PEDOGENESIS OF SