (Table 3.2).

Table 3.2. List of R libraries and their usage as used in pollen analysis and the presentation of data.

Library	Type	Usage	Citation
reshape2	Data manipulation	Convert data tables into differing formats (Changing columns into rows for instance)	Wickham 2007
plyr	Data manipulation	Arranging, splitting and recombining data sets	Wickham 2011
rioja	Statistical	Analysis of Quaternary science data. Used for the constrained cluster analysis (CONISS) done in this study	Juggins 2015
vegan	Statistical	Additional statistical functions	Oksanen et al. 2016
ggtern	Graph production	Ternary diagram production	Hamilton 2016
ggplot2	Graph production	Data presentation	Wickham 2009

Pollen data were separately analyzed in three separate sequences of samples because direct correlation of exposures was inferred rather than visibly evident in many places. Cluster analysis (CONISS) was conducted on each sequence of samples using the rioja library in R (Juggins 2015) to produce dendrograms which were consulted to inform the interpretation. Pollen diagrams and the related statistical diagrams were constructed in R using the libraries listed in Table 3.2.

Chapter 4: Stratigraphy and geochronology

The section at the Highland Valley Copper Valley Pit (HVC) consists of ~235 m of sediment exposed on the north-northeast wall of HVC. The exposure is divided into eleven stratigraphic units which include seven major units and four minor units. These are described in this chapter in the first main section (4.1) and interpreted in the following section (4.2). Geochronologic data collected during this study is reported in the following section. The paleomagnetic data reveals a paleomagnetic reversal roughly half way up the exposed sediments that forms the main constraint for the age of the HVC section. The two other methods, geochemical and radiometric tephrochronology, are also reported even though the results are inconclusive.

4.1 Stratigraphy

The eleven units described in this section are illustrated in Fig. 4.1. In this section the bedrock is briefly described in the first section then followed by a description of each of the seven major units (units 1-7) in order from bottom to top. The three minor units: 5a, 8a and 8b (Fig. 4.1) are also discussed. Unit 5a is reported as a special part of Unit 5 within the same subsection (4.1.6); the reason for special treatment of this bed is made clearer in the interpretation. Units 8a and 8b are discussed last (Sec. 4.1.9) which are far more recently deposited, however are not the focus of this study.

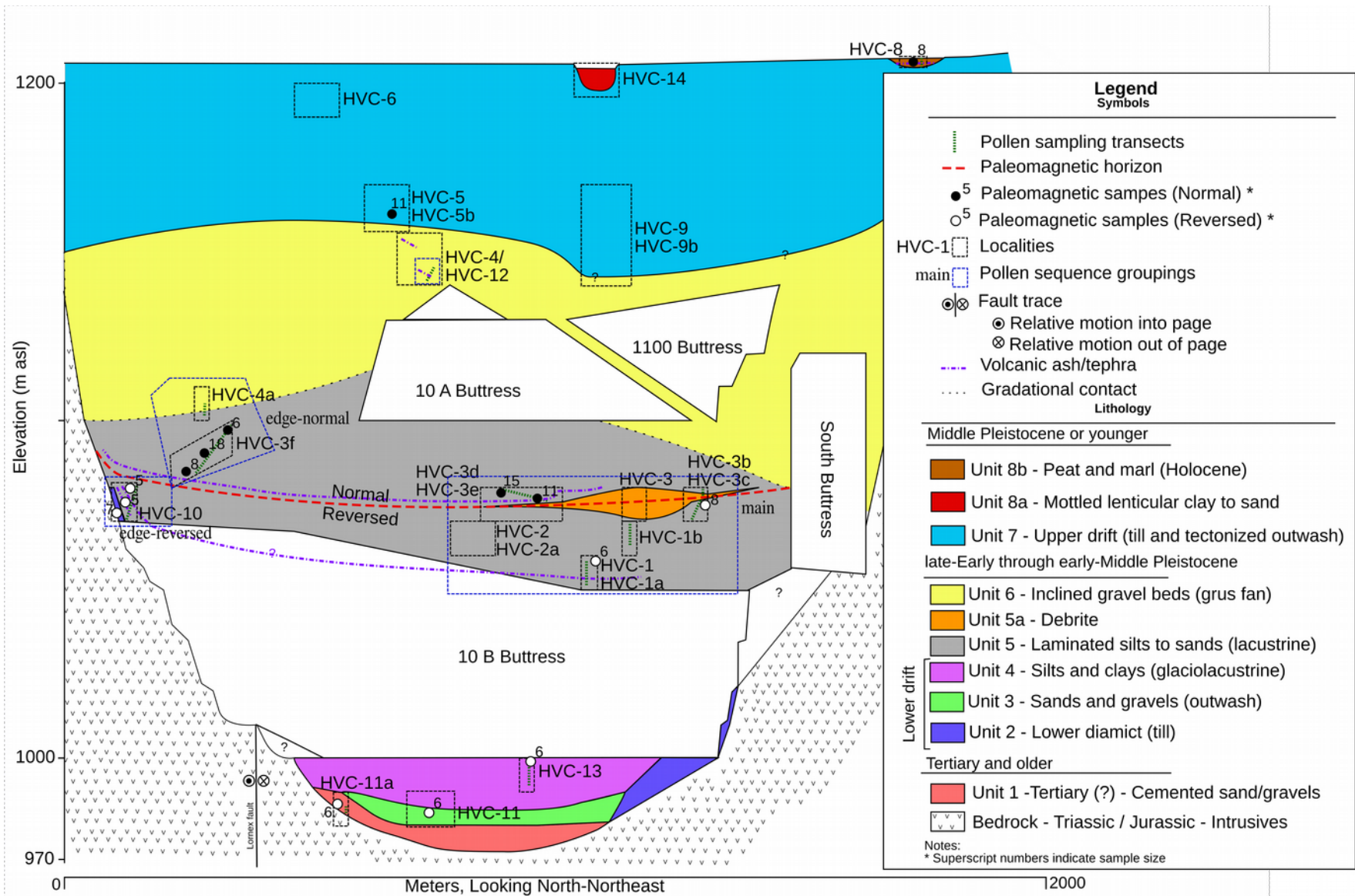


Figure 4.1. Schematic view of the sedimentary exposure at the HVC Valley Pit facing north-northeast.

4.1.1 Bedrock

The bedrock consists of intrusive volcanics (quartz monzonite) of the Bethsaida Phase of the Guichon Creek Batholith (McMillan 1976). A detailed description of this pluton can be found in numerous studies (e.g. Northcote 1969, McMillan 1976, Osatenko & Jones 1976) and has been summarized in Chapter 2. Bedrock is exposed throughout the pit as a result of mining and forms a u-shaped contact beneath the overlying sediments on a large scale when the pit is viewed from the west southwest (Fig. 4.1). The unit was closely observed in contact with overlying sediments at points along the bench at 980 m asl (HVC-11 and HVC-11a; 50°29.458' N, 121°2.338'W and 50°29.534' N, 121°2.541'W, respectively) as well as at ~1070m asl at HVC-10 (50°29.640' N, 121°2.747'W). This contact is well exposed at HVC-11a where angular bedrock-derived cobbles are present in the overlying gravels (Unit 1; see Fig. 4.2a). A similar contact is visible at HVC-10, where substantial cracking and heavy oxidization appear in the upper few meters of the bedrock below and to the contact with overlying material. Oxidized bedrock-derived clasts are also incorporated into the lower part of the overlying diamict (Unit 2, see Fig. 4.2b). In addition, this type of oxidization was also observed on bedrock surfaces along the exposure at HVC-11 in some places where the bedrock was found in contact with Unit 4 (Figure 4.2c).

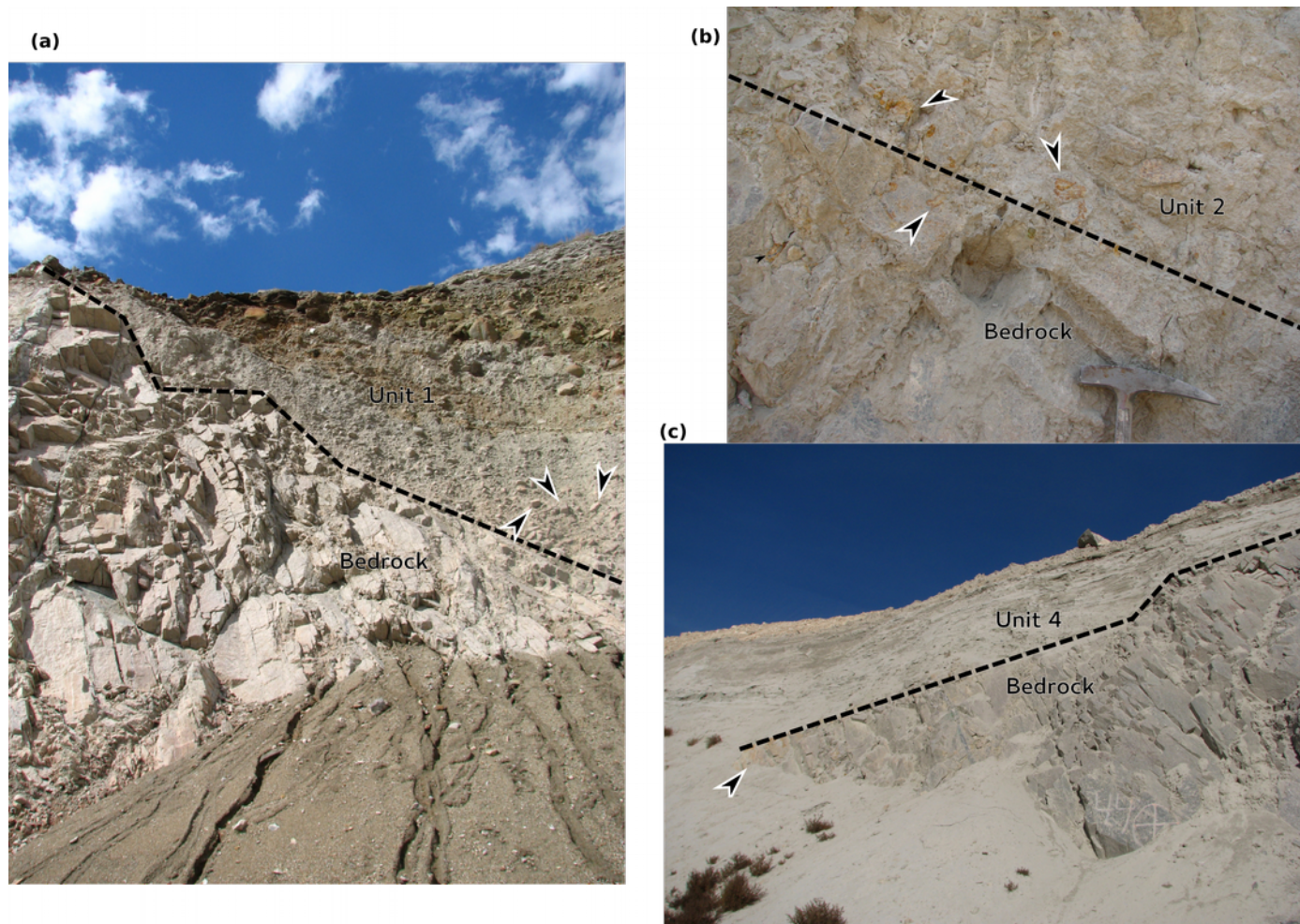


Figure 4.2. Bedrock contacts (dashed lines) with sediment at HVC. **a** - Unit 1 contact with bedrock at HVC-11a. Note the clast angularity and composition of basal Unit 1 material; examples indicated with arrows. Also note rusty red color in the upper part of Unit 1. **b** - Unit 2 contact with bedrock at HVC-10. **c** - Unit 4 contact with Bedrock at HVC-11. Arrows in Figures b and c show examples of weathered bedrock observed at the contact.

4.1.2 Unit 1 – Partially cemented red conglomerates and fine sands

A laterally discontinuous set of non-conformable beds were observed in patches along the bench at 980 m asl (HVC-11) between the bedrock and the overlying sedimentary units. The beds are up to 4 m thick in exposure at the north end of HVC-11. Where a complete sequence is present, the lower ~2 m consists of a basal bolder conglomerate containing poorly sorted mostly angular to occasionally rounded clasts within a sandy matrix. These beds are mostly cemented with non-calcareous cement. This part of the unit is interrupted every half meter or so by beds of loose grey fine to medium grained silty sands with minor black laminae. The upper two meters of these sediments consist of cemented reddish brown, graded pebbly sands to sandy pebbles which coarsen upward towards a non-conformity with overlying sediments. In places this upper contact occurs as a heavily weathered horizon; presumably a paleosol. A boulder lag is also evident between the upper and lower parts of this lower sequence (Fig. 4.3a).

Material from the upper two meters of this unit is highly oxidized and weathered (see Fig. 4.2a and Figs. 4.3a, b & c) and consists of clasts derived from the local bedrock (Fig. 4.2a). An example of the extent and type of weathering was observed in detritus on the bench below exposure where a diorite boulder exhibited a rusty brown weathering rind between 1-2 cm thick (Fig. 4.3c). This rusty colouring is also expressed in pebble conglomerate clasts (Fig. 4.3b) and can be traced back to Unit 1 in the exposure.

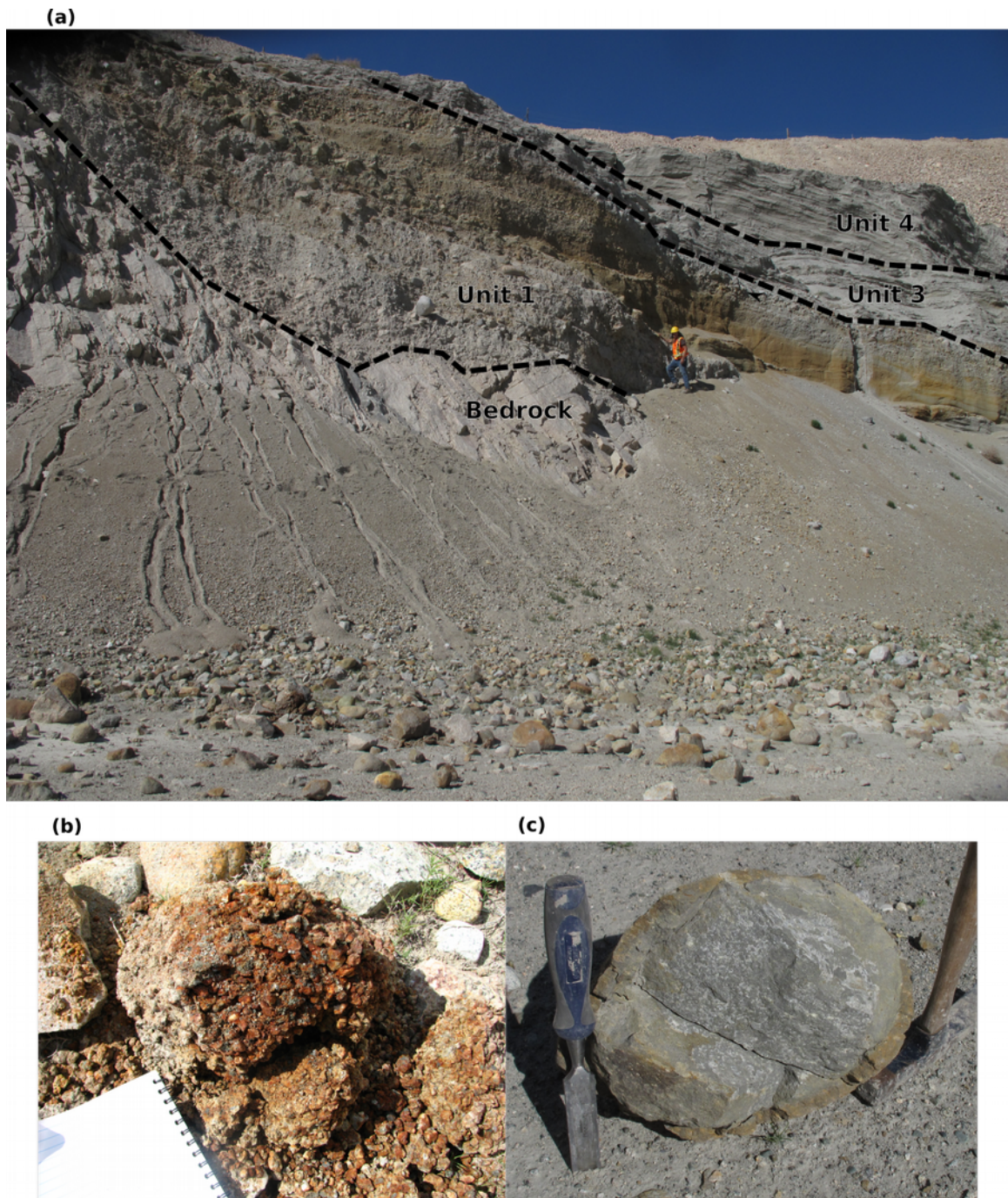


Figure 4.3. **a** - Exposures of units 1, 3, and 4 atop bedrock at HVC-11a. Note rusty red colour in upper part of Unit 1 and the boulder lag at the Unit 1-3 contact (arrow). **b** and **c** - Debris on road below exposure likely derived from Unit 1. Note the heavy oxidation on **a** and thick weathering rind on **b**. Photos **a** and **c** courtesy Richard Hebda, used with permission.

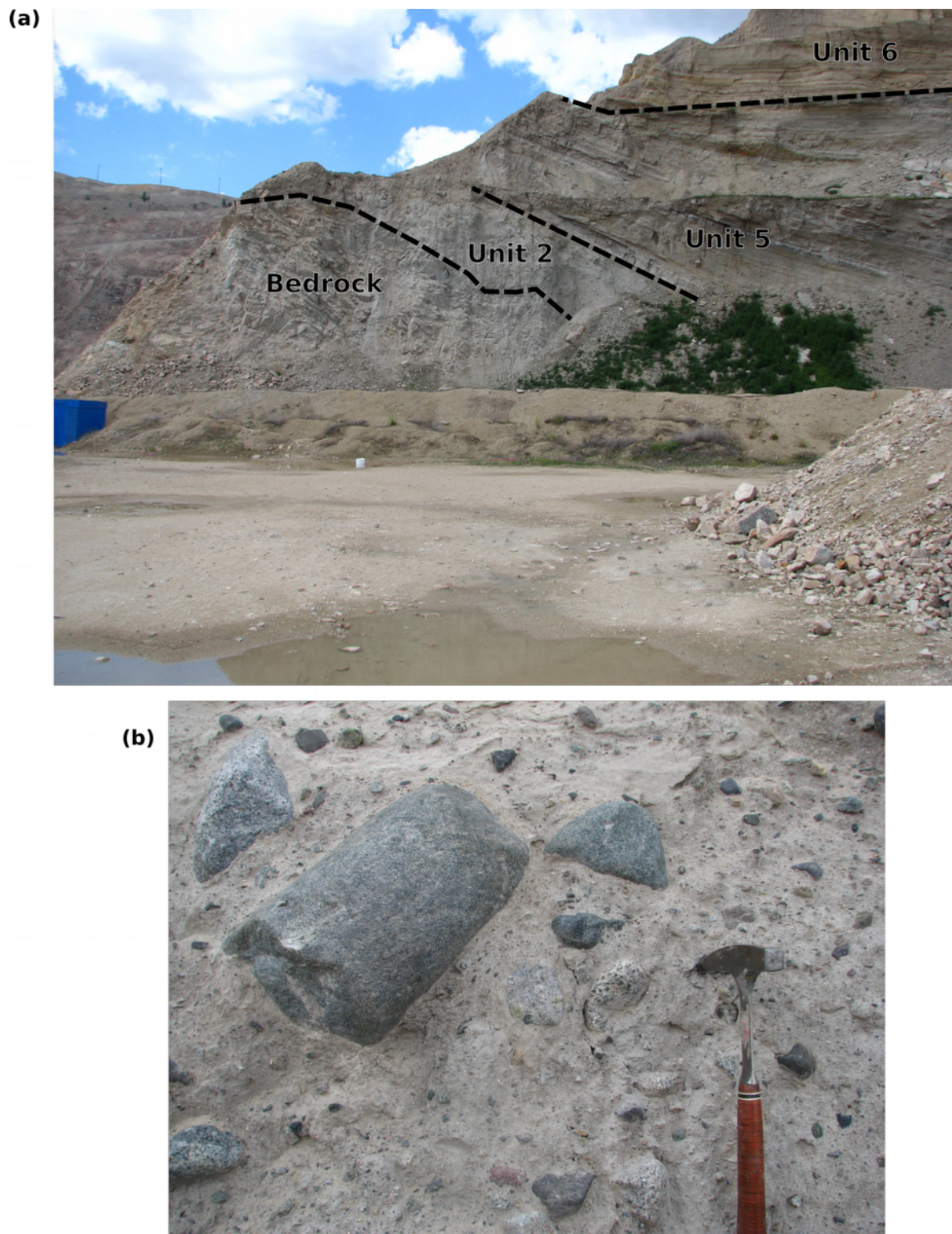


Figure 4.4. a - sedimentary exposure at HVC-10. **b** - close-up view of Unit 2 diamict at HVC-10 showing variety of clasts. Note the bullet shape and faceting present on several clasts. Note also the relatively uniform clast composition compared to Unit 7 (discussed later in this chapter).

4.1.3 Unit 2 – Lower diamicton

Unit 2 consists of indurated matrix-supported diamict with a gray sandy matrix and pebble to cobble sized clasts. Pebble to boulder sized clasts in this unit are frequently faceted, rounded, bullet-shaped and striated (Fig. 4.4b). The unit is laterally discontinuous with an observed thickness of up to an estimated 8 m thick. A brief survey of clast lithology indicates the clasts in this unit include fine grained extrusives and granitoids along with a few quartzites (Fig. 4.4b). No fabric was observed. This unit is exposed at HVC-10 (Fig. 4.1.3.a) at the base of the sedimentary sequence in non-conformable contact with brecciated and weathered bedrock incorporated into the basal parts of the unit (Fig. 4.2b). At HVC-10 Unit 5 laps onto Unit 2 with which it is in sharp contact (Fig. 4.4a). At HVC-11 this unit occurs in partial exposure at the southern part of the sedimentary exposure of the bench at 980 m asl. Also at HVC-11, Unit 2 either lies in contact with bedrock or lies directly on top of Unit 1 sediments and below units 3 or 4.4.1.4 Unit 3 – Sand and cobble conglomerate lenses

Unit 3 broadly consists of moderately sorted clast-supported cobble conglomerate and stratified sands. The unit contains abundant crudely bedded pebble to boulder conglomerate lenses within complexly cross-bedded gray silty sands which include occasional larger clasts. The gravel to boulder lenses are locally well sorted, rounded, and largely clast-supported, and sometimes matrix-supported. The cross-bedded silty sand parts of the unit form just over half the exposed face of this unit at HVC-11 (bench at 980 m asl) while the coarser troughs makes up the remainder. Imbrication was observed in numerous places in the coarser pebble to boulder parts of the unit however inconsistent directions were

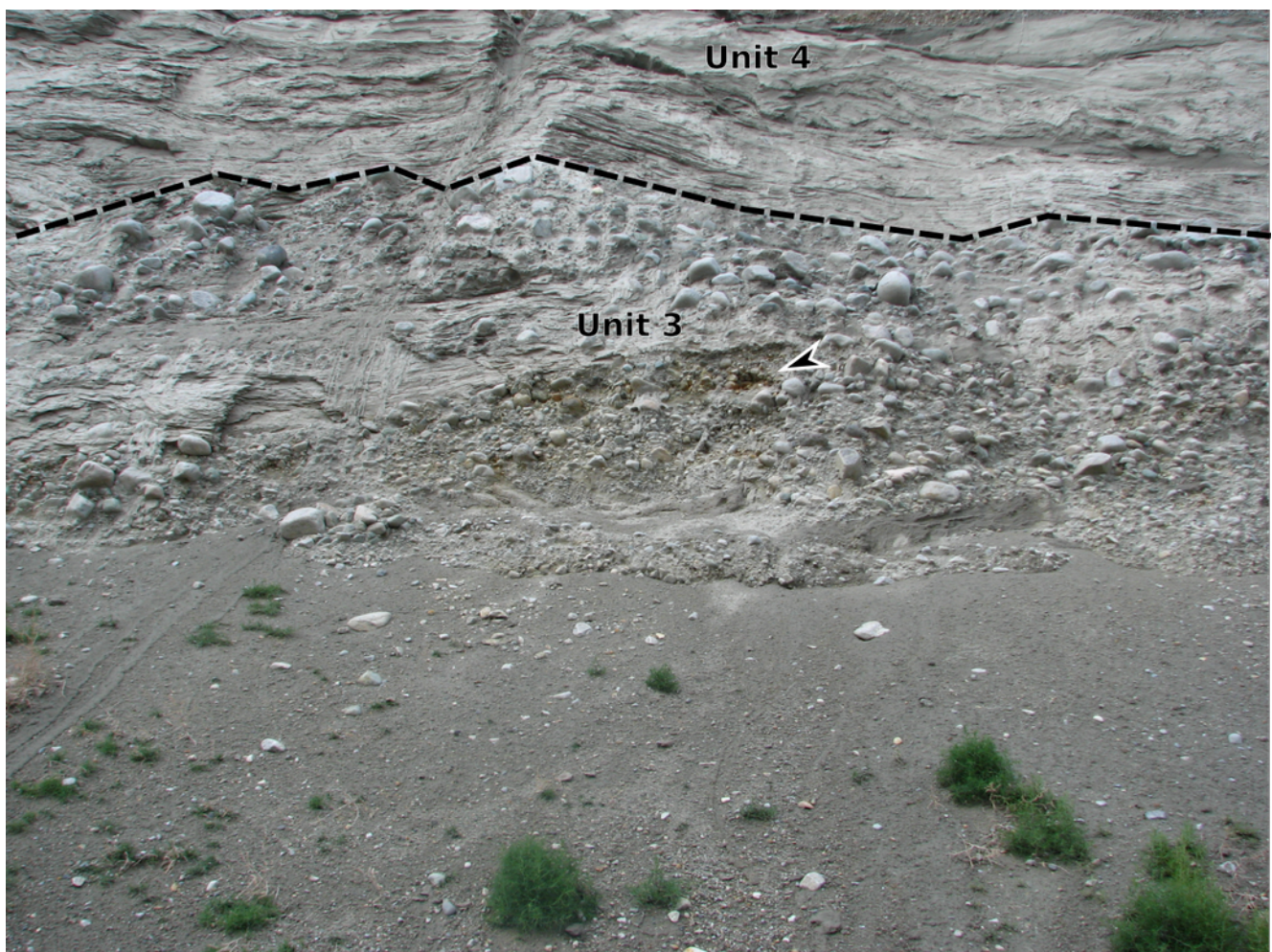


Figure 4.5. Units 3 and 4 at HVC-11. Note scattered imbrication in Unit 3 and disrupted bedding in Unit 4. Arrow indicates rip-up clast from what was likely Unit 1 material.

observed. Pebble to boulder sized clasts in this unit are well faceted, striated and smoothed with many being bullet-shaped. Rip-up clasts from Unit 1 are incorporated into the coarse lenses of this unit (see arrow in Fig. 4.5). The base of this unit is at the road cut level at HVC-11 and overlies either bedrock, Unit 1, or Unit 2 in different places along the south face of the bench at 980 m asl. The transition into the overlying bed (Unit 4) is gradational. The upper contact is approximately 10 m above the bench at 980 m asl and is defined here by the top of the uppermost pebble to boulder lenses (see Fig. 4.5). As such, this unit is about 5-10 m thick and pinches out at the edges of the exposure.

4.1.5 Unit 4 – Sandy silts and clays

This unit consists primarily of gray laminated sandy silts and clay beds with dropstones. The beds are 1-3 cm thick and commonly exhibit syn-depositional deformation (Fig. 4.5). The unit is exposed at HVC-11 (980m asl) and at HVC-13 (990 m asl) but is largely covered by the 10B Buttress above 1000 m asl. Basally these beds are highly deformed and contiguous with the silty sand portions of Unit 3 where the contact is exposed at HVC-11. The beds exposed at HVC-13 are much less deformed than those at HVC-11 below. The buttress covers most of the sediments between 1000 m asl and 1050 m asl so the transition into Unit 5 was not observed. Drill core data (Piteau Associates Engineering Ltd. 2010) suggests this unit grades into Unit 5 at some elevation behind the 10B Buttress but this interpretation should be considered with some caution. The thickness of this unit is between 20 and 70 m thick.

4.1.6 Unit 5 – Fine grained rhythmites

Unit 5 consists of mostly grey laminated-to-bedded clayey to sandy silt (rhythmites; see Fig. 4.6a). As indicated, the lower contact of this unit was not observed, so this unit is inferred to be between 60 and 120 m thick. The bed thickness in the unit varies widely. Most beds range between extremely thin

(<0.1 mm) and moderately thick (~2 cm). Overall, Unit 5 is a coarsens upward containing primarily finely-laminated or bedded, moderately-sorted silts at the base and increasingly sandier beds and laminae towards the top. Pebbly sand beds and sandy pebble beds ranging from ~1 cm to ~50 cm thick occasionally interrupt these beds throughout being very rare near the base yet far more common in the upper part of the unit. These pebbly sands typically fine upward internally and transition sharply with the silty rhythmite bedding above and below. The parent material within these pebbly sands is similar to that found in Unit 6. The unit also hosts several distinct beds as well as a number of macrofossil rich sections which are discussed in the following chapter.

Local exposure-scale variation was not assessed in great detail and the description of this particular unit is mostly generalized, however a few features are notable for this study. At HVC-10 (~1074 m asl) a bed of peaty sandy silts is stratigraphically ~16 m above the bedrock contact and is associated with abundant macrofossils (see Chapter 5, Chapter 6). Another interesting bed of patchy charcoal and reddish sand is present 2.5 m above the bench at HVC-1 (Fig. 4.6b). A similar bed occurs at HVC-10 consisting of charcoal and reddish sand in addition to occasional angular granitic pebbles and may correlate with the HVC-1 beds (discussed in later chapters).

Another notable bed was observed exposed along the bench at 1080 m asl (HVC-3, and -3b through -3e) where there is a reddish gravel and sand lens (Unit 5a; Figs. 4.7a, 4.8a and b). This bed consists of material similar to Unit 6 (see next section; compare Figs. 4.8b and 4.10b) and is associated with tectonized beds both above and below and to the north end of the lens (Fig. 4.7). Rip-up clasts occur in this bed as well (Fig. 4.7c). This unit lies a couple meters below a thick felsic tephra (sampled as HVC-3D-11.1) which was used to correlate beds across the macroexposure (Figs 4.7c and 4.9a). Unit 5 coarsens upward above Unit 5a and transitions into Unit 6. This transition is manifested by the increase in frequency of sandy pebbly beds (4.9b).



Figure 4.6. a - closeup of bedding at HVC-1. b - Charcoal rich part of organic debris layer found at HVC-1 (arrow), similar to one found at HVC-10. Photo credit for a and b: Richard Hebda, used with permission.

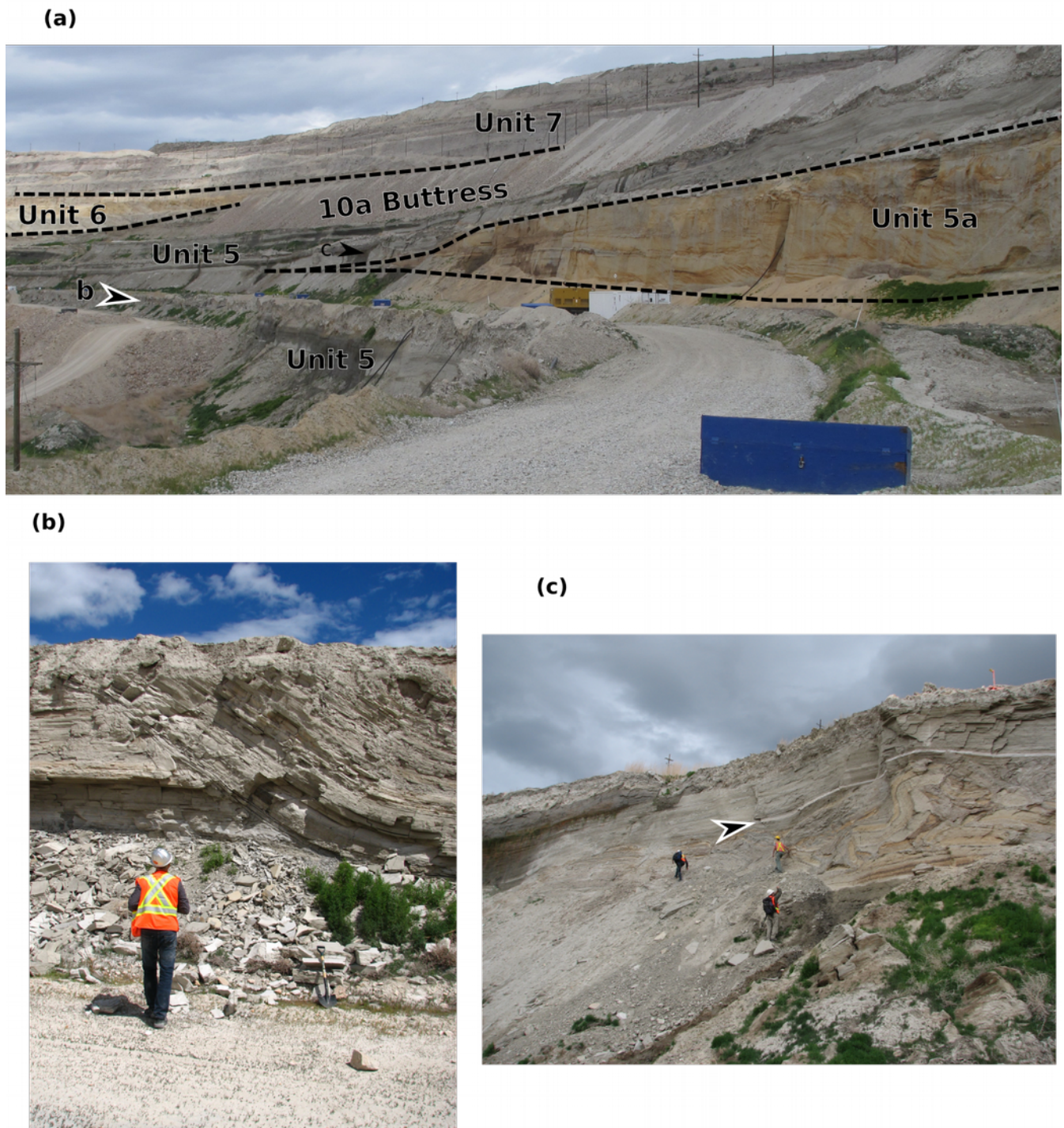


Figure 4.7. Unit 5a and associated features. **a** - View of 5a in context with other units at HVC. Arrows label location of features pictured in Figures b and c (labelled with figure letter). Photo credit: Richard Hebda, used with permission. **b** - Example of tectonic folding and faulting observed at HVC-2. **c** - Folding and rip-up clasts at HVC-3d. Arrow indicates thick tephra discussed in text.



Figure 4.8. Unit 5 and 5a at HVC-3b. **a** - Exposure of Unit 5a at southern end of lens showing the unit pinching out toward the south. **b** - Close up view of Unit 5a gravels.

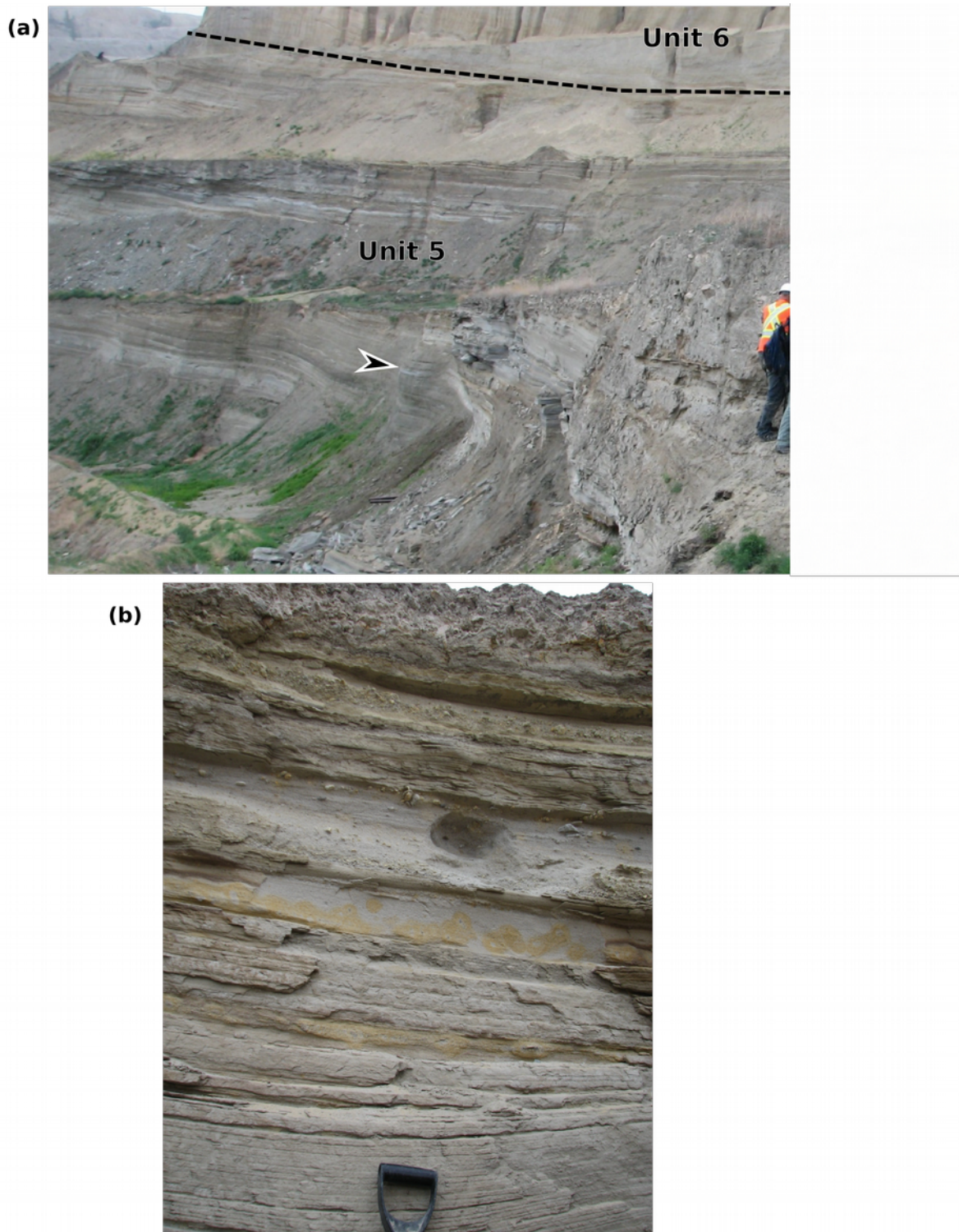


Figure 4.9. a - Exposure at HVC-3f. Arrow indicates thick tephra used to correlate section with other sections. Note continuity of beds well below the tephra bed. **b** - Close up view of coarse beds encountered more frequently towards the transition into Unit 6.

4.1.7 Unit 6 – Inclined sands and gravels

White to rusty brown poorly sorted mostly angular coarse sands to gravels predominate in Unit 6. The unit ranges from about 25 to 50 m thick over the exposure. The material within this unit is primarily felsic crystalline rock similar to the composition of the local bedrock (Fig. 4.10b). This unit consists of numerous large-scale inclined beds ranging from roughly half a meter to five meters thick each predominately massive and internally exhibiting poorly developed stratification with some imbrication near the base (Fig. 4.10a). Beds in this unit dip towards the central axis of the full exposure such that in the northern part of the pit beds of this unit have an apparent dip towards the southeast, yet equivalent beds at the south end of this exposure dip towards the northeast. The beds at the southern end of the pit could not be safely observed closely, however they look similar enough from a distance to regard them as the same unit. The apparent dip of these beds is $\sim 14^\circ$ but variable.

The basal contact of Unit 6 is gradational with Unit 6 beds which intercolate with Unit 5 beds until Unit 6 bed structure becomes predominant. This transition was observed between HVC-3f and HVC-4a coinciding with the bench road cut at 1100 m asl.

Unit 6a is comparatively thin and consists primarily of peats. It occurs slightly below the upper contact of Unit 6 with Unit 7 at HVC-4/HVC-12 (Fig 4.11b). The sequence fines upward with sandy layers interbedded with peat and woody debris at the base, and the upper part consisting of silty peats. This minor unit is associated with old wood and vertebrate fossils, and contains at least two tephra layers, one about half a meter from the base and the second one meter from the base. The colour of the peats vary throughout the unit, however is primarily shades of red or brown.

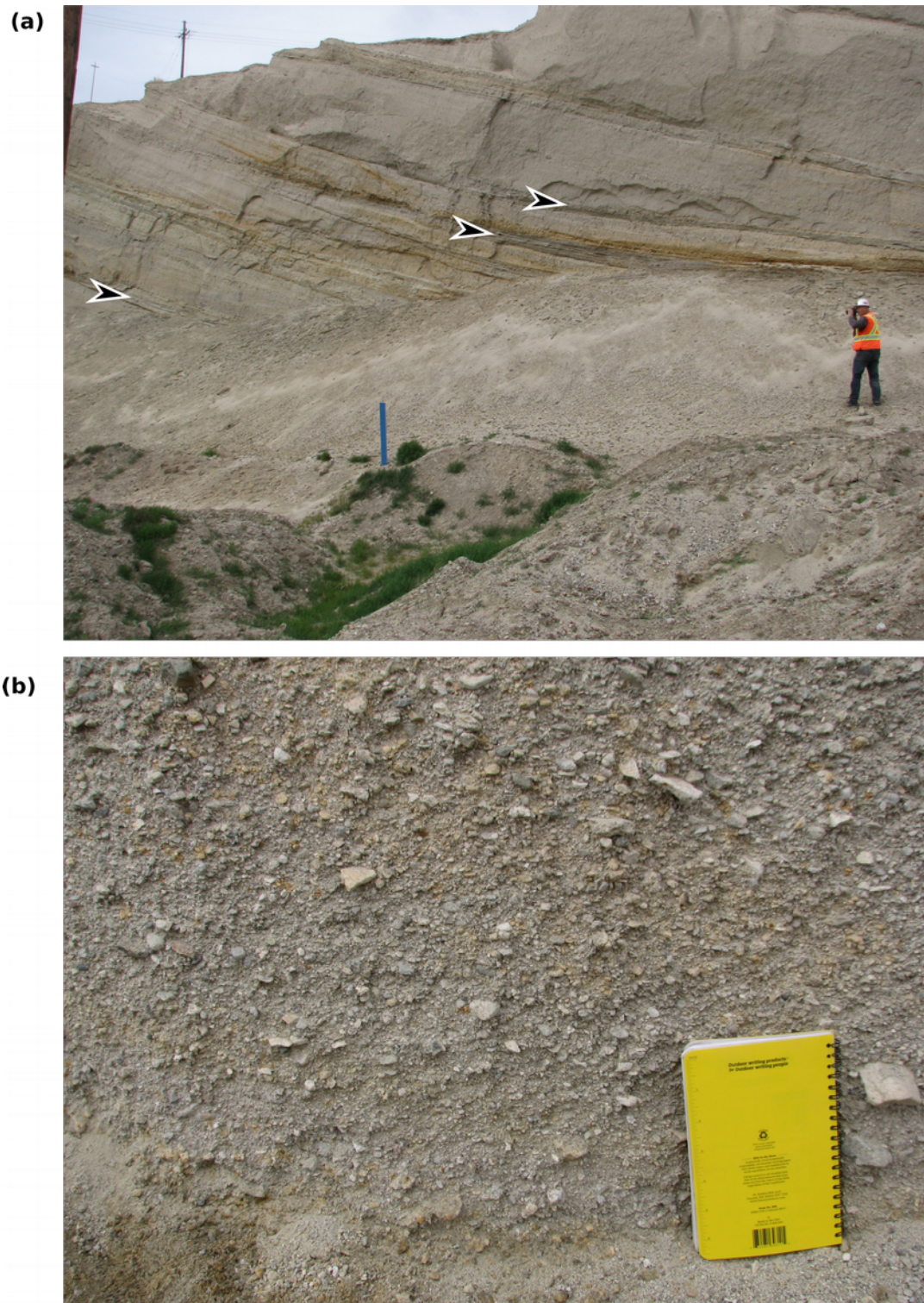


Figure 4.10. a - Exposure at HVC-4a at the base of Unit 6. Arrows show examples of thin rhythmic beds interbedded with the gravels of Unit 6. **b** - Close up view of coarse material within Unit 6. Note the poor sorting and angularity of the grains. Also note the light patchy rusty colour.

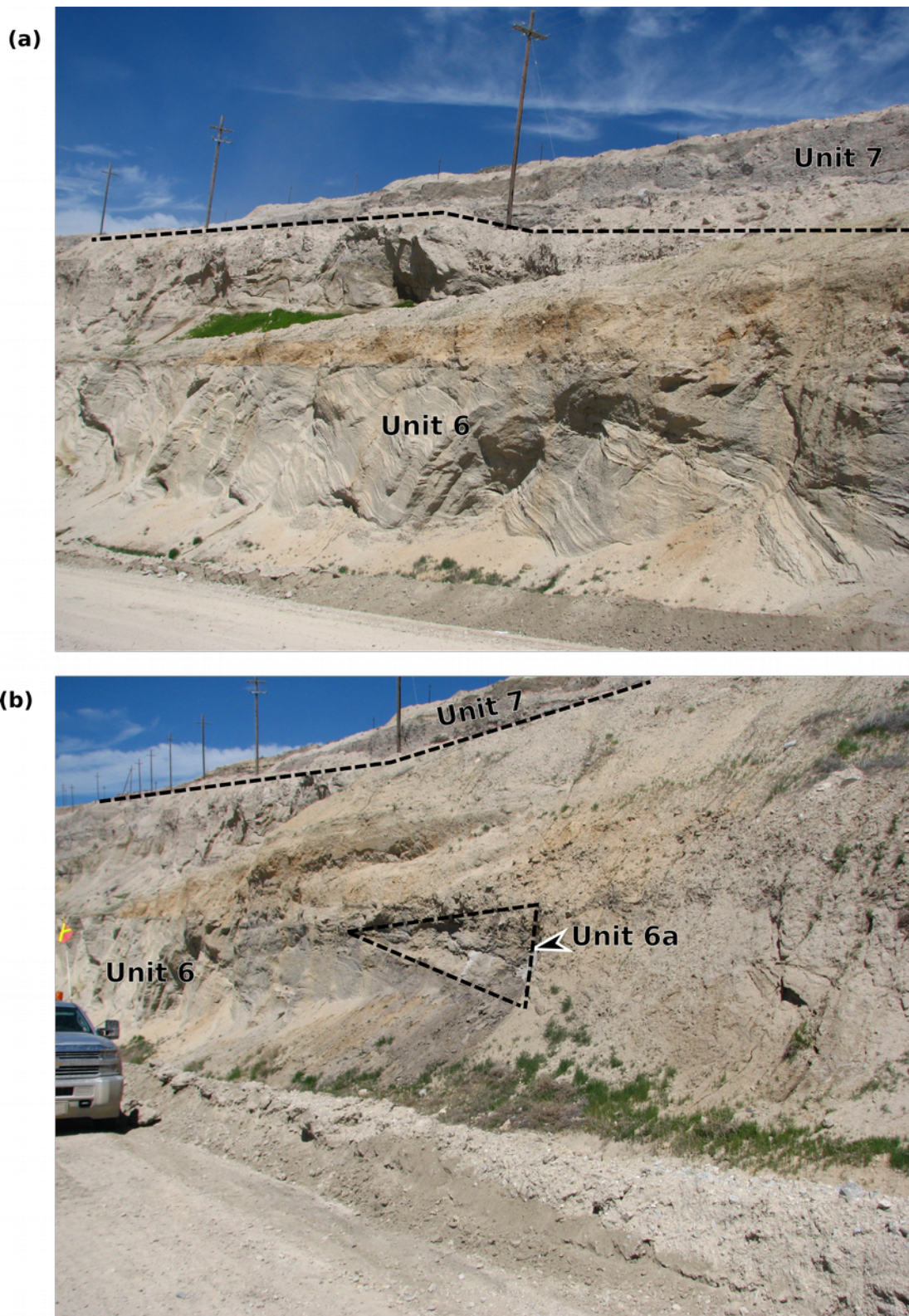


Figure 4.11. a - Exposure at HVC-4/12 at the top of Unit 6. Note the deformation of the gravel beds.

b - View of same locality from about 10 m south showing where Unit 6a is exposed.

Within the upper 5-10 m of Unit 6 moderate deformation of the sediment is observed (Fig. 4.11a). The upper contact with Unit 7 is an unconformable, sharp in places and dips gently south from where it was observed at HVC-5b (1154 m asl) such that it is obscured below the road cut at HVC-9 (1145 m asl).

4.1.8 Unit 7 – Upper diamicton

Unit 7 consists primarily of indurated matrix-supported diamicton with a gray sandy matrix and pebble to boulder sized clasts. Clasts are mostly subrounded but some angular Unit 6 material is incorporated near the base. Like Unit 2, clasts of Unit 7 are faceted, bullet shaped, and striated. Unlike Unit 2 the lithologies of clasts in Unit 7 appear to vary far more than those of Unit 2 (compare Fig. 4.12c & 4.4b). A comprehensive survey of clast lithology was not compiled as this is beyond the scope of this thesis, however there does appear to be a large difference between the number of lithologies observed in each unit in the field (~3 for Unit 2 and >6 for Unit 7). This unit is mostly massive, however localized crude stratification was observed in several places (see Fig. 4.12c for example). The lower-most part and the uppermost part of Unit 6 includes laterally discontinuous tectonized sections of stratified sand and pebble lenses mixed within the diamict (e.g. Figs. 4.12a [arrow s] and 4.12.c). Unit 7 terminates at the surface around 1205 m asl and is continuous with the surface of the surrounding landscape except where debris from mining activities has been placed on top and in places where patchy younger deposits (i.e. units 8a and 8b) are inset into the surface. As such Unit 7 appears to be the last diamicton to be deposited locally.

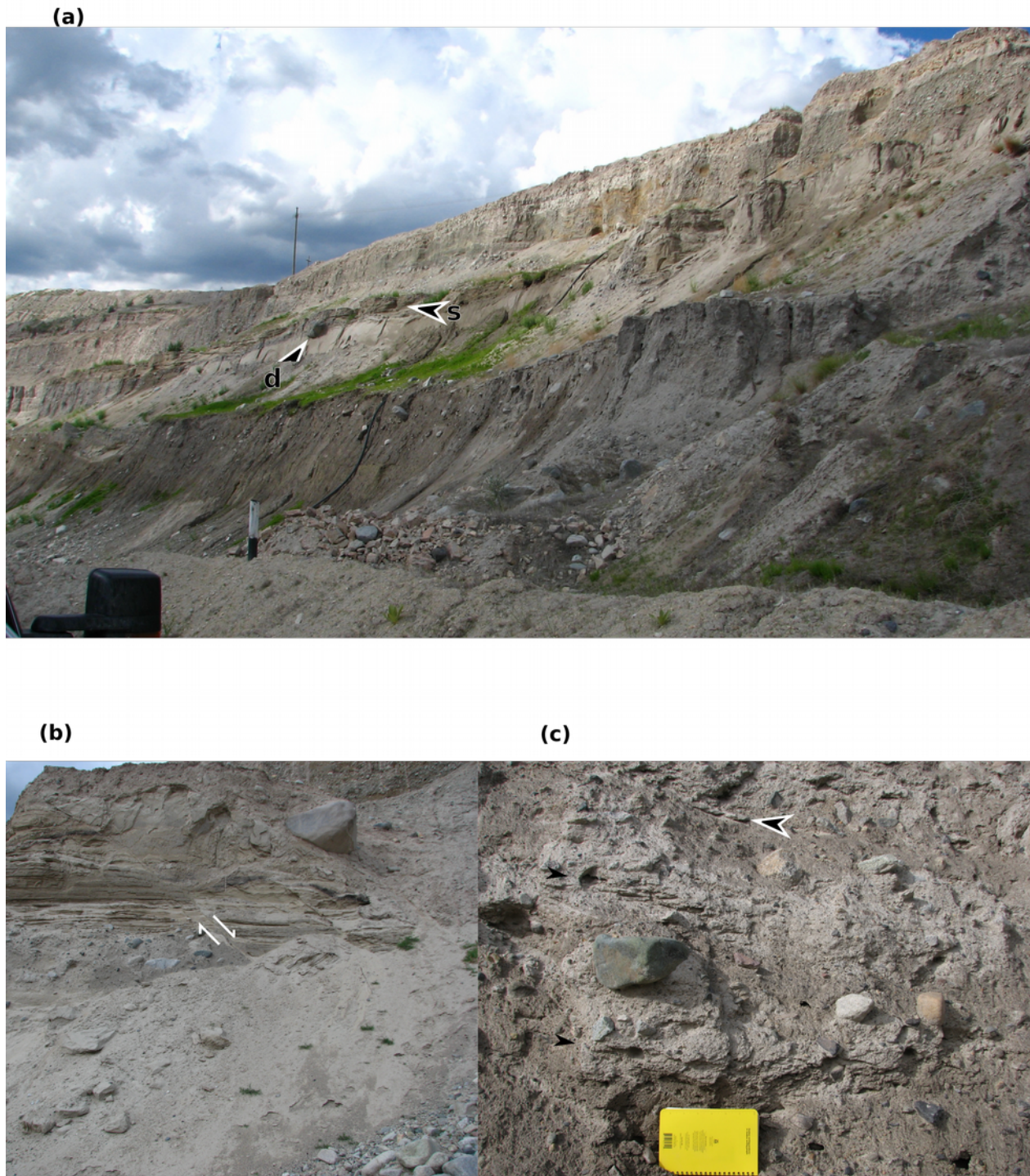


Figure 4.12. **a** - Exposure at HVC-9 looking toward HVC-5. Arrows show dropstones and stratified sand beds. **b** - Stratified sand and diamict at HVC-9 showing normal faulting. **c** - Diamict at HVC-5. Note faceted clasts of a multitude of rock types. Arrows show stratification.

4.1.9 Units 8a and 8b – Red-brown clayey silts/sands and peats/marls

Two distinct deposits occupy horizontally limited, eroded dish-shaped depressions inset into Unit 7 at the 1205 m asl surface. Unit 8a is > 3 m thick occurs at HVC-14 and consists mostly of highly oxidized, reddish brown mottled silty clay with lenticular fracture and minor sandy beds (Fig. 4.13a). The lowermost contact with Unit 7 was not observed, but the lateral contact is erosional. Unit 8a hosts the modern soil at its top, where local vegetation is well developed. The top of Unit 8a is slanted towards the center of the mining pit which could be the result of minor displacement of this unit by slumping.

The lithology of Unit 8b contrasts with that of Unit 8a despite being at roughly the same elevation. It is up to 5 m thick and consists of peat and marl beds with minor silts (Fig. 4.13b). It is limited in extent and was exposed only at HVC-8. The unit contains a thin volcanic ash at 4.25 m above its lower contact. The Unit 8b beds are unconformably sandwiched between Unit 7 diamict below and mining debris above. The lower contact is exceptionally irregular and lies atop angular boulders derived from Unit 7 beds, often with peaty deposits surrounding boulders derived from the underlying unit.

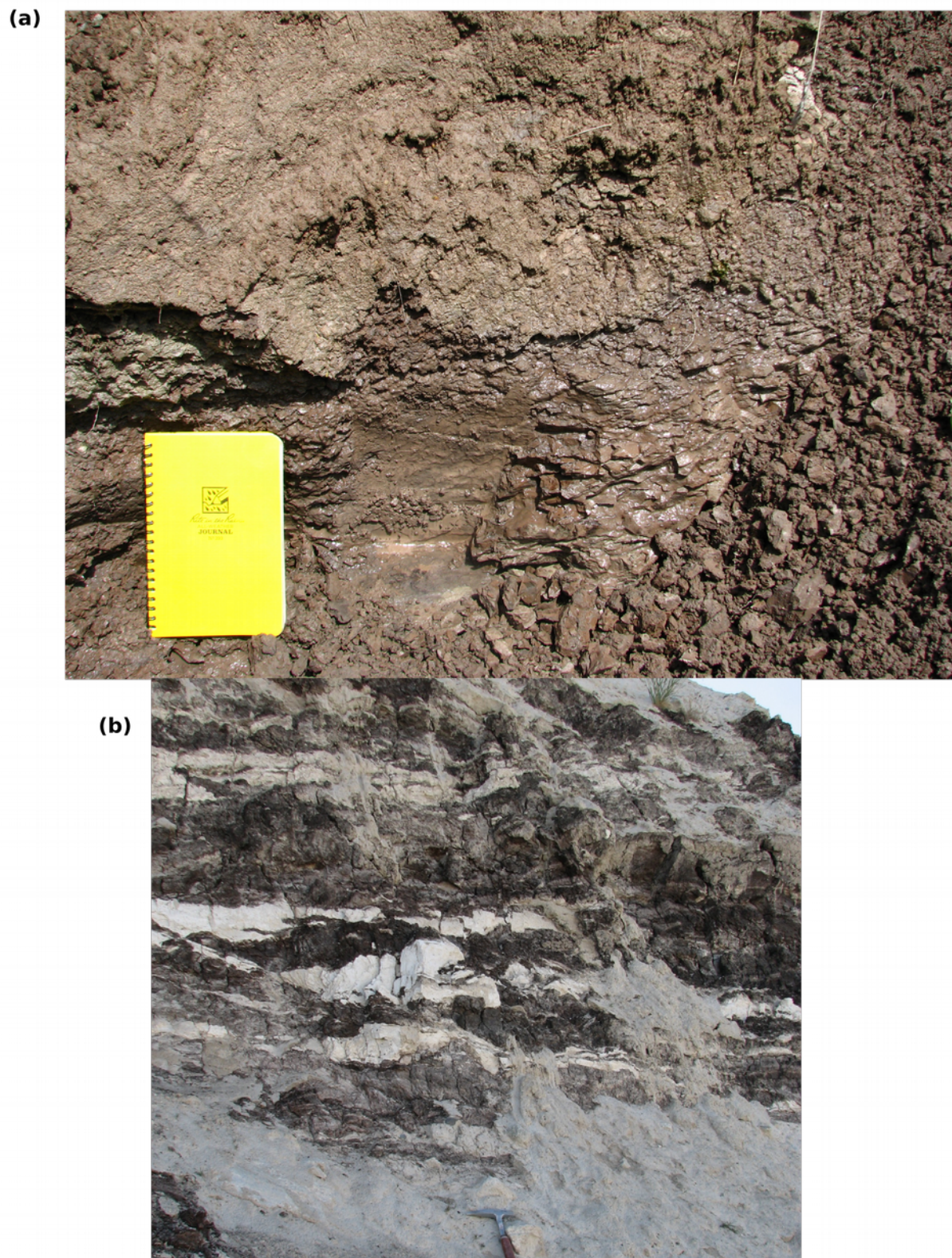


Figure 4.13. **a** - Cleaned surface of Unit 8a material at HVC-14. Note lenticular fracture and slickenside. **b** - Unit 8b beds at HVC-8.

4.2 Interpretation

The stratigraphic sequence described above can be divided as seven main modes of emplacement. These phases are: 1 - batholith formation, 2 - preglacial slope deposition and weathering (Unit 1), 3 - early glaciation (units 2-4), 4 - non-glacial lake with lake-marginal (terrestrial) deposition (units 5 and 6), 5 - ultimate continental glacial deposition (Unit 7), and 6 - post-glacial deposition (units 8a, 8b). In this section, the first two phases are interpreted briefly (4.2.1). Phases 2-4 are considered more extensively, with the fourth phase split between two subsections since the terrestrial and lacustrine facies each require more discussion.

4.2.1 Bedrock and Unit 1: Pre-glacial deposition

The bedrock (Guichon Creek Batholith, Bethsaida Phase) at HVC is largely understood from previous work (e.g. Northcote 1969, McMillan 1979; also see Chapter 2). The bedrock has been determined to be around 200 Ma with the timing of mineralization to have occurred shortly after magmatic cooling (Ash et al. 2007, Mortimer et al. 1990). Subsequent uplift and erosion associated initially with the docking of the Quesnel Terrane during the middle Jurassic (Cordey et al. 1987) and onward (Colpron et al. 2007) led to the eventual erosion of the Highland Valley along the Highland Valley Fault.

Boulders derived from this bedrock and silty sands were later deposited as colluvium and/or alluvium from the slopes of the weathering and eroding bedrock and made up Unit 1. The lithology, angularity of the clasts, and lack of both sorting and weathering indications in the lower part of Unit 1 demonstrates short-distance transport of these early sediments. Both the boulder lag present at the top of this lower part of Unit 1, and the strong oxidation observed in the upper part of the sediments which indicates a hiatus before the next episode of deposition and sub-aerial exposure of these sediments for

an extended time. The character of the uppermost part of Unit 1 (rounding, imbrication, laminated sandy beds, etc.) suggest water played a role in deposition at a later point and suggests a shift from gravity-driven deposition to water-driven deposition, hence an alluvial setting is implied for the upper part of the unit.

A similar weathered deposit was found in a nearby road cut c. 15 km northwest of the valley pit down the valley axis (RS-2 in Fig. 2.4; 50°34'14"W, 121°12'07"N). This deposit is both magnetically reversed (René Barendreght, unpublished data) and contains poorly preserved fossil *Metasequoia* cf. *occidentalis* leaves (personal observation) unambiguously a pre-Pleistocene age as *Metasequoia* occurs widely in Eocene and Miocene beds in the region (e.g. Greenwood et al. 2005, Dillhoff et al. 2005, Moss et al. 2005) and undergoes a late Pliocene extirpation from North America (LePage et al. 2005). Given the similar nature of these deposits and their close proximity to HVC it is possible these could be equivalent and hence Unit 1 could be Tertiary in age. No fossils from Unit 1 were recovered at the HVC exposure however so the age of these beds remains speculative.

Unit 1 deposits are likely much older relative to the overlying deposits in the valley based on sedimentary character of the younger beds. Unit 1 contains what is most likely silica cement and is heavy oxidized in the upper two meters of material. These features were not observed in any of the overlying deposits. Strong oxidation and weathering is also seen on bedrock interfaces in contact with overlying units other than Unit 1 (e.g. Fig. 4.2b). This observation suggests these bedrock and Unit 1 surfaces to be equivalent and that there was a colluvium-bedrock surface that formed the landscape at an early time. Considering the degree of weathering observed in the upper parts of Unit 1 and the bedrock paleosurface this landscape must have occupied the valley slope for a long interval prior to the following episode of deposition.

4.2.2 Units 2-4: Lower drift

These three units are interpreted to be a drift associated with an early valley glacier and the first of only two glaciations to have likely entered Highland Valley. Units 2, 3 and 4 are interpreted as glacial till, outwash and glaciolacustrine sedimentation respectively. The interpretation that Unit 2 is a till from a valley glacier is supported by the unit being indurated, and having rounded, bullet-shaped, and faceted clasts with striations and limited clast lithology. Units 2-4 were not observed above 1085 m asl indicating local ice thickness reached more than 100 m but was apparently confined to the valley.

Unit 3 is interpreted as an outwash facies associated with the same drift package. The gravels in this unit have the same composition and features (rounding, faceting, striations etc.) as in Unit 2 clasts, suggesting this unit was largely derived from the same material. The gravel lensing and stratified sands are typical in outwash sediment. Unit 3 later grades into Unit 4 within which the gravel lenses are no longer observed and gray sandy silt beds become the main components.

This initial glaciation appears to have initiated the long episode of lacustrine deposition which is seen in the sediments of the overlying beds. Unit 4 marks the beginning of a gradually deepening glaciolacustrine phase of deposition. The presence of highly deformed bedding at the base is typical near glacial margins. This feature is largely absent above the lowermost bench (>995 m asl) demarcating ice retreat, however this glacial lake remained ice marginal for some time as dropstones were still observed near the elevation where the beds became obscured by the 10B buttress. Most of the glaciolacustrine parts of the sequence were laid down after ice retreat which seems to indicate that some form of glacial moraine deposition created a permanent dam facilitating lake formation. The location of this hypothetical morainal dam has not been discovered and other damming mechanisms cannot be ruled out.

4.2.3 Units 5 and 5a: Lacustrine deposits

Unit 5 consist of non-glacial lakebed sediment which gradually filled the valley after the formation of a morainal dam. The dominant lithology of the fine grained rhythmites is typical of sediments deposited in standing water. The presence of peaty beds, fish and other fossils, as well as abundant pollen rule out the possibility of these beds were being deposited adjacent to a glacier because high deposition rates in glacial lakes make sediments of these environments usually appear sterile. Beds and laminae within this unit are also highly variable in thickness with some very thin ($\ll 1$ mm) beds appearing in places and some centimetres thick. Thin beds are expected in deep quiet water while the thicker beds appear during events of high sediment input. This seems to presumably indicate a large variety of climatic conditions were present at different during the lake's lifespan.

Unit 5 includes a number of unique beds, several tephtras (see Section 4.3), and a special subunit (5a) as described in Subsection 4.1.6. A specific sandy charcoal layer which is seen at both HVC-10 and HVC-1. These beds are tentatively assumed to correlate in this study, but may have resulted in two similar but separate events. A large nearby wildfire event is the most likely cause for a large influx of charcoal in this bed. This fire must have been also extremely hot as sandy material was found fused with vertebrate fossils found within this bed.

Another important bed is described in this study as Unit 5a; a large sand-pebble lens associated with deformation of the surrounding beds (Fig. 4.7). As mentioned, this bed is very similar in composition to the material in Unit 6. These observations indicate that this bed is likely the result of a catastrophic flow of material into the lake which then caused the deformation of preexisting sediment. The lakebeds must have been soft at the time – most likely still sub-aqueous - as Unit 5a appears to have become inserted between beds of Unit 5, having caused deformation of beds both above and below. The

material displaced above this event also appears to have been thin (~ 1 m) as normal bedding resumes not far above Unit 5a.

The bedding of Unit 5 becomes increasingly coarser with stratigraphic height and includes the addition of increasingly frequent gravelly sand beds. These beds probably represent the increasing influence of Unit 6 style deposition as the lake basin filled with sediment and became locally more shallow. This style of deposition likely occurred more prominently as vegetation cover decreased. Both the internal structures (internal sorting, climbing ripples, etc.) in these beds and the presence of finer lakebeds immediately above and below indicate these were periodic sub-aqueous incursions of the coarse material into the lake. This accumulation eventually resulted in the overriding of the local part of the lake with Unit 6 deposition as the lake was gradually filled in.

4.2.4 Units 6 and 6a

Unit 6 is interpreted as a lake-adjacent colluvial fan deposit associated with the physical weathering of adjacent bedrock into fragments of grus. These fragments would have formed from the exposed crystalline bedrock undergoing freeze-thaw decomposition were eventually transported to the slopes of the valley and began to fill the lake basin. As alluvial fans typically incline at a low angle and contain evidence of stream action (e.g. channel deposits), this mode of transport and fan formation is seen as less likely in this interpretation. The mode of deposition was probably driven by gravity or debris flows associated with heavy rain events. These events occurred coeval with some of the lake beds, as lakebeds intercalate with the fan deposits which explains part of the weak internal structure observed.



Figure 4.14. Grus sample from Colorado (left; collected by Kendrick Marr (Royal BC Museum)) compared to a bulk sample from the base of Unit 6.



Figure 4.15. Example of grus development in the alpine of northern British Columbia. Photo illustrates progression of parent granite (left) to gravel sized grus particles (right) in an environment relatively devoid of other macro-scale biological activity. Taken at 1734 m asl east of Hook Creek ($59^{\circ} 43.321'$ N, $131^{\circ} 16.002'$ W). Photo credit: Richard Hebda, used with permission.

The mechanism for formation of the beds within Unit 6 is interpreted based on clast makeup, sorting, and angularity of the grains primarily where the material is massive. Examination of the bulk material that makes up this unit yields two common clast types: coarse grained felsic intrusive clasts make up the bulk of the material while there are a number of clasts derived from andesitic material. Neither of these is surprising since these match the immediately available bedrock materials (Secs. 2.1, 4.1.1). Sorting of the material is similar to that seen in grus formed at high elevation parts of Colorado with granitic bedrock (Fig. 4.14). The degree of rounding is slightly higher in Unit 6 material (Fig. 4.14). Accumulation of this material is observed in mountainous areas where granitic bedrock is exposed (see Fig 4.15 for example). The amount of rounding is much higher in the andesitic clasts, which is probably due to andesitic material being both easier to weather into round pebbles and the probable travel distance of the andesitic material locally. Further rounding may have also been a result of local wave activity from the HVC paleolake since intercalating lakebeds suggest the lake's shoreline was fluctuating while Unit 6 was deposited.

Unit 5a was probably derived from this material resulting from a landslide or sheet flow of grus accumulated on the valley slopes. Based on a number of associated features this unit was deposited catastrophically. The tectonized beds below and north to the Unit 5a lens and the deformed beds north and above (Fig. 4.7) may have been a result of this event. Unit 5a also contains rip-up clasts of Unit 5 which indicate this is the case.

This type of grusification is a physical weathering process involving short term, large-scale changes in temperature driving crystal expansion and contraction over short times (i.e. day-night cycles). The inferred climate responsible for this type of weathering is arid to semiarid since little cloud cover enables these large-scale scale shifts in temperature on a day-night scale, promoting the breakdown of coarse grained rock along grain interfaces. The transport of this type of sediment also indicates that the

ground around the source and down-slope of the source would need to be practically devoid of vegetation, as this would stabilize the material in place. This stabilization is observed in places where grus forms in other places (e.g. Northern BC; Richard Hebda [personal communication], slopes of Zopkios Peak, southern British Columbia; personal observation).

To accumulate large fans of the material such as that observed at HVC, the landscape was probably barren for a some time and associated with a large area of grus development. This is because the rate of this process is usually slow (e.g. approx 1 cm ka^{-1} of accumulation at the source east of Hook Creek seen in Fig. 4.15; Richard Hebda, personal communication) and the fan deposits observed at HVC were thick. Increased grus generation may have been aided if much of the upstream catchment had much exposed bedrock and lacked vegetation, with a large areas of sediment production. The presence of some rounded clasts supports this hypothesis as it indicates there was some transport from somewhat distant sources and the weak internal stratification does indicate some water was involved at the point of deposition. Sorting is poor however, so the depositional events may have been driven by occasional strong rainfall events washing sediment into the basin rather than consistent colluviation.

4.2.5 Unit 7

Unit 7 is interpreted as a glacial drift produced by a large and thick ice sheet. As in units 2 and 3, large bullet-shapes, faceted and striated clasts are typical of glacially-derived material provides little doubt of this unit's origins. The majority of the unit is made up of till. Minor facies within the drift include proglacial outwash (tectonized gravels and stratified sands) observed at HVC-9 and 9b (~1150 m asl), indurated till, which makes up most of the unit between 1154 m and ~1200 m asl, an upper tectonized, stratified sand and gravel facies ~1202 m asl (observed along the upper bench, e.g. HVC-6) and an additional till facies making up the upper few meters of the unit at the surface (~1205 m asl).

The latter three facies are interpreted as a classical tripartite till sequence which can remain after ice collapse (Boulton 1977).

4.2.6 Units 8a, 8b

Units 8a and 8b were both produced in postglacial lakes. The first of these two units (mottled lenticular fractured clay to sand) is interpreted as a small postglacial lake/pond. This unit is unlike Unit 8b meaning they could have resulted from different events. Unlike Unit 8a, the source of Unit 8b is unambiguous. Unit 8b originates from the edge of lake Quiltanton, which was drained as part of mining activities (Bobrowsky et al. 1993). These two units are out of the scope of this thesis, however future work should keep these observations in mind.

Chapter 5. Palynology and Paleontology Results

Pollen and spores were recovered throughout the sequence with a total of 85 samples processed and examined. With only a few exceptions, all the samples reported here were taken from the lake bed unit (Unit 5). Some samples taken from fine grained sediment interbedded with the gravel fan unit (Unit 6 and 6a) and two of the samples from the glaciolacustrine beds (Unit 4) . The glaciolacustrine beds were found to lack adequate pollen for analysis so will not be reported in this chapter. This latter result was expected and supports the interpretation of Unit 4 as glaciolacustrine beds as the sedimentation dilutes pollen content. As indicated previously (Chapter 3), two further samples were not considered due to ambiguous stratigraphic placement. The data from the remaining 81 samples are reported in this chapter.

Because of challenges correlating individual beds (see Section 3.1) the samples were analyzed as three separate sequences based on where they were collected. This approach avoids errors in the analysis caused by uncertain differences in bed thickness and correlation of beds. These three sequences are series of samples where the relationship is unambiguous. This use of three separate sequences also allows to verify what at first seemed ambiguous correlations of beds by using biostratigraphic data.

From stratigraphically lowest to highest these sequences are called the edge-reversed (ER), main (M), and edge-normal (EN) sequences for the purposes of this study (note the "normal" and "reversed" terms in these sequence names refers to the magnetic polarity of the beds). The sequences were further divided into ten palynological (pollen and spore) zones in total based primarily on stratigraphically constrained tests for similarity (CONISS). The zones include three from the edge-reversed sequence, four from the main sequence, and three from the edge-normal sequence. One further sub-zone was defined from within the edge-reversed sequence for reasons discussed in Section 5.1.3 in this chapter.

In addition to the three sequences, the four samples reported here from Unit 6a (peaty beds near base of the Unit 7 till) are treated separately as these are separated from the remaining samples by a substantial amount (~20 m) of gravels and related beds and hence an unknown amount of time. In this chapter each of these four sets of samples (three sequences and the Unit 6a samples) are treated separately then correlated in the final section of this chapter. Unlike the previous chapter, interpretation of these results is reserved for Chapter 6 in order to integrate them into a chronology and broaden the discussion.

5.1 Edge reversed sequence (ER)

This sequence of 21 samples was collected along the northern wall of the exposure where the bedrock and units 3 (till) and 5 (lakebeds) are observed (HVC-10; 50°29.621'N 121°02.747'W, 1074m asl; also see Chapter 4). Paleontological and palynological observations reported in this section were all made from Unit 5 at this locality. From these data, three palynological zones were identified using the CONISS analysis as a guide (Fig. 5.1). Two closely spaced samples at the base of zone ER-3 were assigned to a subzone (ER-3a) for reasons discussed in this section. Data resolution at this location was a major limitation. Specifically, the two single samples in the upper part of zone ER-2 are outliers in this zone and potentially fall within yet-to-be defined zones which might emerge with higher resolution sampling. Pollen concentration ranged from ~12 g⁻¹ to ~23 thousand g⁻¹ (Table 5.1).

This section is divided into three subsections for each main zone in the edge-reversed sequence. Heights are reported relative to the stratigraphic position in meters above bedrock measured perpendicular to the lake bed sediments (referred to as "local height") and as such these data begin at the Unit 2 (till) - Unit 5 (lakebeds) interface at a position of 8 m local height.

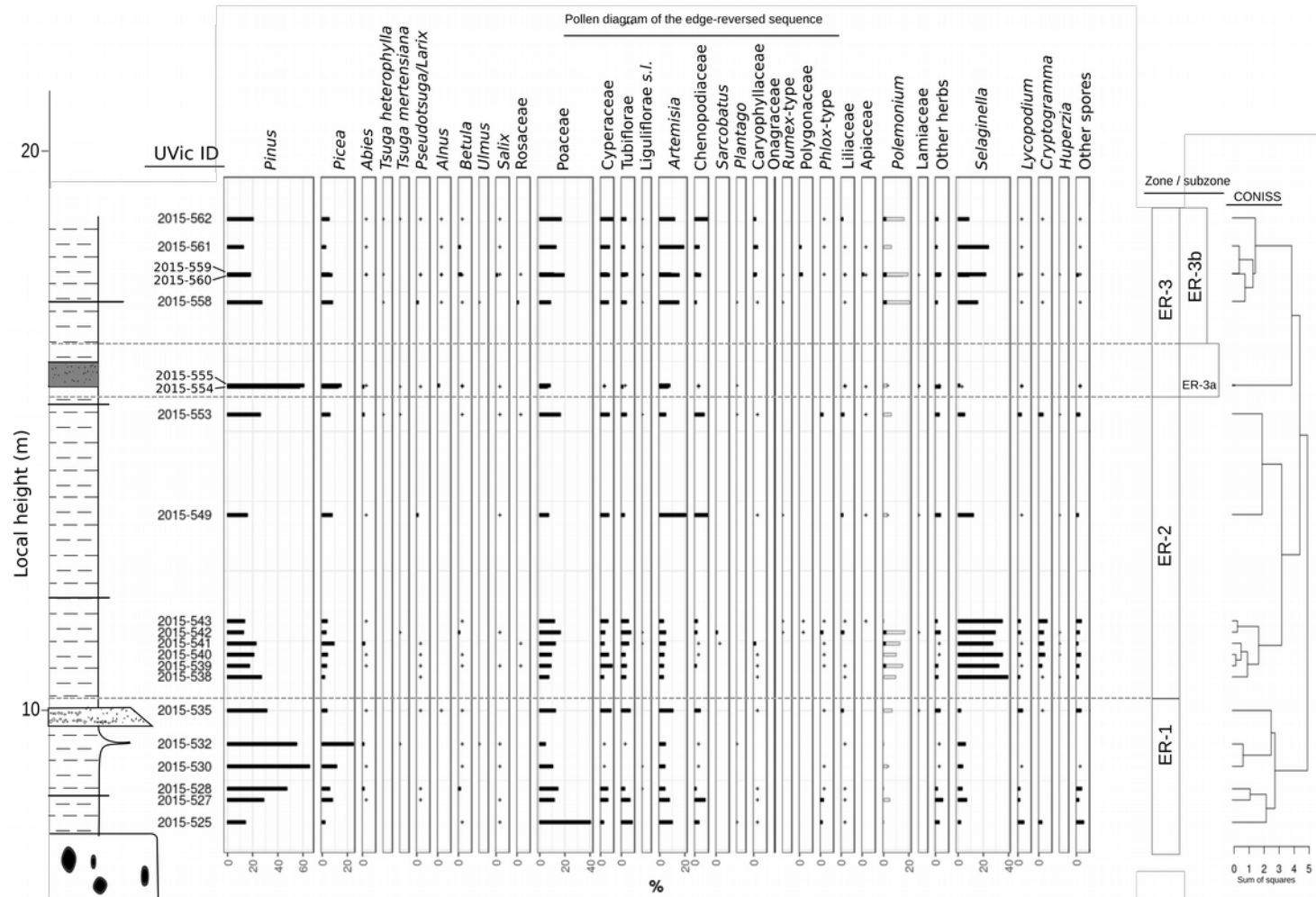


Figure 5.1. Pollen and spore diagram from the edge-normal sequence (HVC-10). Open bars show 10x the percentage for selected palynomorphs. Occurrence of a palynomorph at 1% or less in an assemblage is indicated by a plus sign (+). Height is stratigraphic height relative to bedrock at HVC-10 (see Table 3.1 for locality position). The cluster analysis tree (CONISS) is also shown with the interpreted numbered pollen and spore zones. These zones correspond to those referred to in the text.

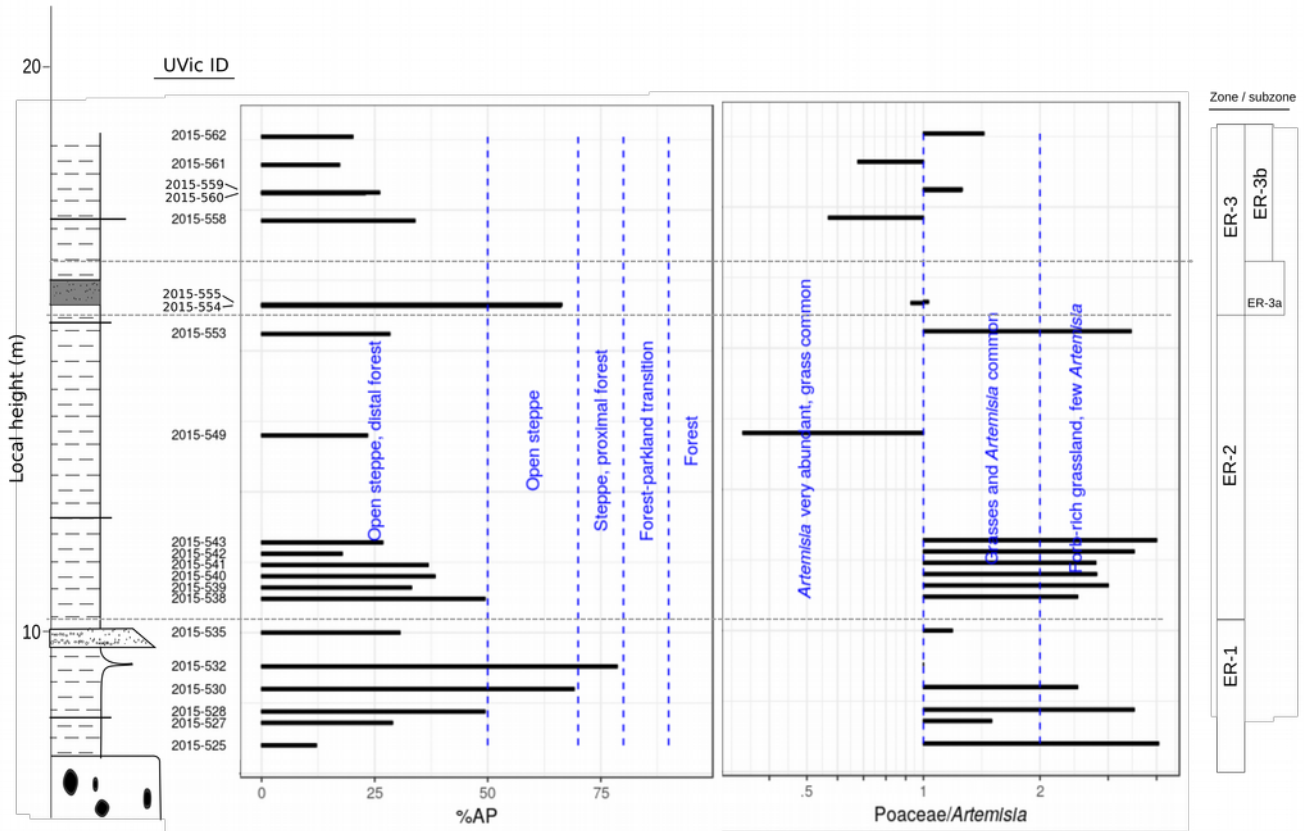


Figure 5.2. Percent arboreal pollen (%AP) and the ratio of Poaceae to *Artemisia* pollen for pollen and spore samples of the edge-reversed sequence. Blue annotations are the suggested interpretation scheme from Hebda (1982) and used later in this thesis for interpretation.

Table 5.1. Pollen and spore concentrations from Edge reversed sequence samples per gram of sediment. Values were determined by calculating the total added *Lycopodium* spores by weight and multiplying that value by the ratio of pollen and spores to counted *Lycopodium* spores (added type only).

Uvic ID	Local height (m)	Pollen and spores (g ⁻¹)	Uvic ID	Local height (m)	Pollen and spores (g ⁻¹)
2015-525	8	13	2015-543	11.6	193
2015-527	8.4	574	2015-549	13.5	1985
2015-528	8.6	107	2015-553	15.3	603
2015-530	9	7474	2015-554	15.8	14783
2015-532	9.4	10629	2015-555	15.82	22558
2015-535	10	343	2015-558	17.31	4425
2015-538	10.6	234	2015-560	17.8	5274
2015-539	10.8	702	2015-559	17.81	1897
2015-540	11	178	2015-561	18.3	3754
2015-541	11.2	757	2015-562	18.8	968
2015-542	11.4	158			

5.1.1 Zone ER-1: *Pinus-Picea* (8 to 10.3 m)

ER-1 begins at the contact between units 3 (till) and 6 (8 m above bedrock), continues for 2.3 m (10.3 m above bedrock) all within silts. It includes 6 samples (2015-525, 2015-527, 2015-528, 2015-530, 2015-532 and 2015-535; Fig. 5.1). Pollen and spore concentrations range from very low (13 g⁻¹) to very high (10628 g⁻¹) (Table 5.1). Grains in this group of samples were often somewhat crumpled and torn but preservation was adequate for identification. This zone is dominated by arboreal pollen (40.5 to 82.5% and 1 observation at 19%; Fig. 5.2). The arboreal assemblage is mostly *Pinus* (28.8 to 65.2%, 1 observation at 14%), and *Picea* (2.1 to 24.7%) pollen (Fig. 5.1). Non-arboreal pollen and spores (NAP) make up the remainder of the counted grains with grasses (Poaceae) pollen being the most abundant NAP type found in the zone (4.5 to 14.4%, 1 observation at 40.3%) and *Artemisia* pollen

grains accounting for less than 11% of the zone assemblage (4.1-10.5%) (Fig. 5.1). Chenopodiaceae type pollen is also found in low amounts (0.6-4.3%, 1 observation at 8.2%) and the abundance of Cyperaceae pollen counts vary substantially (0.6-8.2%) (Fig. 5.1). As expected with high arboreal counts the non-arboreal assemblage is subdued leading to high variation in non-arboreal values, affected especially by lower total pollen counts achieved in this zone (194 to 339 grains). Poaceae values generally outnumber *Artemisia* in this zone by a substantial margin (Poaceae:*Artemisia* = 1.0 to 4.0; Fig. 5.2).

A small number of macrofossils were found in association with this zone: small (~0.5 cm diameter) animal (worm?) burrows were observed at around 8.5m and small mollusc shell fragments were recovered during pollen processing in sample material from beds between 9 to 9.4 m above the bedrock (UVic id 2015-529 through 2015-532).

5.1.2 Zone ER-2: *Selaginella*-Poaceae (10.3 to 15.5 m)

Zone ER-2 is defined between 10.3 m and 15.5 m at HVC-10 and contains a total of 8 samples (2015-538 through 2015-543, 2015-549 and 2015-553; Fig. 5.1) all from within silts. The pollen and spore concentration is relatively low (158 g⁻¹ to 1984 g⁻¹; Table 5.1). Preservation was generally good except on some arboreal grains which were torn or degraded. This zone may only be valid for the lower part (10.3 to 12 m) since the sample resolution for the upper part is very low. Because of this the upper two samples (lab id 15-549 and 15-553) which lie between 12 and 15.5 m should be considered outliers and are not included in the text of this section. As a result this zone is defined mainly by samples which were retrieved from 10.6-11.6 m local height. No macrofossils were found in association with this zone.

The zone is dominated by non-arboreal types (19.2 to 38.5% AP; Fig. 5.2). The arboreal pollen in this zone included mostly *Pinus* (12.7 to 26.9%), and *Picea* (1.9 to 9.4%) (Fig. 5.1). Non-arboreal types are dominant, with *Selaginella* spores making up the largest component of the zone (27.4 to 39.4%).

The zone also includes high amounts of Poaceae (7.2 to 12.4%), Tubuliflorae (3.0 to 7.3%), Cyperaceae (2.4 to 9.2%) pollen, and *Cryptogramma* (0.5 to 6.5%) spores (Fig. 5.1). *Polemonium* pollen was also found sporadically, but present only in some samples (up to 1.7%) (Fig. 5.1). Poaceae outnumbered *Artemisia* by more than 2x in this assemblage except for the two uppermost outliers mentioned previously (Poaceae:*Artemisia* = 2.5 to 4.0; Fig. 5.2).

Some of the *Polemonium* grains were identified as *Polemonium pulcherrimum*-type based on their relatively smooth cross section and striato-reticulate sculpturing with indistinct granules on the lirae (Mathewes 1979; Figs. 5.3e-h).

The *Selaginella* spores examined (Figs. 5.3a-d) appeared superficially similar to a number of species found in the Cordillera. These spores were well-preserved and closely matched images and descriptions in the dichotomous key used (Heusser and Peteet 1988). In particular, *S. densa*, *S. watsonii*, *S. wallacei* and *S. sibirica*. Most other *Selaginella* spore types were ruled out based on these spores having a thick perine envelope with inconspicuous structures that other *Selaginella* have (e.g. *S. oregana*, *S. douglasii*, *S. selaginoides*; Heusser and Peteet 1988). The perine envelope of these specimens were relatively thick (~2 µm) which distinguishes them from *S. wallacei*, *S. densa* and *S. oregana* which have only a thin (< 1 µm) perine envelope (Heusser and Peteet 1988). A few other species with a modern presence in BC do not seem to have good spore morphology descriptions in the literature if any such as *S. rupestris*, and *S. standleyi* so this comparison could not be made. Of these *S. rupestris* can be ruled out given the lack of "dumbbell" spores and the less common wrinkled appearance of these spores than that described by Reeve (1935). Of the remaining *Selaginella* this was compared to, *S. watsonii* is an unlikely candidate as it inhabits low latitudes today (Oregon and California; Heusser and Peteet 1988). Based on these observations *S. sibirica* appears to have been present at the time of deposition.

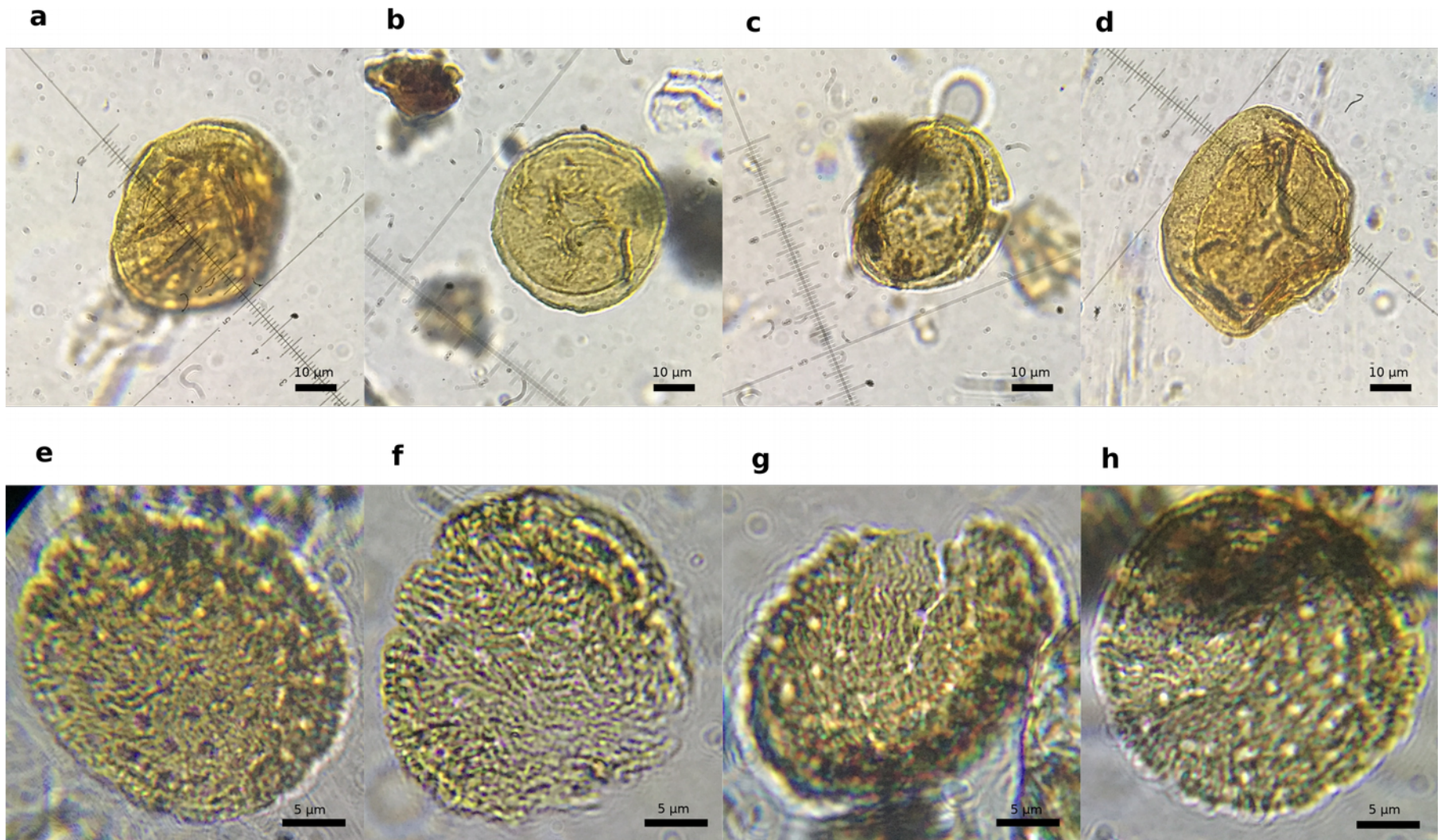


Figure 5.3. Light microscope photographs of indicator pollen types from the ER-2 zone at HVC. (a-d) *Selaginella sibirica*-type. (e-h)

Polemonium pulcherrimum-type.

5.1.3 Zone ER-3: *Pinus-Picea* and *Artemisia-Poaceae* (15.5 to 19 m)

Zone ER-3 contains seven samples between 15.5 and 19 m above local height (2015-554, 2015-555 and 2015-558 through 2015-562; Fig. 5.1). Preservation was generally good except for the occasional arboreal grain. These are all from within the silt beds, however one sample (2015-555) was from the peaty silts at HVC-10. Pollen and spore concentrations range from moderate (968 g^{-1}) to very high (22558 g^{-1}) (Table 5.1) with the highest concentrations in the ER-3a subzone (2015-554 and 2015-555 in Table 5.1). Arboreal pollen dominates in the lower two samples (both 78.4%) and are placed in a separate subzone (ER-3a; 2015-554, 2015-555; Figs. 5.1 and 5.2) supported by macrofossil data (discussed later). This separation is made to facilitate discussion as two samples are not enough to confidently qualify them as a pollen zone. The remaining five samples (subzone ER-3b) are dominated by non-arboreal pollen and spores (58.2 to 79.4%) (Fig. 5.2).

The ER-3a subzone assemblage consists primarily of arboreal pollen (two samples with 78.4 %; Fig. 5.2) with mainly *Pinus* (57.3 and 60.7%) and *Picea* pollen (12.7 and 15.1%) (Fig. 5.1). The non-arboreal assemblage is composed of almost equal amounts of *Artemisia* (6.6 and 8.1%) and Poaceae (6.1 and 8.3%) pollen, and low amounts of other non-arboreal types (e.g. 1.2 and 0.2% Tubuliflorae, 0.7 and 1.0% Chenopodiaceae, 2.1 and 2.2% spores) (Fig. 5.1). Indeterminate types made up for much of the remainder; for instance "Other bisaccate" (4.9 and 0%) and "Other herbs" (3.8 and 0.7%) (Fig. 5.1). The category "indeterminate type" was typically recorded when many grains were too degraded to be confidently identified further. The ratio of Poaceae and *Artemisia* is almost even in this subzone (Poaceae:*Artemisia* = 0.9 and 1.0; Fig. 5.2).

Subzone ER-3a is associated with abundant, excellently preserved, macrofossils which include *Pinus* (cones), *Picea* (needles), *Myriophyllum* (stems, leaves and flowers), Salmonid fish (complete specimens; cf. *Oncorhynchus* sp.), small mollusc shells, and wood charcoal fragments. In addition, a thin organic debris layer with mostly charcoal, plant debris and reddish sand is found associated with

this subzone and is similar to a debris layer found in association with zone M-1. The importance of this observation is discussed in later sections.

ER-3b, which consists of the remaining samples of zone ER-3, is characterized by mainly non-arboreal types. The arboreal pollen assemblage (21.5 to 42.1%) consists of *Pinus* (12.6 to 27.3%) and *Picea* (2.8 to 8.2%) (Fig. 5.1). Like ER-3a, the non-arboreal assemblage is mostly Poaceae (10.9 to 19.4%) and *Artemisia* (8.7 to 19.1%) (Fig. 5.1) with the two types in roughly even proportions (Fig. 5.2). A variety of other non-arboreal pollen types make up this subzone, notably Cyperaceae (5.8 to 10.0%), *Selaginella* (8.4 to 24%), Tubuliflorae (2.5 to 4.8%), Chenopodiaceae (1.2 to 4.5% and an observation at 10.3%) and Caryophyllaceae (0.3 to 3.1%) (Fig. 5.1). *Polemonium* (0.6 to 2.1%) is also an important contributor to the non-arboreal pollen assemblage of this subzone (Fig. 5.1). Poaceae outnumber *Artemisia* in three of these samples (Poaceae:*Artemisia* = 1.3 to 1.4) and the reverse is true in the other two of the samples (Poaceae:*Artemisia* = 0.6 and 0.7) in this subzone (Fig. 5.2). Unlike subzone ER-3a, no fossils were observed in association with ER-3b.

5.2 Main sequence (M)

The main sequence includes samples from exposures south of the two "edge" sequences where the beds lie horizontal (HVC-1, HVC-1a, HVC-1b, HVC-2, HVC-2a, HVC-3, HVC-3b, HVC-3c, HVC-3d, and HVC-3e; see Fig. 4.1 and Table 3.1). These were combined as these beds at each site are close to each other and have an unambiguous stratigraphic relationship. This sequence is drawn from Unit 5 beds exclusively, however Unit 5a (catastrophic debris flow) is present at ~20-20.5 m local height which has implications for separating out zones in this sequence. Local heights reported here are relative to the 1050 bench road cut (1050 m asl) surface at HVC-1 (see Table 3.1 for locality data). Sample 15-022 was excluded from the CONISS analysis because of possible tephra effect on the data since tephra deposition is known to produce brief short term effects on pollen rain; particularly

affecting non-arboreal species (Long et al. 2011). This sample lies within zone M-4 reported here and is reported in Figs. 5.3 and 5.4. In total, four zones were identified in this sequence based on the CONISS model (Fig. 5.4).

Table 5.2. Pollen and spore concentrations from Main sequence samples per gram of sediment. Values were determined by calculating the total added *Lycopodium* spores by weight and multiplying that value by the ratio of pollen and spores to counted *Lycopodium* spores (added type only).

Uvic ID	Local height (m)	Pollen and spores (g ⁻¹)	Uvic ID	Local height (m)	Pollen and spores (g ⁻¹)
2014-263	1	1970	2015-005	19.5	745
2015-001	2	3779	2015-011	20.01	2115
2015-190	2.5	6745	2015-015	20.5	409
2015-002	3	147559	2015-016	21	695
2015-003	4	10436	2015-017	21.7	124
2015-004	5	1100	2015-018	22.2	225
2015-034	9	2390	2015-020	23.5	403
2015-035	10	5872	2015-021	24	710
2015-036	11	5594	2015-022	24.4	756
2015-037	12	3748	2015-023	25	1473
2015-039	14	1190	2015-024	26	1382
2015-014	14.5	577	2015-025	26	392
2015-040	15	475	2015-026	26.4	1502
2015-013	15.5	586	2015-027	26.9	1990
2015-041	16	333	2015-028	27.9	127
2015-042	17	419	2015-029	27.95	963
2015-007	17.5	205	2015-031	28.8	855
2015-006	18.5	707			

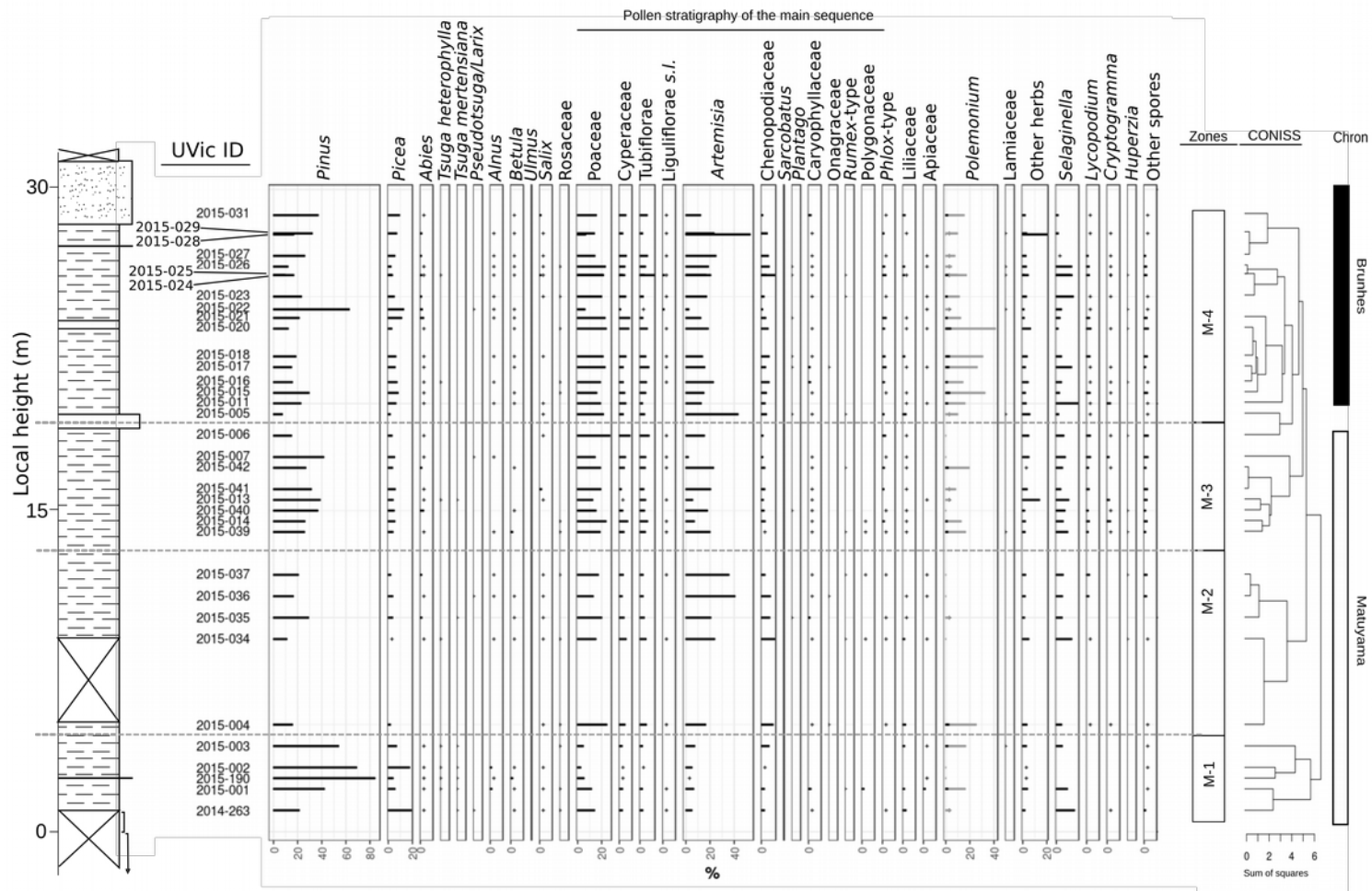


Figure 5.4. Pollen and spore diagram from the main sequence. Open bars show 10x the percentage for selected palynomorphs. Occurrence of a palynomorph at 1% or less in an assemblage is indicated by a plus sign (+). Height is stratigraphic height relative to the 1050 m asl roadcut at HVC-1 (see Table 3.1 for locality position). The cluster analysis tree (CONISS) is also shown with the interpreted numbered pollen and spore zones. These zones correspond to those referred to in the text.

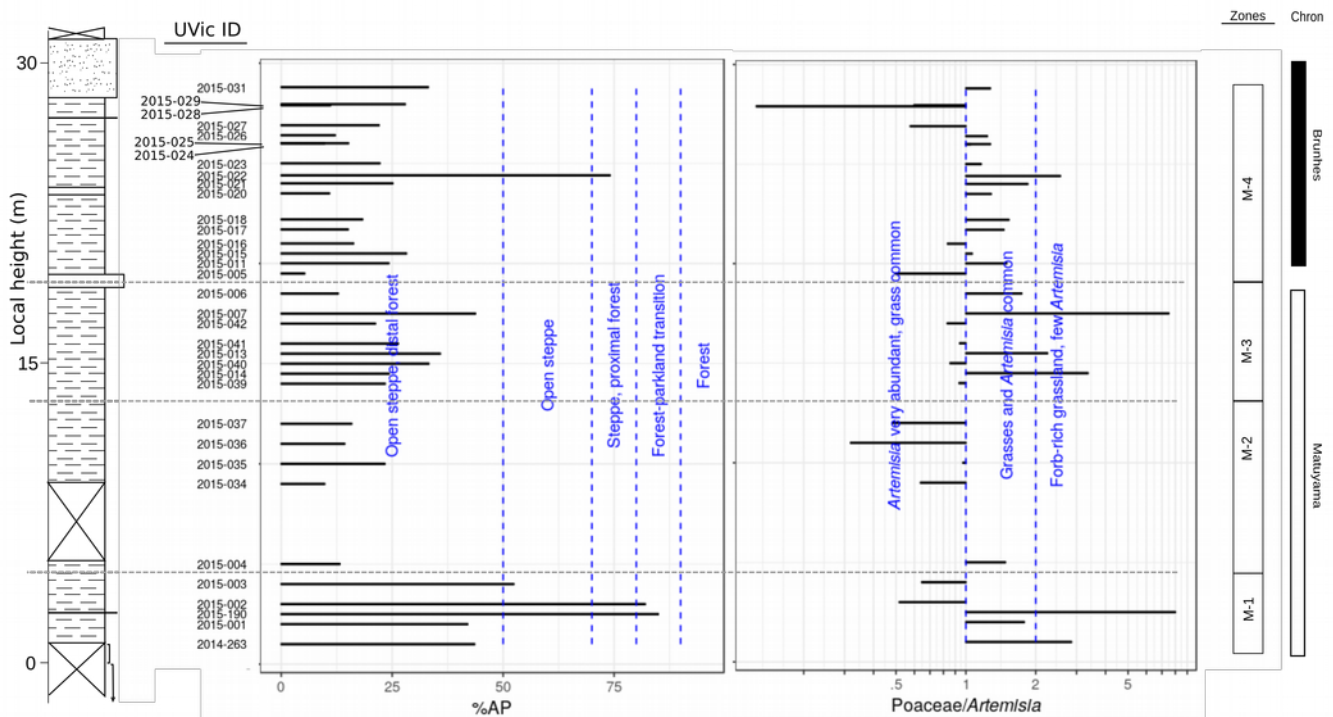


Figure 5.5. Percent arboreal pollen (%AP) and the ratio of Poaceae to *Artemisia* pollen for pollen and spore assemblages of the main sequence. Blue annotations are the suggested interpretation scheme from Hebda (1982) and used later in this thesis for interpretation.

5.2.1 Zone M-1: *Pinus-Picea* (0 to 4.5 m)

Five samples from between 0 to 4.5 m local height (2014-263, 2015-001 through 2015-003, 2015-549 and 2015-190; Fig. 5.4) all taken from silts. Pollen and spore concentrations ranged from moderate (1970 g^{-1}) to very high (147559 g^{-1} ; Table 5.2). Preservation was generally excellent with the occasional arboreal pollen grain broken up, torn or worn down. Arboreal pollen dominates this zone (50.3 to 92.0%; Fig. 5.5). The arboreal part of the assemblage mainly consists of *Pinus* pollen (21.3 to 84.1%) with less *Picea* pollen (2.6 to 14.1%) (Fig. 5.4). The non-arboreal assemblage includes Poaceae (2.6 to 14.1%), *Artemisia* (0.7 to 7.3%) and Chenopodiaceae (0 to 6.4%), Cyperaceae (0.3 to 2.8%) and Tubuliflorae (0 to 2.4%) (Fig. 5.4). Poaceae pollen appear to outnumber *Artemisia* pollen grains in the lower 3 samples in this zone (Fig. 5.5), however this tendency is reversed in the remaining upper two

samples. The arboreal pollen percentages were found to be higher in the central part of the zone, with the non-arboreal signal weakened substantially in the center of the zone despite high pollen counts (301 to 620 grains).

Diverse well preserved macrofossils were found in association with this zone. These include plant fossils (*Picea* (needles and cones), *Pinus ponderosa* (branches with attached needles), *P. cf. contorta* (cones), *Salix* spp. (leaves), *Fontinalis* sp. (whole plant), *Myriophyllum* sp. (fragments)), and vertebrate remains (cf. *Oncorhynchus* sp. (whole fish), *Odocoileus* sp. (cf. lumbar vertebrae L4 or L5) and a bird feather). A thin layer of plant debris, charcoal and reddish sand occurs at 2.5 m which is similar to that found within zone ER-3a.

5.2.2 Zone M-2: *Artemisia-Poaceae* (4.5 to 13 m)

Five samples were assigned to this zone from between 4.5 and 13 m local height (2015-004 and 2015-034 through 2015-037; Fig. 5.4) all taken from silts. Pollen and spore concentrations were moderate (1100 g⁻¹ to 5872 g⁻¹; Table 5.2). The preservation for most grains in this zone was excellent with some arboreal grains being torn or broken up. The zone is dominated by non-arboreal pollen and spores (65.0 to 84.9 %; Fig. 5.5). The arboreal assemblage contains mostly *Pinus* (11.0 to 29.0 %), and low percentages of *Picea* (0.7 to 3.8%) (Fig. 5.4). The non-arboreal assemblage is composed primarily *Artemisia* (16.4 to 40.7%), *Poaceae* (13 to 24.3%), *Chenopodiaceae* (3.0 to 11.0%), *Cyperaceae* (2.4 to 5.7%) and *Tubuliflorae* (2.7 to 5.4%) pollen (Fig. 5.4). *Selaginella* spores are also an important component of the observed assemblage (4.4 to 12.8%) (Fig. 5.4). Other non-arboreal pollen types occur sporadically and in low quantities (< 2%) with *Polemonium* pollen absent in most samples (0.3 and 2.5 % in 2 of the 5 only) (Fig. 5.4). *Artemisia* typically outnumbered *Poaceae* in this assemblage (*Poaceae:Artemisia* = 0.5 to 1.0 mostly with one value of 1.5; Fig. 5.5). No macrofossils were recovered from this zone.

5.2.3 Zone M-3: Poaceae-*Artemisia* (13 to 20.25 m)

The zone is based on ten samples between 13 and 20.25 m local height (2015-039 through 2015-042, 2015-006, 2015-007, 2015-013 and 2015-014; Fig. 5.4) all taken from silts. Pollen and spore concentrations were low to moderate (205 g⁻¹ to 1190 g⁻¹; Table 5.2). Moderate to poor preservation in primarily the arboreal pollen, with good to excellent preservation of non-arboreal types. The lower limit of this zone is informed by the CONISS model which separates out all remaining samples from the previous zones, however the upper limit is defined at ~ 20 - 20.5 m where Unit 5a is located. This is because the event responsible for this event bed (a sub-aqueous debris flow; see Sec. 4.2.3) could have removed a relatively small (a few meters) part of the record here, thus the record above and below the unit are probably non-continuous. The assemblages are not very different from one another either (Fig. 5.4; see this and the following section as well) and could arguably be part of the same zone if the CONISS tree is followed strictly. Since the degree of continuity of these data across Unit 5a is in doubt, the record above and below this bed was separated into two zones.

In this zone (M-3) non-arboreal types dominate the assemblage, however the arboreal pollen is higher than the previous zone (20.1 to 45.0 % with a minimum at 8.9% AP; Fig. 5.5). The arboreal assemblage contains mostly *Pinus* (15.0 to 41.6 % with one observation of 7.26 %), and small amounts of *Picea* (1.7 to 6.3%) (Fig. 5.4). Poaceae (12.6 to 29.8%) and *Artemisia* (7.0 to 22.9% with additional observations of 1.9, 5.6, and 43.2%) pollen tend to dominate the non-arboreal assemblage in this zone (Fig. 5.4). Other main pollen and spore contributors include *Selaginella* (2.0 to 10.3% with one observation at 17.8%), Tubuliflorae (2.2 to 7.7%), Cyperaceae (0.8 to 8.8%), and Chenopodiaceae (0.7 to 4.3%). *Polemonium* pollen is present as well (up to 1.9%). Poaceae pollen typically outnumbered *Artemisia* in this assemblage (Poaceae:*Artemisia* = 0.8 to 3.4 mostly with additional values at 0.5 and 7.5; Fig. 5.5). No macrofossils were recovered from this zone.

5.2.4 Zone M-4: *Poaceae-Artemisia-Polemonium-Forb* (20.25 to 29 m)

Seventeen samples make up zone M-4 between 20.25 and 29 m local height (2015-005, 2015-011, 2015-015 through 2015-018, 2015-020 through 2015-029 and 2015-031; Fig. 5.4) all taken from silts. Pollen and spore concentrations were low to moderate (124 g^{-1} to 2115 g^{-1} ; Table 5.2). Mostly good preservation with some arboreal grains with appearing worn and broken. The zone contains a single sample with a peak in arboreal pollen (Fig. 5.4), and a sharp increase in the *Poaceae:Artemisia* ratio at 24.4 m which coincides with sediment deposited shortly after the "thick felsic tephra" in Unit 5 (see Sec. 4.1.6) which was temporarily removed from the data set prior to CONISS analysis for reasons discussed in the beginning of Section 5.2. Whether this data point is a result of a volcanic event (or other anomaly) or reflects long-term climate change will require better knowledge of deposition rates at HVC and potentially higher resolution work.

This assemblage is dominated by non-arboreal pollen (14.5 to 47.6% AP with one notable peak at 81.3%; Fig. 5.5). The arboreal assemblage consists of mostly *Pinus* (9.3 to 37.0% with one peak at 62.8%) and *Picea* (up to 12.7%) pollen (Fig. 5.4). The non-arboreal assemblage is composed mainly of *Poaceae* (13.9 to 23.8% with low values of 6.2 and 6.7%), *Artemisia* (12.2 to 25.0% plus two observations of 2.4 and 53.3%) pollen (Fig. 5.4). Other major non-arboreal pollen and spore contributors include *Selaginella* (up to 14.1%), Cyperaceae (up to 8.6%), Chenopodiaceae (up to 11.4%), Tubuliflorae (up to 11.9%) and *Polemonium* (up to 4.1%) (Fig. 5.4). *Artemisia* and *Poaceae* pollen occur in more or less similar amounts in this assemblage but the values vary widely (*Poaceae:Artemisia* = 0.6 to 1.9 mostly with two observations of 0.1 and 2.6; Fig. 5.5). As is apparent percentages vary widely in this zone. Such variation sometimes reflects under-sampling within pollen and spore zones (Bennett 1996). No macrofossils were recovered from this zone.

5.3 Edge-normal Sequence (EN)

The edge-normal sequence samples consist of those about 500 m west-northwest of the last sample of the main sequence at 1081 m asl (HVC-3f and HVC-4a; see Table 3.1 and Fig. 4.1 for locations). This sequence includes mainly samples from Unit 5 (lakebed) beds but also includes a small number of samples from intercalated lakebeds within Unit 6 (gravel; at HVC-4a) at the top of the sequence

Table 5.3. Pollen and spore concentrations from Edge normal sequence samples per gram of sediment. Values were determined by calculating the total added *Lycopodium* spores by weight and multiplying that value by the ratio of pollen and spores to counted *Lycopodium* spores (added type only).

Uvic ID	Local height (m)	Pollen and spores (g ⁻¹)	Uvic ID	Local height (m)	Pollen and spores (g ⁻¹)
2015-044	3	36335	2015-054	14	122
2015-045	3.5	5095	2015-056	16	785
2015-046	4	5995	2015-057	18	426
2015-047	5	979	2015-058	18.3	337
2015-048	8	60	2015-059	20	217
2015-049	9	1257	2015-060	22	914
2015-050	10	49	2015-061	23.9	736
2015-051	11	254	2015-063	26.4	326
2015-052	12	270	2015-066	28.4	271
2015-053	13	358	2015-067	28.9	440

because the transition is gradational between the two units. Sampling was not attempted on beds immediately above HVC-4a as fine grained sediments were largely absent. A distinct tephra bed occurs in these beds and was used to correlate sections (the "thick felsic tephra" mentioned in Section 4.1.6 and in the previous section). This sequence is separated from the others because it is separated from the edge-reversed sequence by tens of meters horizontally and differences in relative bed thickness

between this sequence and the main sequence was suspected because of differences in sedimentary facies (i.e. different sedimentation rates were likely). The samples from this sequence were grouped into three pollen zones on the basis of the CONISS model (Fig. 5.6) and are described in each of the following subsections.

5.3.1 Zone EN-1: *Pinus-Picea* (0 to 9 m)

Five samples between 0 and <9 m local height make up this zone (2015-044 through 2015-048; Fig. 5.6) all taken from sandy silts. Pollen and spore concentrations ranged from very low to very high (60 g^{-1} to 36335 g^{-1} ; Table 5.3). Moderately good to excellent preservation of grains, with some arboreal grains broken up but mostly well preserved. However one sample (at 5 m; 15-047) is excluded from analysis because the pollen count was low (82 grains); nevertheless it is displayed in Fig. 5.6. The upper sample from this zone (8 m; 15-048) also had a relatively low pollen count (140) but was not excluded because it exceeds the minimum standard set for this study (100). In contrast, the lower three samples had very high pollen counts (335.5 to 695 grains).

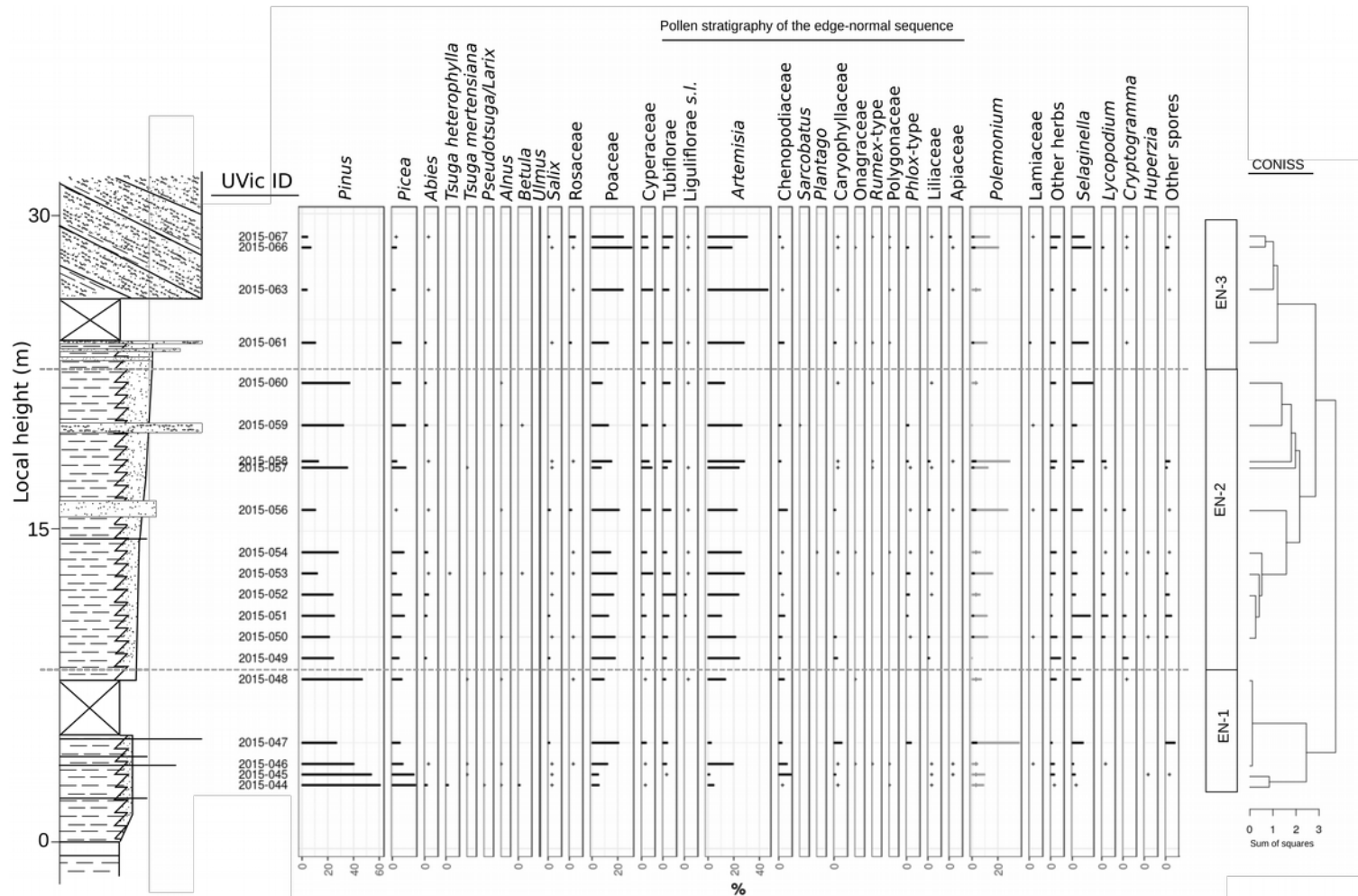


Figure 5.6. Pollen and spore diagram from the edge-normal sequence. Open bars show 10x the percentage for selected palynomorphs. Occurrence of a palynomorph at 1% or less in an assemblage is indicated by a plus sign (+). Height is stratigraphic height relative to the "thick felsic tephra" at HVC-3f (see Table 3.1 for locality position and text for further information). The cluster analysis tree (CONISS) is also shown with the interpreted numbered pollen and spore zones. These zones correspond to those referred to in the text.

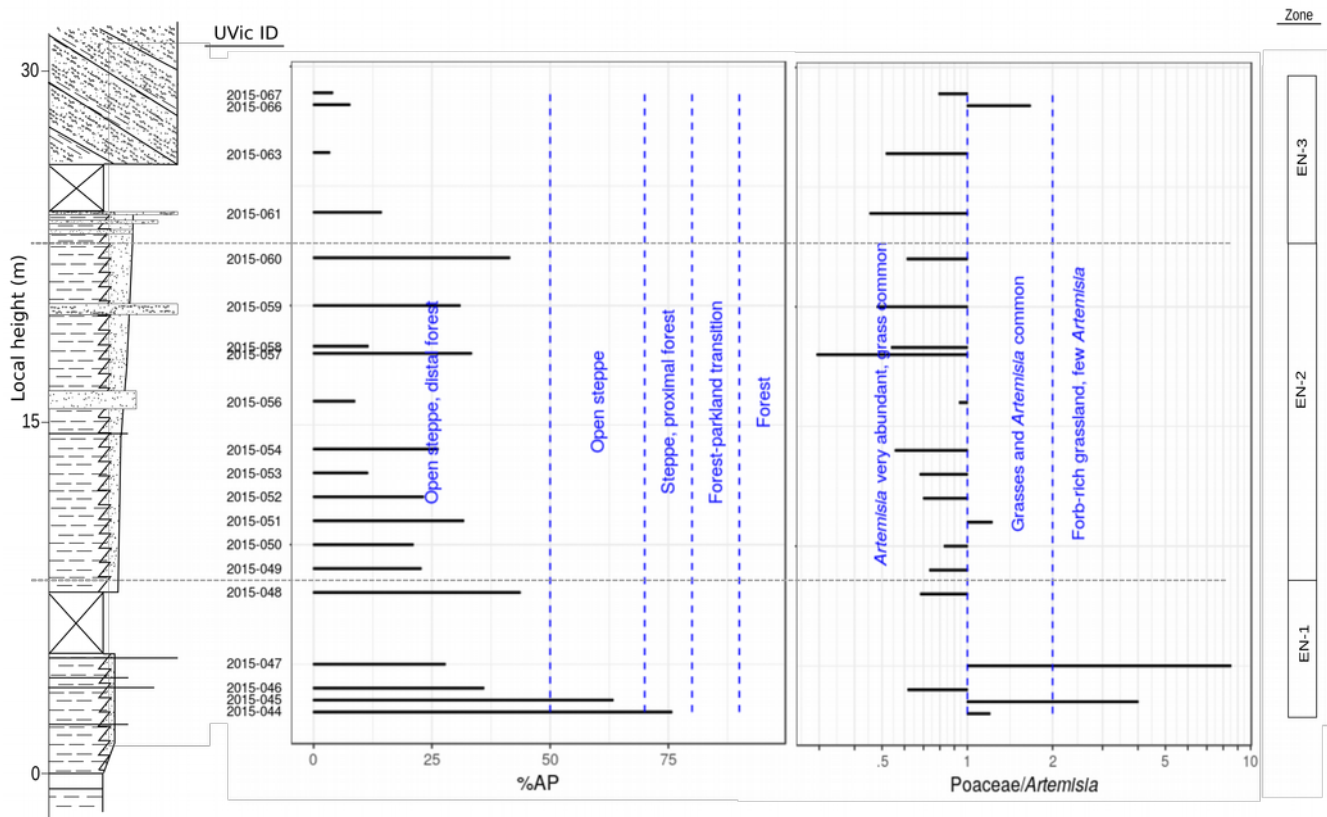


Figure 5.7. Percent arboreal pollen (%AP) and the ratio of Poaceae to *Artemisia* pollen for pollen and spore samples of the edge-normal sequence. Blue annotations are the suggested interpretation scheme from Hebda (1982) and used later in this thesis for interpretation.

Arboreal types are most abundant (51.5 to 85.1% AP; Fig. 5.7) with *Pinus* (40.3 to 60.7%) and *Picea* (7.5 to 18.2%) making up the arboreal assemblage (Fig. 5.6). Non-arboreal pollen includes mostly Poaceae (4.9 to 12.1%), *Artemisia* (1.2 to 19.6%) and Chenopodiaceae (0.6 to 9.6%) grains with low amounts of other herb pollen present such as Caryophyllaceae (up to 1.2%) and *Polemonium* (0.4 to 1.0%) (Fig. 5.6). *Selaginella* spores also occur (0.9 to 6.4%) (Fig. 5.6). Poaceae and *Artemisia* proportions vary sample to sample but appear to favour *Artemisia* near the top of the zone (Poaceae:*Artemisia* = 0.6 to 4.0; Fig. 5.7). There is a trend in this zone for arboreal types to be found less abundantly up the sequence and non-arboreal types to gradually become more abundant.

Some macrofossils were recovered in association with this zone, however these were mostly limited to aquatic taxa (*Myriophyllum* sp., Gastropoda, and Bivalva). Large wood charcoal fragments were also abundant in the sediment but could not be identified. These charcoal fragments are likely arboreal in origin as many of them are too large (> ~1 cm) to be from any common shrub or forb.

5.3.2 Zone EN-2: *Artemisia*-Poaceae (9 to 23 m)

Eleven samples from 9 and 23 m local height make up this zone (2015-049 through 2015-054 and 2015-056 through 2015-060; Fig. 5.6) all taken from sandy silts. Pollen and spore concentrations ranged from very low to moderate (49 g⁻¹ to 1257 g⁻¹; Table 5.3). Generally good to excellent preservation overall. Two of these samples had counts too low for inclusion in the analysis (78 at 9 m [UVic id 2015-049] and 86 at 11 m [UVic id 2015-051]). These are both near the bottom of the zone. The remaining counts reached adequate numbers for analysis (most >300 and one at 247.5).

The dominant pollen and spore types in this zone were non-arboreal (50.7 to 87.4 %; Fig. 5.7). The arboreal assemblage contains mainly *Pinus* (10.4 to 37.0%) and *Picea* (0.9 to 10.5%) (Fig. 5.6). The non-arboreal assemblage is made up of mostly *Artemisia* (12.8 to 28.3%), Poaceae (7.1 to 21.1%), *Selaginella* (1.2 to 8.8% with one value of 16.0%), Tubuliflorae (2.0 to 10.2%), Chenopodiaceae (up to 6.7%), Cyperaceae (1.9 to 8.6%), *Polemonium* (up to 2.9%) and numerous other herbs (Fig. 5.6). *Artemisia* outnumbers Poaceae pollen in this assemblage (Poaceae:*Artemisia* = 0.3 to 0.9; Fig. 5.5). No macrofossils were found in association with this zone.

5.3.3 Zone EN-3: *Artemisia*-Poaceae (23 to 29 m)

Only four samples from 23 and 29 m local height in this zone (2015-061, 2015-063, 2015-066 and 2015-067; Fig. 5.6) all taken from sandy silts. The upper three of these samples were taken from sandy silt lakebeds which were intercalated with the coarser material within Unit 6. Pollen and spore concentrations are moderate (271 g⁻¹ to 735 g⁻¹; Table 5.3). Good to excellent preservation overall. All

counts resulted in a total of more than 303 grains. Like the previous zone, the dominant pollen and spore types are non-arboreal (79.1 to 94.3 %), however the arboreal signal is much weaker (5.7 to 20.9 %; Fig. 5.7) than the underlying zone. The arboreal assemblage contains mainly *Pinus* (3.8 to 10.4%) and *Picea* (0.8 to 6.8%) (Fig. 5.6). The non-arboreal assemblage is made up of mostly *Artemisia* (18.5 to 46.5%), Poaceae (12.7 to 30.9%), *Selaginella* (2.3 to 14.4%), Cyperaceae (4.6 to 8.6%), Tubuliflorae (4.6 to 7.6%), Chenopodiaceae (0.3 to 4.0%) and numerous other herbs (Fig. 5.6). *Artemisia* mostly outnumbers Poaceae in this assemblage (Poaceae:*Artemisia* = 0.5 to 0.8 plus one sample at 1.7; Fig. 5.7). No macrofossils were found in association with this zone.

5.4 HVC-4/HVC-12

Four of the samples from HVC-4/HVC-12 (peat and silty peat beds) were processed and analyzed and yielded two distinct assemblages (Table 5.4). This group of samples contained good to excellently preserved grains. The lower two samples contain a strong arboreal signal (84.1 and 88.3% AP) whereas

Table 5.4. Selected palynomorph percentages from samples from locality HVC-12 by local height and lab ID. Stated local heights are relative to the base of Unit 7a (sands and peats) with Unit 7 (gravels). All values are in percentages except height and the ratio of Poaceae to *Artemisia*.

Lab (2015-xxxx)	Local height (m)	<i>Pinus</i>	<i>Picea</i>	<i>Abies</i>	Other arboreal	Total arboreal	Shrubs	Poaceae	Tubuliflorae	Liguliflorae s. l.	<i>Artemisia</i>	Chenopodiaceae	<i>Polemonium</i>	Cyperaceae	Other herbs	<i>Selaginella</i>	<i>Lycopodium</i>	Other spores	Total non-arboreal	Poaceae: <i>Artemisia</i>	Pollen and Spores (g-1)
570	0.5	74.8	1.9	0.3	11.2	88.3	0.0	2.3	0.3	0.0	2.3	1.0	0.0	3.2	2.3	0.0	0.3	0.3	12.0	0.5	9844
572	0.9	70.2	3.3	1.0	9.7	84.1	0.0	6.3	0.6	0.0	1.6	1.3	0.0	3.8	1.6	0.3	0.3	0.3	16.2	0.8	5580
574	1.4	36.3	11.2	1.0	5.4	53.9	1.3	22.7	2.6	0.0	9.9	1.0	1.0	2.6	3.6	0.3	1.6	1.6	47.7	0.7	3479
576	1.8	35.4	4.8	0.5	4.4	45.1	0.3	24.6	3.2	0.3	9.0	1.9	0.0	6.5	7.1	1.6	1.0	1.0	55.9	0.7	2633

the upper two contain a weaker arboreal signal (45.1 and 53.9% AP) (Table 5.1). As with other zones, *Pinus* and *Picea* are the main tree pollen types (Table 5.1). The non-arboreal types in the upper two samples are dominated by Poaceae, *Artemisia*, and some Cyperaceae with other herb types not exceeding 2% (Table 5.1). In all four samples, Poaceae pollen outnumber *Artemisia* pollen (Poaceae:*Artemisia* = 1.0 to 4.0).

5.5 Taphonomy

Pollen and spore preservation was generally good to excellent. In cases where grains were found to be torn, degraded or broken, the grains were usually arboreal pollen which are anemophilous. This would imply that distal pollen input was primarily wind-borne and hence agrees with the dominant forms of pollen and spore transport being wind and slope wash which is predicted by the lack of evidence for much fluvial input. This also agrees with the implied catchment if it is similar to the relative present catchment size of the surrounding uplands which only supports short fluvial networks. In sum, based on taphonomy, geology and present conditions, the pollen and spores in this record were probably transported mostly by wind and slope wash.

5.6 Pollen zone correlation

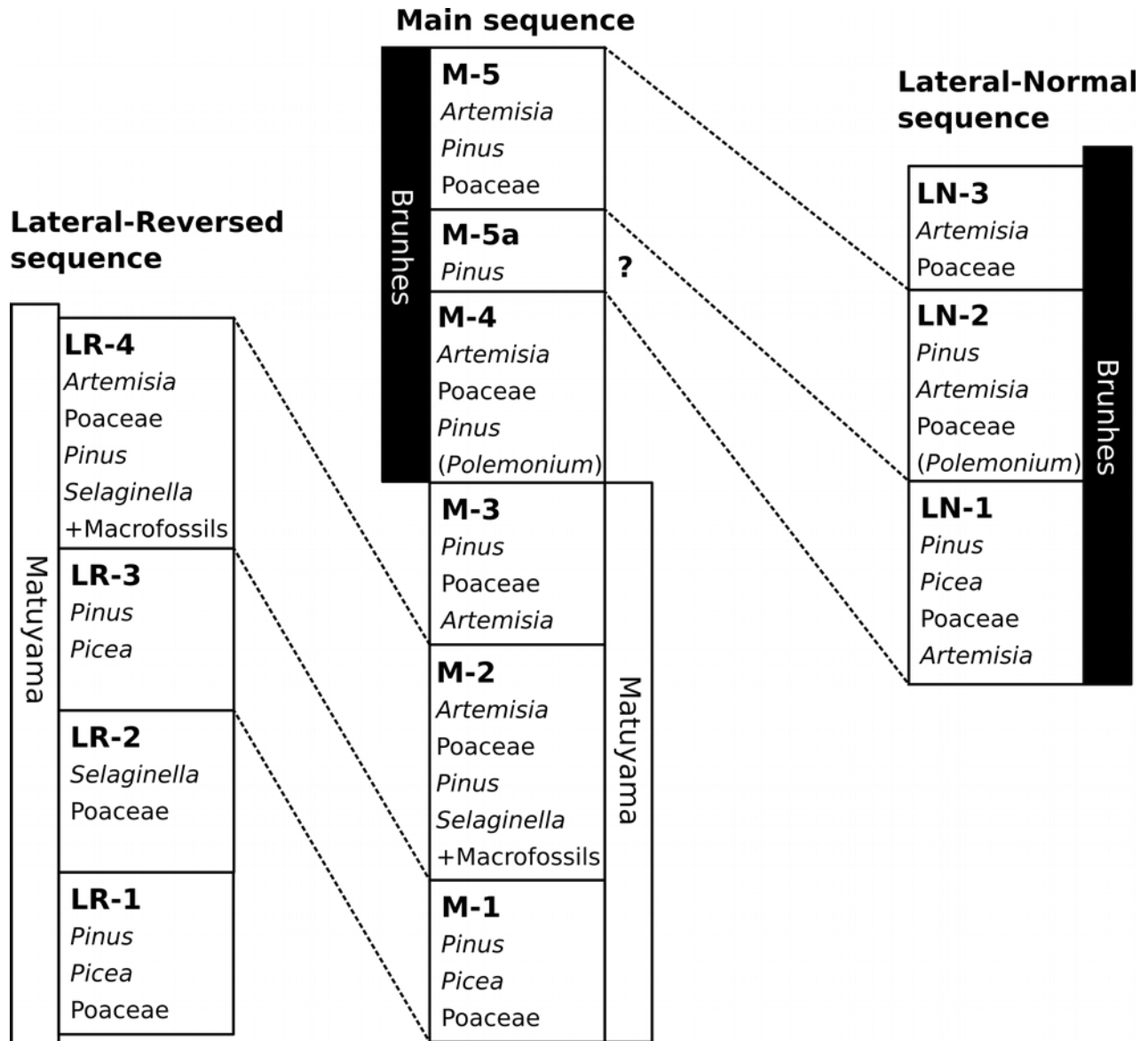


Figure 5.8. Proposed correlation of zones at HVC between the three defined sequences. See text for explanation.

The correlation of pollen and spore zones at HVC is necessary because of the large separation in space and the unclear relationship between some of the beds. Certain correlations can easily be ruled out initially. First, the EN sequence is stratigraphically higher than the ER sequence, so none of the pollen and spore zones between the two are correlated. Second, only beds with similar magnetic

polarity can be correlated because of the implied difference in age. Accordingly the EN sequence (all normally magnetized) should only be compared to the normally magnetized portion of the M sequence and the ER sequence (all reversely magnetized) with the reversed part of the M sequence. Lastly, the EN sequence originates from beds all above the easily seen "thick felsic tephra" which was also part of the strata of the M sequence. It follows only zones above this tephra in the M sequence can possibly correlate with zones in the EN sequence. This section considers a number of correlations and settles on the proposed scheme shown in Fig. 5.8.

In the comparison between the ER sequence and the M sequence, three scenarios are possible: First, the ER sequence could be stratigraphically lower, which is impossible to rule out without further physical examination of the beds. Second, ER-3a and ER-3b could correlate with M-1 and M-2 respectively, which seems likely from simple examination of the pollen and spore zones. Lastly, ER-1 and M-1 could be correlates based on their similarity. This third option seems unlikely as it would require additional undetected zones in the reversed part of the M sequence. Even though there are some gaps in the sampling due to inaccessibility of some beds, there is still a notable absence of both a strong *Selaginella* signal and arboreal signal above M-1 within the reversed part of the M sequence which should be present if these zones correlate. In addition, both ER-3b and M-2 have similar assemblages and notably similar proportions of *Artemisia* relative to grasses. ER-3b and M-1 are also associated with a similar macrofossil assemblage and contain a sandy charcoal bed that may represent the same fire event. Together these observations support the hypothesis that these are of the same age and represent the same pollen and spore zone. On this basis there is a strong possibility ER-3a correlates with M-1 and ER-3b correlates with M-2.

When comparing the EN with the normal part of the M sequence, there are two options for correlation. First, the entire EN sequence may lie above the M sequence. Second, there may be a

undetected strong arboreal zone within M-4 which correlates with EN-1, and M-4 above this undetected zone would correlate with EN-2. One count with abnormally high arboreal pollen for this zone (UVic id 2015-022 at 24.4 m local height) within M-1 hints that this second option may be valid, but more sampling and analysis above and below this sample is needed first.

With these considerations, the correlations shown in Fig. 5.8 are suggested here, with the two upper subzones of the ER sequence correlating with the lower part of the the M sequence, but correlation of the EN sequence with the M sequence remaining ambiguous.

Chapter 6. Interpretation and Discussion

This chapter broadly integrates the geological and paleoecological results into an account of the history represented in the record at the Highland Valley Copper mine, places these results in a broad regional and global context, and addresses some of the key challenges faced by the study. The results of this study have broad implications with respect to understanding the characteristics of vegetation and climate of the Pleistocene. This chapter first interprets and discusses the paleoecological results then proposes a timeline for events at Highland Valley and links them to global climatic events. Lastly, the major conclusions of this study are discussed and summarized.

6.1 Vegetation history and inferred paleoclimate of Highland Valley

Nine intervals broadly defined by vegetation were identified previously in Chapter 5. These consist of correlated zones and subzones described in Section 5.2.1 (Table 6.1). The pollen and spore zones vary internally and suggest a complex history for the interval of time represented by the record. A more recent example of such complexity is seen at Crater Lake BC where five different pollen and spore zones were identified from the last 12 ka (Heinrichs et al. 2002). These zones were often differentiated by abundance changes of only one or two palynomorph types (Heinrichs et al. 2002) in contrast with this study where major groups of palynomorphs, such as arboreal and non-arboreal pollen, fluctuate greatly. The focus of this section is to provide a history of vegetation based on pollen, spore and macrofossil data.

Table 6.1. Summary of the pollen and spore zones and macrofossil record exposed at the Highland Valley Copper Valley Pit. Zones listed in stratigraphic order from youngest to oldest. Dominant pollen and spores are listed from highest to lowest abundance.

Polarity (Chron)	Zone or (locality)	Dominant pollen and spore types	Common indicator pollen and spores	Macrofossils	Lithology
Normal (Brunhes)	(HVC-12)	<i>Pinus</i> , Poaceae		Wood logs indet. mammal bones	Peat and silty peat
		<i>Pinus</i> , <i>Picea</i>			
	EN-3	<i>Artemisia</i> , Poaceae			Sandy silt
	EN-2*	<i>Pinus</i> , <i>Artemisia</i> , Poaceae	<i>Polemonium pulcherrimum</i> -type		Sandy silt
	EN-1*	<i>Pinus</i> , <i>Picea</i> , Poaceae		Freshwater gastropods and bivalves Wood charcoal cf. <i>Fontinalis</i> sp.	Sandy silt
M-4*	<i>Pinus</i> , <i>Artemisia</i> , Poaceae	<i>Polemonium pulcherrimum</i> -type		Silt	
Reversed (Matuyama)	M-3	<i>Pinus</i> , <i>Artemisia</i> , Poaceae	<i>Polemonium pulcherrimum</i> -type		Silt
	ER-3b/M-2	<i>Artemisia</i> , Poaceae, <i>Pinus</i> , <i>Selaginella</i>			Silt
	ER-3a/M-1	<i>Pinus</i> , <i>Picea</i> , Poaceae		<i>Picea</i> needles <i>Picea</i> cf. <i>engelmannii</i> cones <i>Pinus</i> cones <i>Pinus ponderosa</i> needles <i>Myriophyllum</i> sp. cf. <i>Oncorhynchus</i> spp. Freshwater gastropods and bivalves Wood charcoal	Silt and peaty silt (ER-3a)
	ER-2	<i>Selaginella</i> , <i>Pinus</i> , Poaceae	<i>Polemonium pulcherrimum</i> -type, <i>Selaginella sibirica</i> -type		Silt
	ER-1	<i>Pinus</i> , <i>Picea</i> , Poaceae		Gastropods Worm (?) burrows	Silt

Notes:

* - Stratigraphic placement of M-4 relative to EN-1 and EN-2 is uncertain. See Ch. 5 for explanation.

Numerous studies have examined differences in pollen rain in British Columbia (BC) and Washington State with respect to their biogeoclimatic classification and plant communities (e.g. Alley 1976, Cawker 1978, Heusser 1978, Mehringer 1985, Hebda & Allen 1993). As noted in Section 2.4 much of the Highland Valley is classified as part of a dry-cool subzone of the Interior Douglas-fir (IDF) biogeoclimatic zone (British Columbia Ministry of Forests, Lands and Natural Resource Operations 2016a). Warmer and drier conditions at lower elevations support Ponderosa pine (PP) and Bunchgrass (BG) zones in the valleys surrounding the plateau (e.g. Thompson River Valley). At higher elevations IDF transitions into very dry, cool variants of Montane Spruce (MS) and Engelmann Spruce - Subalpine Fir (ESSF) zones. The pollen rain of these zones has been documented at various sites in British Columbia and Washington State and similar pollen rain is assumed to be expressed at HVC and the surrounding area.

One of the more useful studies which informs the results analyzed surface samples from a west-east transect from Bella Coola, BC to just east of Nimpo Lake, BC which included Coastal Western Hemlock (CWH), IDF, ESSF, MS, and Sub-boreal Pine-Spruce (SBPS) zones (Hebda & Allen 1993). This sequence of biogeoclimatic zones applies to the Highland Valley area where all but SBPS occur immediately westward of HVC. However, unlike Hebda and Allen's (1993) transect, BG and PP zones also occur close to HVC in the nearby Thompson River Valley immediately west of the site. Westerly winds prevail and anemophilous pollen from the region west of HVC can be an important contributor to the pollen and spore spectra at HVC as is also the case along the transect at Bella Coola (Hebda & Allen 1993). We can thus expect modern pollen rain at HVC to be similar to that in the IDF zone of the Bella Coola transect but also to include contributions from the PP biogeoclimatic zone and, to a lesser extent, contribution from the Thompson Valley BG biogeoclimatic zone.

The modern pollen and spore spectra of steppe zones such as BG, and transitions into other zones in the interior, such as PP, have been documented previously (e.g. Hebda 1982, Cawker 1978, Alley 1976) and summarized by Hebda (1982). Proposed interpretations of pollen ratio and percentage values of pollen types are also presented by Hebda (1982) and shown in Table 6.2. These ratios and percentages provide important quantitative data to guide the interpretation of the HVC data. Hebda's (1982) analysis provides a method of distinguishing forested from non-forested steppe and intermediate vegetation in much of southern British Columbia, and the intermontane region of the United States. Because these are applicable to the region around HVC the same approach has been adopted in this thesis to provide systematic criteria to distinguish between these types of vegetation and landscapes.

Table 6.2. Guide for interpretation of pollen and spore zones on the BC interior after recommendations in Hebda (1982).

Steppe vs. forest	
% NAP	Interpretation
0-10	Forest
10-20	Forest to parkland, transitional
20-30	Steppe with forest nearby
30-50	Major steppe around site
50 +	Steppe, forests distant or very small stands
Type of steppe using the Poaceae vs. <i>Artemisia</i> pollen ratio	
Poaceae 2x > <i>Artemisia</i>	Forb rich grassland, few <i>Artemisia</i>
Poaceae 1-2 x <i>Artemisia</i>	Grasses and <i>Artemisia</i> common
<i>Artemisia</i> > Poaceae	<i>Artemisia</i> very abundant, grasses common

Notes:

NAP - Non-arboreal pollen types.

Another useful analysis involves the occurrence of Chenopodiaceae with Poaceae and *Artemisia* to distinguish Sagebrush-Shadscale/Saltbrush (*Atriplex* spp.) steppe from grassland or sagebrush-grasslands (Mehringer 1985). Mehringer (1985) found that in general when only Chenopodiaceae-

Poaceae-*Artemisia* pollen is considered from recent Oregon and Washington samples, Chenopodiaceae pollen accounts for > 50% in Sagebrush-Shadscale steppes, Poaceae pollen accounts for > 50% in Bunchgrass steppe, and *Artemisia* pollen accounts for > 65% in Sagebrush-grass steppe assemblages. This is consistent with the interpretation method used by Hebda (1982; see Table 6.2). Of these ratios only one sample in the pollen data contained enough Chenopodiaceae pollen to qualify, a situation which can easily result from a single Chenopodiaceae anther in the sample. Since this outlier is the only case, this sort of analysis was limited to a comparison of relative *Artemisia* and Poaceae abundance and a Sagebrush-Shadscale steppe was ruled out as a vegetation type.

Based on these tools, three generalized types of landscapes can be inferred from the data presented in this study: Pine-Spruce forest and parkland, *Selaginella* dominated steppe, and *Artemisia*-Poaceae steppe. The following three sections discuss these in turn.

6.1.1 Pine-Spruce forest and parkland

This vegetation type is expressed in three pollen/spore/macrofossil zones at HVC: ER-1, ER-3a/M-1, and EN-1. These zones are characterized by *Pinus* and *Picea* pollen being dominant in an arboreal assemblage which generally exceeds 70%, and peaks above 90% (Fig 6.1). The landscapes inferred to be represented in these zones range from open steppe to parkland and forest, usually becoming forested and transitioning back to open steppe (e.g. M-1 zone, Fig 6.1). This variation in structure is a likely consequence of the low temporal resolution represented by the samples and more detailed sampling may yield more discrete and clearly defined vegetation types in the intervals currently represented by these low resolution zones.

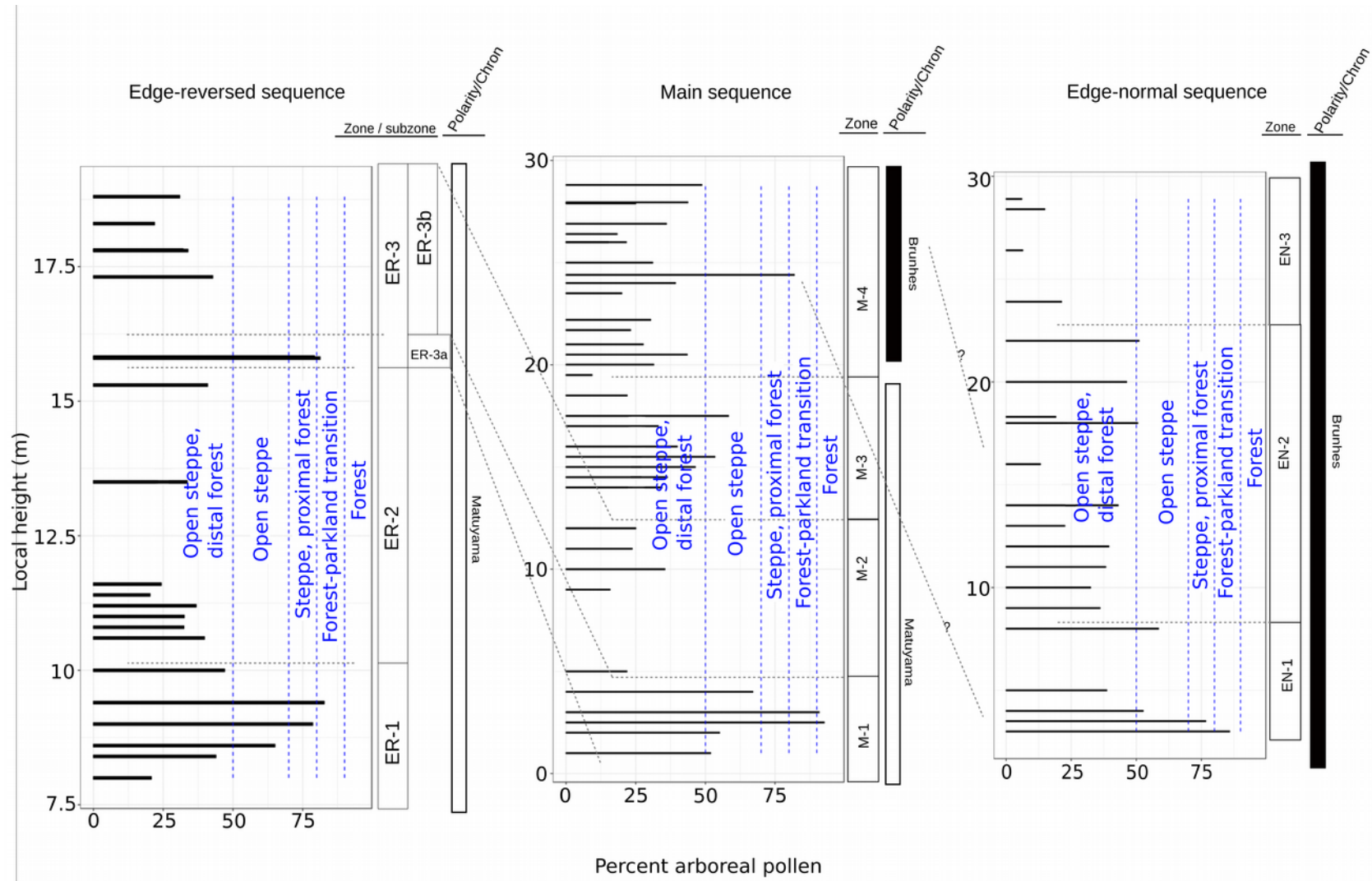


Figure 6.1. Percent arboreal pollen and *Poaceae:Artemisia* ratios for samples counted at HVC for the present study. Refer to Fig. 4.1 and the text for locations and groupings of each sequence. Interpretations of general landscape are after Hebda (1982) are indicated by blue dashed lines and blue text (see Table 6.1 for cutoff values).

The arboreal pollen spectra for these intervals contain primarily *Pinus* pollen (Figs. 5.1, 5.2, 5.3). This pine signal is expected as pollen production in *Pinus* is abundant at interior sites and is manifested by a strong background pollen rain from sources as far as 100 km away (e.g. Heusser 1978, Hebda & Allen 1993). A background signal of 10 - 15% *Pinus* is recognized for the southern BC interior (Hebda & Allen 1993) and can reach 40% with *Pinus* stands being 20 km away (e.g. Heusser 1978). This differs from pollen rain data from arctic sites where *Picea*, *Betula*, and *Alnus* form a strong background signal (e.g. Ritchie et al. 1987) and coastal assemblages where *Tsuga heterophylla* is the primary contributor to the pollen rain (Hebda & Allen 1993).

Picea pollen is a secondary contributor to the pollen and spore spectra of these zones. *Picea* contributed mostly 5-10% of the pollen and spores, reaching peaks as much as 25%. With only a small number of samples containing this abundance of *Picea* pollen, further work will be required to determine if these values represent a true fluctuation in the tree population, or are simply outlier values.

Macrofossils associated with these zones were recovered at three of the localities coinciding with ER-3a, M-1, and EN-1 as well as from HVC-12 where another arboreal-rich pollen spectrum was observed (Table 6.1). The macrofossils include cones, needles and wood from pines and spruces and possibly other arboreal taxa (Table 6.1). *Pinus ponderosa* was one species identified from needles in the strata that fall within the M-1 zone. This species occupies what are very dry hot environments in the modern BC context, particularly in the Ponderosa Pine BGC zone where precipitation is limited to 280-500 mm per year and a summer temperature mean of 17-22°C (Hope et al. 1991a). On a continental scale, *P. ponderosa* is widespread mostly throughout the North American Cordillera with some distribution east of the Rocky Mountains and occurs as far south as northern Mexico (Thompson et al. 2015). The species rarely if ever occurs where winter temperatures fall below -10°C and at summer

temperatures above 28°C (Thompson et al. 2015, Little 1971). *P. ponderosa* occurs mostly in areas of moisture deficit (actual evaporation/potential evaporation typically 0.35-0.65, Thompson et al. 2015). In BC, Ponderosa pine occurs mainly in the Ponderosa Pine BGC zone where it occurs in abundance along with certain grasses (particularly *Agropyron spicatum*, *Festuca scabrella* and *F. idahoensis*) which can account for the same amount of ground cover as *P. ponderosa* (Hope et al. 1991a). This species is also found in dry hot parts of the IDF zone (Hope et al. 1991b) and occasionally in the Bunchgrass zone (Nicholson et al. 1991) mostly in the transition from the Ponderosa Pine BGC zone.

Picea macrofossils were also recovered from within the same zone as Ponderosa pine (M-1). These include needles, and cones which were of indeterminate species due to preservation. However, two of the cones recovered were the same size and shape as *Picea engelmannii* (Engelmann spruce) or even *P. engelmannii* × *glauca* (Hybrid white spruce) cones. These observations are consistent with modern vegetation in parts of the upland zones within the region. *P. engelmannii* × *glauca* can be found in moist, higher elevation localities in the IDF zone near the transition into the higher elevation Montane Spruce zone (Hope et al. 1991b) where *P. engelmannii* × *glauca* is one of the primary tree species along with Douglas-fir (*Pseudotsuga menziesii*), Lodgepole pine (*Pinus contorta*) and Subalpine fir (*Abies lasiocarpa*) (Lloyd et al, 1990). Engelmann spruce also occurs at high elevations in the ESSF BGC zone (Coupé et al 1991).

Based on modern assessments, there is very little overlap in range of spruce and Ponderosa pine in southern British Columbia (Meidinger & Pojar 1991). Locally, this overlap occurs in the IDF zone, where Ponderosa pine occurs at dryer low elevation sites, whereas Hybrid white spruce occurs at higher elevation moister sites (Hope et al 1991b). This would seem to indicate that zone M-1, and possibly other arboreal rich zones at HVC are manifestations of local IDF-like biogeoclimatic conditions, however the rarity of *Pseudotsuga/Larix* (likely Douglas-fir) pollen in these zones is conspicuous in

this case since amounts in the range of 5-20% have been observed in IDF pollen rain (e.g. Mathewes & King 1989, Alley 1976, Britnell 2012) and can make up as high as 50% of a pollen assemblage in the IDF biogeoclimatic zone (Hebda & Allen 1993). A small (<1%) signal can also originate from neighbouring plant communities which contain a large Douglas-fir component (e.g. Heinrichs et al. 2002). Indeed this absence of Douglas-fir pollen throughout presents an interesting question about the state of North American Pleistocene forests in general. It is clear that more detailed analysis of the sediments of ER-1, ER-3a/M-1, and EN-1 is required to adequately understand the ecological characteristics and dynamics of these intervals.

With the exception of *Pseudotsuga/Larix* absence, the arboreal assemblages observed here are similar to those reported for Holocene ones in the IDF zone of nearby Hat Creek (Britnell 2012). However these pollen and spore zones are much more similar to the pollen rain of ESSF zone than the IDF zone in Hebda & Allen (1993). In the case of Hebda & Allen (1993), *Pseudotsuga/Larix* pollen was found to be more abundant than even *Pinus* pollen in the IDF zone, and *T. heterophylla* was over-represented. Proximity and direction of adjacent and upwind ecosystem types may be the reason for this discrepancy. This pollen and spore assemblage similar to the ESSF BGC zone reported by Heinrichs et al. (2002) at Crater Lake (2120m asl, ~180km south of HVC) with albeit more *Pinus* pollen.

In this study, this group of pollen and spore zones is interpreted to reflect warm dry intervals somewhat similar to today. Note that these arboreal intervals are interpreted as still being somewhat damper than those of the non-arboreal ones reported in the following sections. At one point (during deposition of M-1) the climate was warm and dry enough for Ponderosa pine to occupy the Highland Valley at a higher elevation than it does today. Ponderosa pine was observed very rarely near Mamit Lake (~1000 m asl) about 25 km southeast of HVC (personal observation) which may be its highest

local extent today. As a species which requires very warm conditions to thrive, its occurrence in the HVC lake sediments strongly suggests conditions warmer and drier than today. This interpretation however should be treated with some caution since the community species composition may have been different during this interval than today. In particular, a lack of competition from Douglas-fir, as implied in the pollen and spore assemblage, may have allowed Ponderosa pine or other species to occupy a broader niche and climate range than they do today.

The non-arboreal pollen and spore assemblages of these zones vary in composition. They include a strong Poaceae signal (5-15%) as would be expected in a parkland setting or grassland steppe with trees nearby (Hebda 1982). This is consistent with the modern conditions in the area around HVC, as grasses commonly take up a large amount of the ground cover in the local IDF zone (Meidinger & Pojar 1991, Lloyd et al. 1990). In sum, based on both microfossil and macrofossil content a number of pollen and spore zones at HVC are interpreted to represent intervals with nearby or local forested conditions at Highland Valley which coincide with relatively warm climate stages.

6.1.2 *Selaginella* steppe

This unique assemblage and inferred vegetation type occurred once in the record at HVC in the pollen and spore zone ER-2. No other records of this type of assemblage appear to have been described elsewhere which leads to a more speculative interpretation than other pollen and spore zones. Typically assemblages for which similar *Selaginella* spores are found contain fewer than 10% *Selaginella* spores (e.g. Mathewes & Rouse 1975) compared to the 30-40% reported here. For any *Selaginella* species to be in the abundance observed in the zone ER-2, other pollen and spore producers must have been few in number as *Selaginella* typically grows in open landscapes (Klinkenberg 2017). In addition, the dispersal of spores appears limited to tens of centimetres in calm laboratory conditions (Koller & Scheckler 1986) which can be extended to just over a meter when moderate winds (1.16m/s) are

introduced (Filippini-De Giorgi et al. 1997). Abnormally large numbers of *Selaginella* spores should indicate a very strong local presence of the taxon especially when they outnumber anemophilous palynomorphs as they tend to do in zone ER-2.

It is also likely that the local rocky talus substrate may have promoted *Selaginella* growth which would partially explain the background amount of 10-20% observed throughout the column. While *Selaginella* itself is not an indicator of any particular climate regime, the lack of other species which would grow locally in different conditions may be an indication of climate itself. Close examination of the spores in this assemblage indicate the dominant *Selaginella* species is likely *S. sibirica* (Sec. 2.1.2) which has a modern distribution throughout Alaska, Yukon, west Northwest Territories, northeast Asia, and infrequently in northern BC as far south as China Nose Mountain (~54.4 degrees north) (Klinkenberg 2017). A local presence of this species suggests the range of this species extended an additional 500km or more southward during the ER-2 interval, implying much colder conditions than today.

Along with *Selaginella*, the non-arboreal assemblage contains moderate amounts of pollen from grasses (~10%) and *Artemisia* (~4%). A grass signal around 10% is typical in open landscapes (Hebda 1982). Strong *Artemisia tridentata* pollen signals have been shown to travel up to 10 km but weak background signals can be expected >30 km away (e.g. Solomon & Silkworth 1986). The very low *Artemisia* content indicates *Artemisia* must have been absent at least within a 10 km radius while the amount of Poaceae pollen observed does not rule out local grass presence. Steppe vegetations like the one represented by this assemblage (zone ER-2) are likely too moist for *Artemisia* to compete since most species of *Artemisia* in North America persist in very dry conditions (generally drier than Ponderosa pine; Thompson et al. 2015, Little 1976). However some cold-adapted species of this genus can be highly underrepresented in pollen spectra (e.g. *A. borealis* and *A. norvegica* in Birks 1977).

Other forb types in the zone are also merely present or low in number, suggesting conditions which are too cold or too dry for most forbs to flourish.

The interpretation of this assemblage is that it represents a phase where an open rocky landscape, devoid of trees was present in the vicinity of Highland Valley. This phase was most likely accompanied by a climate inhospitable to trees, being colder and drier than today. Poorly developed soils with rocky slopes promoted the establishment of *Selaginella*, *Polemonium* and other small herbs on what were probably scree slopes and rocky outcrops locally. Distal grasslands with an *Artemisia* component probably occupied lower elevations as they do today in slightly warmer conditions than the plateau, and in better developed soils.

6.1.3 *Artemisia*-Poaceae steppe

Artemisia-Poaceae steppe predominates throughout the sequence. The pollen and spore zones reflecting this assemblage include ER-3b, M-2, M-3, M-4, EN-2 and EN-3. The main common trait shared by these assemblages is the *Artemisia* pollen percentage generally exceeding that of grasses (1 to 2 times) and arboreal pollen values less than 70%. In many samples the total arboreal pollen makes up less than 50% indicating forests are distal to the site.

Present pollen rain similar to these zones is found in association with landscapes nearby having abundant *Artemisia tridentata* particularly within very dry Bunchgrass steppe vegetation in the Thompson River Valley (Cawker 1978), the Columbia Basin in Washington State (Mack & Bryant 1974), and Montana (McAndrews & Wright 1969). Counts with much more *Artemisia* than grass (2 to 3 times) are typical when *Artemisia tridentata* dominates the immediate landscape (e.g. Alley 1976, McAndrews & Wright 1969, Mack & Bryant 1974) which suggests *Artemisia* at HVC was simply locally abundant and/or dominant at lower elevations nearby. Additionally, in all these cases the arboreal pollen count is less than 70% (Hebda 1982). Together these observations suggest that the

modern Thompson River Valley may be a good analog for much of the Thompson River Plateau landscape between the late-Early and early-Middle Pleistocene under conditions that must have been much drier than today.

Arboreal pollen percentages are variable within these zones, and are interpreted here to reflect forest stands varying in distance from site. In some cases these differences in arboreal pollen are the primary criterion for defining some of the zones (e.g. Zone M-3; see Sec. 5.2.3). The primary arboreal pollen type is *Pinus* which, as mentioned previously, can be transported hundreds of kilometres from the source. Fluctuations in pine values presumably are driven by widespread shifts in distribution range caused by major, hemispheric-scale climatic changes rather than variations near the study site. In the case of M-2/ER-3b, arboreal pollen counts are relatively consistent around 25% (Fig. 6.1). These counts are 5-15% in zone EN-3 and generally fluctuate between 25-50% in the remaining zones (M-3, M-4 & EN-2) of this type (Fig. 6.1). Such differences are interpreted to reflect wide-ranging changes in temperature that forced the migration of tree lines at some distance from HVC while local conditions were relatively stable.

This type of *Artemisia* steppe can persist during both glacial and non-glacial intervals. A good analogue for this may be a pollen and spore sequence extracted from a core at Carp Lake in south Washington State (Whitlock & Bartlein 1997). The Carp Lake sequence covers the last 125 thousand years and contains two long intervals of strong *Artemisia*-Poaceae signal similar to the one reported in the current study. These assemblages predominated at Carp Lake only to be broken by a brief wet period at 73-83 ka (Whitlock & Bartlein 1997). There are two features of the Carp Lake study that are of interest here: First, each interval of *Artemisia*-Poaceae steppe pollen and spores at Carp Lake showed a gradual increase in *Artemisia* and Poaceae pollen prior to a sudden regime changes at 83 (*Quercus*-Cupressaceae) and 13 ka (various) (Whitlock & Bartlein 1997). Second, the vegetation

reported reflected changes in global climate parameters, primarily ice volume ($\delta^{18}\text{O}$ proxy), and July insolation (Whitlock & Bartlein 1997). Regarding this second point, the *Artemisia* and Poaceae pollen percentage during these intervals was inversely proportionate to *Pinus* pollen (reduced from ~70 to ~10% over time) and relatively proportionate to ice volume (Whitlock & Bartlein 1997).

Carp Lake is an excellent past analogue for HVC. Modern day Carp Lake lies near an ecotone between Ponderosa pine forest and *Artemisia* steppe at 714 m asl (Whitlock & Bartlein 1997) so has a modern ecology not very different from locations close to HVC and is under a similar rain shadow effect with a high mountain range to the west. Being at a different latitude (45°55' N) compared to HVC (50°29' N) gives the Carp Lake site only slightly higher insolation. Because of these similarities it is proposed here that a similar climate and vegetation response as recorded at Carp Lake occurred at HVC during the MPT. With good age control Whitlock and Bartlein (1997) linked this similar vegetation type to cooler, drier climatic conditions at Carp Lake, coinciding with continental scale glaciations. It is also worth noting that steppes where *Artemisia* was a major contributor were also abundant in northern Alaska ~18 - 14 ka (Anderson & Brubaker 1994) suggesting this type of response to the latest continental-scale glaciation was widespread. If this relationship is true at HVC as it is at Carp Lake, then these *Artemisia* steppe assemblages likely also coincide with globally cool to cold climates as well.

6.1.4 HVC-12/4

The four samples from HVC-12 (also known as HVC-4) contain evidence for the possibility of two more climate intervals. Although these samples should be interpreted with caution because of the small number a few key points can be ascertained. First, since two of the samples contained very high arboreal pollen counts (84.5% and 88.6%) it is likely that Highland Valley was forested sometime between when sediments of zone EN-3 were deposited and the ultimate glaciation at the site as

reflected by the immediately overlying glacial drift (Unit 7). Second, a high non-arboreal pollen and spore pair (49.1% and 58.2%) of samples above the former suggest a landscape that subsequently opened up and the preceding forests retreated to distant lower elevations. Finally, the low *Artemisia* compared to Poaceae values in these samples indicate a relatively moist climate compared to earlier conditions. This interval probably had a similar moisture and temperature regime as today.

6.1.5 Climate and vegetation summary

The Pleistocene climatic history at HVC can be divided into at least 11 intervals after the pollen and spore zonation (Table 6.3) and an additional two from lithological data. These zones are summarized in Table 6.3 and discussed in context by comparison with the probable marine isotope ($\delta^{18}\text{O}$) stage stack in the following section. Overall, most of the record indicates local presence of taxa well adapted to dry environments, particularly *Artemisia*. With these taxa growing well above the modern elevation of interior steppe, the climate must have been much drier than today during most of the record. Moisture aside, the history inferred from the pollen and spore data reveals alternation between warm and cool climates as might be expected in a long Quaternary record.

Following the end of a glaciation, the local late-Early Pleistocene begins with a warm interval characterized by a local parkland environment (zone ER-1) with forests persisting nearby and periodically entering the valley. This is one of the Pine-Spruce parkland zones, but contains a non-arboreal grassland-forb assemblage with mostly grasses and only some *Artemisia* suggesting higher moisture than other zones of this type. It is one of the few times in the Pleistocene record where local forests may have been present.

Table 6.3. Interpretation of pollen and spore zone data at HVC.

Polarity (Chron)	Zone	Landscape type	Notes	Climate	MIS*	Age (ka BP)*
Normal (Brunhes)	HVC-12 samples**	Poaceae steppe	42.9-52.5% AP Low <i>Artemisia</i> vs Poaceae	cool, mesic	<16 >2	< ~630 > ~40
		Pine-spruce parkland/forest	Low <i>Artemisia</i> vs Poaceae	warm, mesic		
	EN-3	<i>Artemisia</i> - Poaceae steppe	<i>Pinus</i> < 10 %	very cold, very dry	16	~630
	EN-2***	<i>Artemisia</i> - Poaceae steppe	Increasing <i>Artemisia</i> . Steadily decreasing <i>Pinus</i>	cooling, very dry	17-16	~630 - ~700
	EN-1***	Pine-spruce parkland	Low <i>Artemisia</i> vs Poaceae, but varies	warm, dry- mesic	17	~700
	M-4***	<i>Artemisia</i> - Poaceae steppe	mostly low (<30%), variable <i>Pinus</i> . high <i>Polemonium pulcherrimum</i> -type	cold, dry- mesic	18	~750
Reversed (Matuyama)	M-3	<i>Artemisia</i> - Poaceae steppe	Pine >40% in places, Poaceae ~= <i>Artemisia</i>	cool, dry- mesic	19	~790****
	ER-3b/M-2	<i>Artemisia</i> - Poaceae steppe	low (<30%) pine	cold, very dry	20	~800
	ER-3a/M-1	Pine-spruce parkland/forest	Macrofossil Ponderosa Pine and Spruce	warm, dry- mesic to very dry	21	~860
	ER-2	<i>Selaginella</i> steppe	low (<30%) pine	cold, dry- mesic?	22	~880
	ER-1	Pine-spruce parkland	Low <i>Artemisia</i> vs Poaceae	warm, dry- mesic	23	~910

Notes:

* - Marine isotope stages and approximate ages based on data from Lisiecki & Ramo (2005)

** - HVC-12 contains only four samples.

*** - Stratigraphic placement of M-4 relative to EN-1 and EN-2 is uncertain. See Section 5.5 for explanation.

**** - Approximated based on positioning below paleomagnetic horizon

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The following interval of *Selaginella* steppe (ER-2) is unique as the plant community appears to be dominated by *Selaginella* and other herbs. This assemblage is interpreted to likely reflect a cold and possibly dry climate, however the high Poaceae:*Artemisia* ratio (Fig. 6.1), if this measure is valid in this context, does suggest moister conditions than the remaining zones. More information is needed before fully understanding this interval.

The *Selaginella* steppe zone is followed by another interval (ER-3a/M-1) of warm and dry climate. During this time, forests surrounded the lake once more with the constituents of the plant communities varying through time. The boundary between forest and open landscape may have reached the modern lower limit at some point during this interval, but almost certainly passed through the valley elevation at HVC during this time, as both taxa from modern low (*Pinus ponderosa*) and high elevation (*Picea* sp.) were found in the macrofossil assemblage of this zone. The zone also has an increase in *Artemisia* values relative to other non-arboreal types suggesting emergence of sagelands in low-elevation valleys nearby. These characteristics support the interpretation that the climate became very dry during this interval before the onset of the next cold period.

The following zone (ER-3b/M-2) likely represents a cool open dry landscape. *Pinus* counts <30% indicate the nearest pine stands may have been tens to a hundred kilometres away. High *Artemisia* counts relative to grass support the interpretation of a dry climate. Locally, Sagebrush was very abundant and grew with grasses in a vegetation type similar to the grassland communities of the modern Thompson River Valley (Bunchgrass Biogeoclimatic Zone). With an exceptionally low arboreal pollen and spore count it is doubtful that many trees persisted on the Thompson Plateau during this interval, so this open community probably dominated most of the remaining plateau as well.

The following zone M-3 resembles the previous zone. The landscape remained open, but with more grasses than *Artemisia*, and possibly a resurgence of forests in the region either distally or in

scattered stands. A return of trees to the Thompson Plateau is a possibility, but the pollen and spore data suggests that if trees were on the plateau these took the form of patches in a parkland landscape rather than forests. The climate was likely slightly warmer and moister than in the previous zone. This interval occurs just below the Matuyama-Brunhes transition so may reflect the corresponding interglacial (MIS-19).

The Middle Pleistocene of Highland Valley begins with another *Artemisia*-*Poaceae* steppe assemblage (M-4). This zone is similar to both previous zones with the arboreal signal and the *Poaceae:Artemisia* ratio at values intermediate between the two former zones. The climate is interpreted to have had temperatures and moisture somewhere between those two. For reasons discussed in Chapter 5 (Section 5.5), the stratigraphic relationship of this zone with later ones is not fully certain. A high degree of variation of the pollen and spore values within the zone M-4 suggests under-sampling. Higher resolution sampling may reveal a more complex story.

Both EN-1 and EN-2 may either follow or fall within M-4 (Section 5.5). EN-1 is interpreted as a warm interval with moderate, and possibly varying, moisture. The HVC valley was once again parkland and may have contained forests. Further sampling at higher resolution is needed in this zone however, as its beginning appears to lie below the lowest sample, and the zone is represented by a low number of samples.

EN-2 and EN-3 are both intervals of *Artemisia*-dominated steppe. These two zones are distinguished by a decline in arboreal signal between them, where the ~50% arboreal signal in EN-2 changes to only ~10 to 25% in EN-3 (Fig. 6.1). This decrease indicates that forests occurred in the region though not near the site during the EN-2 interval, then they largely disappeared from the region during EN-3. This change is interpreted here to reflect the gradual development of an extreme cold

period (EN-3). Also unlike other zones, the Poaceae:*Artemisia* ratio is at its lowest (Fig. 6.1) suggesting dry conditions, and possibly the driest period of time in the record at HVC.

The last two pollen and spore intervals are those at the HVC-12 locality at the base of the upper drift which caps the Pleistocene record. The climatic interpretation of these samples is tentative because only four samples were examined. The lower two samples contain high amounts of arboreal pollen (84.5 and 88.6%) whereas the upper two contain low amounts (52.5 and 42.9%). The high AP values and associated macrofossils of the lower two samples reveal that at least one further warm period is recorded at HVC after those previously described. The upper two samples indicate a return of open landscapes in addition to those previously described. These upper two samples contain more grass pollen than *Artemisia* suggesting the climate was not as dry as in previous intervals. Further sampling is required to fully understand this period as only four samples were examined.

6.2 Correlation with the marine isotope stage (MIS) record

The chronological framework of the Highland Valley sediments has proven challenging to establish due to ambiguous radiometric dates (Section 4.3.3). However the middle of the sequence is well anchored at 781 ka based on paleomagnetic results (Sec. 4.3.1). The purpose of this section is to offer several possible scenarios, rule out others and provide a best guess for the temporal extent of the record at HVC given the limitations of this study. There are paleomagnetic, radiocarbon, palynological and paleoclimatic (e.g. glacial records and marine isotope data) constraints that can be used to propose a most likely time scale. In this section emphasis is placed on correlation with marine isotope stages (MIS) using palynological zones and lithological data (drifts) as constraints.

Marine isotope stages are useful here because they serve as a good standard in communicating time in the Quaternary, are well studied and established, and the defining data set ($\delta^{18}\text{O}$) approximates ice volume well (e.g. Lisiecki & Ramo 2005). Also, while ice volume is not a direct proxy of temperature,

it is closely linked to it so that extended cold periods (glaciations) can be inferred from positive excursions (Lisiecki & Ramo 2005). In calcareous foraminifera tests, the typical source of $\delta^{18}\text{O}$ measurements, the value can also vary between location due to differences in the water temperature and salinity (Lisiecki & Ramo 2005). The Lisiecki and Ramo (2005) $\delta^{18}\text{O}$ stack is used here because it integrates 57 separate such records from different locations to improve the signal-to-noise ratio compared to previous work.

An attempt to correlate the record at Highland Valley with the marine isotope stage (MIS) can be accomplished using the Brunhes-Matuyama paleomagnetic reversal as a constraint and working down and up pollen and spore zone sequence. The pollen and spore record below the magnetic reversal indicates two warm intervals, two cool intervals, and an intermediate temperature interval just below the reversal (Table 6.3). From youngest to oldest these probably correspond to MIS 19-23, or possibly to 25, in this interpretation (see Table 6.3). The basal glaciation recorded by the lower drift in the valley (units 2-4) would have likely corresponded to MIS 24 or 26 as the drift sediments are reversely magnetized (Chapter 4) Also if the corresponding glaciation was the event which initially dammed the valley, then it probably occurred not long before the pollen and spore record started, hence after the Jaramillo normal subchron. This interpretation assumes this subchron was not missed during sampling because the sediments are covered by the 10B buttress.

Above the Brunhes-Matuyama paleomagnetic reversal the main pollen and spore record indicates one warm (EN-1) and two cold (M-4 and EN-2, EN-3) episodes below the point at which sands and gravels (Unit 6) dominate the exposure. These zones presumably correspond with MIS 16-18 (Table 6.3). The sands and gravels that lie between zone EN-3 and the uppermost pollen and spore samples (HVC-12) represent an unknown amount of time, thus corresponding stages cannot be inferred at this point. However, the arboreal-rich pollen assemblage observed at HVC-12 near the base of the upper

drift and infinite radiocarbon ages from around the same elevation (see Table 2.3) indicate an old (>~45 ka) age for HVC-12 sediments.

Lastly, the upper drift could belong to any of the numerous even-numbered stages after MIS 15. Most drifts found at the top of the landscape across the interior of BC are inferred to belong to the Kamloops Lake Drift of the Fraser Glaciation (MIS-2; e.g. Lian et al. 1999) however the lack of age controls on the upper drift at HVC and drifts throughout the southern interior of BC makes this inference speculative. Determining the exact age of the upper drift at HVC requires more research and is beyond the scope of this thesis, however this issue is discussed in some more detail later.

In summary, the continuous part of the Pleistocene record at HVC appears to extend from MIS-24 through MIS-16. With further work it may be discovered that the record extends further back or forward in time.

6.3 Discussion

The investigations at the Highland Valley Copper mine have yielded a number of noteworthy findings. First, the HVC sediments contain evidence for Early Pleistocene glaciation in the southern interior of BC which only a small number of other studies have previously documented (see Table 6.4). Second, these results reveal a rare, and unique continuous pollen and spore record for the region for the Mid Pleistocene Transition extending across multiple marine isotope stages. Third, during this transition much drier than present conditions persisted in the southern interior of BC and the region hosted different assemblages of vegetation than today. Last, data from this study suggests that the local part of the Thompson Plateau was ice free during all parts of the Pleistocene except for two events. In the following subsections each of these findings is discussed in a broader context.

6.3.1 Early Pleistocene glaciation in the Highland Valley

The early glaciation in this record may have been a valley glacier originating from nearby mountainous terrain. Such a glaciation may coincide with other Early Pleistocene glaciation events recorded elsewhere in southern British Columbia. To date only a few of these records have been identified (Table 6.4). The nearest of these records takes the form of a single till ("unit 47-4") found in the Big Bar Creek Valley and Jesmond Road sections in the Marble Range ~100 km northwest of Highland Valley. This till is magnetically reversed and lies above normally magnetized material (Lian et al. 1999). Lian et al. (1999) were hesitant to assign a specific age to the reversed till, noting that it could be of pre-Jaramillo age. They argued that pre-Jaramillo till (1.1-1.4 Ma) has been documented previously at Dog Creek (Mathews & Rouse 1986) and the single set of samples with normal polarity at the base of the Big Bar Creek Valley sequence below the till could have originated from either the Gauss Chron or any normal subchron within the Matuyama chron (Lian et al. 1999). Another drift deposit was found near Merritt where Fulton et al. (1992) described glaciolacustrine sediment (Sub-Coutlee and Coldwater silts) below interglacial basin fill deposits (Coutlee Sediments) which are all magnetically reversed. In turn, these units all lie unconformably below a variety of normally magnetized sediments (Fulton et al. 1992) including a least two later drift deposits. Finally, Roed et al. (2014) identified one of the better constrained Early Pleistocene tills in British Columbia, having a capping basalt age (0.97 +/- 0.03 Ma) and a normal magnetic polarity coinciding with the Jaramillo subchron (Table 6.4).

Table 6.4. Early Pleistocene glacial records from British Columbia prior to this study.

	Age	Supporting data	Name	Location
Mathews & Rouse 1986	1-1.4 Ma	Basal (1.4-2.9 Ma) and capping basalt dates (1-1.2 Ma)	Dog Creek Formation	Dog Creek Valley
Fulton et al. 1992	Matuyama	Magnetically reversed glaciolacustrine sediments	Sub-Coutlee Silts Coldwater Silts	Merritt
Lian et al. 1999	Matuyama	Magnetically reversed till over normally polarized sediment	"unit 47-4"	Marble Range
Roed et al. 2014	Jaramillo	Capping basalt dates (>0.97 \pm 0.03Ma) and magnetically normal till	Westbank First Nations Till	West Kelowna, Okanagan Valley

Unlike the Big Bar Creek and Jesmond Road tills, the earliest Highland Valley till is more confidently placed between the Jaramillo Subchron and the Brunhes Chron for reasons previously stated (Section 6.2). This age also apparently rules out the correlation of the lower drift with the early till of the Dog Creek formation (Mathews & Rouse 1986) and the Westbank First Nations Till (Roed et al. 2014) since they are confidently placed as Jaramillo or older. The Sub-Coutlee and Coldwater silts (Fulton et al. 1992) and the "unit 47-4" till at Big Bar Creek and Jesmond Road (Lian et al. 1999) still constitute possible correlates with the early glaciation at Highland Valley but require better dating to constrain their ages.

The ice extent in North America during the Matuyama Chron has been reviewed previously based on paleomagnetic data (Barendregt & Duk Rodkin 2011, Andriashek & Barendregt 2017). A number of sites throughout Canada and the northern part of the United States contain till and drift deposits associated with the lower and upper Matuyama and a handful in the Gauss Chron (Barendregt & Duk Rodkin 2011). East of the Cordillera, these drifts are associated with an extensive Laurentide Ice sheet which extended south of the Great Lakes and terminated within hundreds of kilometres of the Rocky

Mountains (Andriashek & Barendregt 2017). A number of drifts in the Cordillera lead to the proposal that there was an upper Matuyama equivalent to the Cordilleran Ice Sheet (Barendregt & Duk Rodkin 2011). Based on the observations in this study however (see Sec. 4.2.2), glaciation in the Cordillera was probably composed of numerous alpine glaciers or possibly high elevation ice fields which spilled into lower-lying areas. Details such as the local source of enclosed clasts support this hypothesis. A more comprehensive survey of these materials at HVC and other upper Matuyama drifts should be used to test the proposed model.

6.3.2 A unique pollen and spore record

Vegetation records of the MPT are both scarce and generally of low resolution in North America (Table 6.5). Overall, the records indicate that a long gradual change in climate from warm to cool took place over the course of the Pleistocene (Table 6.5). The record at HVC adds to these records, but differs from the other sequences in two important ways. First, the HVC record comes from a region where the paleoclimate of MPT age is unknown. To the author's knowledge there are no other records of this age for the British Columbian Cordillera. Second, all other records of comparable or longer length are derived from cores, so lack the comprehensive stratigraphic and macrofossil context available at HVC (Table 6.5).

The flora reported in most records is regionally specific. For example, sites at high latitudes shifted from temperate mixed forests to spruce forests to sedge tundra over Pleistocene times (Old Crow, Yukon; Litchi-Federovich 1974). In south central North America vegetation changed from mixed deciduous forests to arid steppes (San Agustin Plains, New Mexico; Clisby & Sears 1956, Clisby & Forman 1958, Foreman et al. 1959, Sears 1961). Long-lived basins such as the Great Salt Lake, Utah also record an impressively long pollen and spore record but with a relatively moist climate coupled with a long term cooling trend (Davis 1998, Davis & Montoux 1998).

One long record from Tulelake, California possibly reflects the vegetation history at HVC (Adam et al. 1989). The modern vegetation around Tulelake is Sagebrush steppe which grows under drier and warmer conditions than at HVC. The pollen and spore record at Tulelake reveals a gradual, but punctuated transition from Pine-'Juniper' (possibly *Metasequoia*) during the Pliocene, to *Artemisia*-herb steppe which occupies the landscape today (Adam et al. 1989). Unfortunately, no published data at any higher resolutions seems to be available for comparison to the HVC assemblage. The HVC column adds to this list of records for the Mid-Pleistocene Transition. Importantly, this is the only known record for this region that includes material from this time period.

Table 6.5. Terrestrial pollen and spore records of the Middle Pleistocene Transition of North America.

Location/Formation	Age	References	Modern communities	Notes
Old Crow, Yukon (exposure)	Early to Late Pleistocene	Lichi-Federovich 1974 ^a , Tarnocai & Schweger 1991 ^b , Schweger et al. 2011	Taiga	- Late-Early Pleistocene tundra conditions possibly. temperate conditions earlier. - Early-Middle Pleistocene <i>Picea-Alnus</i> - Few, scattered samples of many ages
Stirling Bend, Yukon (paleosol)	Early Pleistocene	Tarnocai & Schweger 1991 ^b	Subarctic forest	-Poorly constrained age. - Early tundra followed by Spruce forest.
Central Yukon (paleosols)	Early Middle Pleistocene	Jackson et al. 1999 ^c	Subarctic forest	- Spruce forest, followed by tundra.
Midnight Dome Terrace, Yukon	Late Early to Middle Pleistocene	Schweger et al. 2011	Spruce boreal forest	- one <i>Picea</i> dominated (70%) sample with low count (n=59) possibly early Middle Pleistocene
Tulelake, California (core)	Pliocene-recent	Adam et al. 1989	Sagebrush steppe	- Very low resolution data. - Large scale change from Pine-Cupressaceae to modern (cooling).
San Agustin Plains, New Mexico (core)	mid-Early Pleistocene through recent	Clisby & Sears 1956, Clisby & Forman 1958, Foreman et al. 1959, Sears, 1961 ^d	Greasewood/Saltbrush steppe	- Very low resolution data. - Gradual change from deciduous forest to modern (cooling, drying).
Great Salt Lake, Utah (core)	Late Pliocene through recent	Davis (1998) ^e , Davis & Montoux (1998) ^f	Greasewood steppe	- Very low resolution data. - Chenopodiaceae to <i>Artemisia</i> (cooling, wetter).
Sonoran Desert, Arizona (cores)	Early Pleistocene	Gray 1961	Shrub desert	- Only 5 samples. - Open savannah-parkland conditions during Early Pleistocene (cooler, wetter)
Alamosa Formation, Colorado (exposure)	Early to Middle Pleistocene	Rogers et al. 1984, 1985, 1992, Price 1971	Greasewood/Sagebrush steppe	- MIS 22-18 present with cold/wet (<i>Pinus</i>) and warm/dry (<i>Artemisia</i>) intervals

(a) Ages after Pearce et al. (1982) and Briggs and Westgate (1978). Lower pollen and spore zone correlated with Tarnocai & Schweger (1991) Burnt Hills and Bluefish Paleosols. (b) Ages after Fulton & Prest (1987). (c) Directly above Pony Creek Paleosols and under 10 m sediment; probably >190 ka <780 ka based on paleosols (Jackson et al. 1999). < 3 samples per assemblage. (d) Chronology after Markgraf et al. (1984). (e) Low resolution. (f) Scattered single records (cores) in Safford Valley but below the Blancan-Irvingtonian transition (~1.5 Ma).

6.3.3 Plant communities of the late Early-Middle Pleistocene BC interior

The late-Early through early-Middle Pleistocene landscape appears to be characterized by vegetation communities adapted to drier conditions than today. These communities were probably similar in structure to modern ones, with analogue biogeoclimatic zones such as BG, PP and ESSF reflected down- and up-elevation from Highland Valley today. It seems apparent that these zones migrated up and down the elevation gradient with fluctuating climate.

One biogeoclimatic zone not reflected in the pollen data observed in this study is the Interior Douglas-fir zone. *P. menziesii* is the dominant tree species at HVC today, and is widespread at the same elevation throughout the southern interior of BC (Hope et al. 1991a). The species is also a contributor to the tree assemblage of adjacent BGC zones near HVC as well (Lloyd et al. 1990, Hope et al. 1991b). *P. menziesii* pollen composes roughly 5-20% of the pollen and spore assemblage at Phair, Chilhil, Fishblue (Blue) and Horseshoe Lakes near Lillooet, BC (lake cores; Mathewes & King 1989) Kelowna Bog near Kelowna, BC (peat core; Alley 1976), and in the Hat Creek Valley (peat cores; Britnell 2012) where Douglas-fir forms much of the arboreal component of the plant community. This peculiar difference in assemblage is noted earlier (Sec. 6.1.1) and is an unexpected situation if the other plant assemblages were similar to those today. Interestingly, having Douglas-fir as a major contributor to the pollen rain appears to be a Holocene phenomenon in a region where Douglas-fir forests occur today (e.g. Whitlock & Bartlein 1997). Whether this absence reflects the true composition of the vegetation or is an artifact of sampling resolution or another mechanism such as differential preservation potential of *Pseudotsuga* pollen remains an open question which future research may answer.

Another interesting anomaly in the pollen and spore assemblages seen in this study is the presence of a pollen and spore zone dominated by *Selaginella* (ER-2). This phenomenon was interpreted with

some speculation in Sec. 6.1.2 since it is not known if there is a modern analogue assemblage for comparison. Based on the presence of *Selaginella* throughout the record at HVC, it is likely that the terrain had many areas of exposed rock and scree. This situation does not occur today as the terrain is underlain by extensive thick till and vegetated by forest. A more in-depth study of the zone in addition to a more thorough search for modern analogues is needed.

Samples from arboreal-rich sections need more work to understand their composition and structure; a comprehensive investigation of co-occurring macrofossils would help as might analysis of samples at higher resolution since these appear to be at too low resolution to capture the discrete forest communities which may play a role (see Sec. 6.1.1). The *Artemisia*-Poaceae steppe communities reflected by several pollen and spore zones in this study seem to be similar to those of the Bunchgrass communities found in low elevation valleys near HVC (Hebda 1982). It would appear that these intervals were much drier than today given the local presence of *Artemisia* at the now-forested elevations at HVC. Perhaps this difference reflects overall higher position of the lower treeline in the interior; a boundary dictated by moisture availability.

As mentioned earlier, this fossil pollen and spore assemblage and inferred plant community have been found elsewhere in the pollen record for the last glacial maximum at Carp Lake (Whitlock & Bartlein 1997). Similar pollen assemblages appear to have occurred over much of the central Alaska at the same time (Anderson & Brubaker 1994). These data suggest that *Artemisia*-dominated communities may have been widespread throughout the interior during glacial intervals.

6.3.4 Two glaciations at Highland Valley

The sedimentary record at HVC provides direct evidence for only two glaciations (Chapter 4). These include a less extensive “valley” glaciation (lower drift; units 2-4) at the start of the record, and a massive ice sheet glaciation (upper drift; Unit 7) at the end of the record. The lower drift has not been

described previously in detail. This work provides a description of the drift as seen in outcrop which provides an opportunity for its interpretation.

The upper drift sequence was observed in earlier excavations and is interpreted here, as in other studies (Bobrowsky et al. 1993, Fulton 1995), to have resulted from a single event of a large ice sheet overriding the site (Chapter 4). Previous work has shown that the pebble fabrics within the upper drift are consistent in direction with north-northwest to south-southeast ice flow indicators from the Interior Plateau (Bobrowsky 1993, e.g. Fulton 1975, Plouffe & Ferbey 2015). This pattern is consistent with the large Cordilleran Ice Sheet with a flow divide on the Fraser Plateau to the north northwest of HVC (Ryder et al. 1991). The Unit 7 drift must have been generated by the last ice to cover the Thompson Plateau because it visibly extends onto the surface of the surrounding landscape.

The upper drift has been assigned to the Fraser Glaciation by previous workers (Fulton 1995) which implies correlation with the Kamloops Lake Drift. Both the Kamloops Lake Drift and the Okanagan Centre Drift which compose the late Pleistocene stratigraphy of the BC southern interior and consist of a lower stratified unit, middle unstratified till unit and an upper stratified unit (Fulton & Smith 1978). This pattern is similar to Unit 7, since stratified sediments appear almost exclusively at both the base of the unit and at the top of the unit. Radiometric data from near Lumby (~100km east of HVC) constrains the age of the Kamloops Lake Drift to $< 19.1 \pm 0.24$ ka BP (GSC-913; Fulton & Smith 1978). The Okanagan Centre Drift is older than 43.8 ka BP and likely older than 51 ka BP (Fulton 1968). To date the Okanagan Center Drift is poorly constrained, but generally assumed to be Late Pleistocene in age (Fulton & Smith 1978). Till sediments of Middle Pleistocene age or younger and stratigraphically older than the Kamloops Lake Drift are present in the Merritt Basin based on a paleomagnetic assessment (Fulton et al. 1992). Both of these drifts are found extensively in the valleys of the region, suggesting multiple large Pleistocene ice sheets (Fulton & Smith 1978).

Either of these two drifts could correlate with the Unit 7 drift at HVC, as neither can reasonably be ruled out at present. Radiometric data that constrain the age of Unit 7 include many infinite radiocarbon ages from wood found immediately below the drift (see units II and III in Table 2.3, Bobrowsky 1993, Fulton 1995, McNeely 2005) and Holocene (<9.6 ka BP) aged peats from sediments above (see Unit IX in Table 2.3, McNeely & McCuaig 1991, Bobrowsky et al. 1993). None of these data satisfactorily distinguishes either of the possible correlations presented earlier. The lower drift is unambiguously older than the Middle Pleistocene so it can be concluded that only one Middle Pleistocene to recent glaciation overrode the plateau. Accordingly, only one glaciation appears to have occurred at HVC during the climatically most intense period of Quaternary glaciation (the past 781 thousand years) with ice build-up thick enough to cover the Thompson Plateau.

6.4 - Conclusions and future work

The sediments of Highland Valley contain a unique and valuable record of the late Early Pleistocene to Middle Pleistocene. The apparently continuous record straddles the Brunhes-Matuyama magnetic reversal and consists of fossiliferous lake beds between two glacial deposits. The pollen and spore analyses indicate that the interior of BC was mostly dry during the late Early-Middle Pleistocene, with local vegetation communities generally alternating from cold arid steppes dominated by *Artemisia* and grasses, and parkland to forest of pine and spruce near or at Highland Valley during warmer intervals. The occurrence of Ponderosa pine macrofossils indicates that at least one of these warm intervals was warmer than today. The sequence is tentatively correlated with multiple marine isotope stages (MIS); including at least five interglacial intervals and five cold "glacial" stages. The pollen and spore record likely extends from MIS-23 to some point later than MIS-15 beginning and ending with glaciations at the site

Apparently out of the numerous cold episodes in the global record (Lisiecki & Ramo 2005 for instance) only two resulted in glacial ice at Highland Valley with the second event being far more intense and widespread. These observations seem to rule out multiple Cordilleran Ice Sheet scale glaciations in BC, despite multiple occurrences of cold climates. The record reveals a long unglaciated Pleistocene interval north of the typical North American ice limit during the Middle Pleistocene.

This study also adds to the Early Pleistocene glacial history of BC. While a number of glacial drift deposits have already been identified (Table 6.4), the observations and interpretation from the present study suggests limited glaciations during the Early Pleistocene of BC.

The deposits at HVC offer unique opportunities for several paths of research. A few future directions for research based on these findings include:

- Comprehensive dating and descriptions of the volcanic ashes in the beds.
- Higher resolution sampling to detect more vegetation intervals. Such work might focus on portions of the record which have high internally variability, especially with those showing high arboreal values.
- Building an improved macrofossil record from a period of time which is poorly represented in North America.
- A comprehensive stratigraphic study of the Highland Valley sediments for sections now obscured by cover and those with unusual composition such as the inclined gravel and sand beds.
- Testing of interpreted ages of events (MIS) recorded in the palynological, paleontological and sedimentological record (e.g. glacial drifts) against new data such as tephra dates.

The exposure at HVC provides an exceptional glance into the poorly known Middle Pleistocene Transition in British Columbia, and adds substantially to understanding the history of this interval in North America. This reconnaissance work only begins to suggest the richness of the deposit; a record that will reveal much more about a key time in the Earth's history.

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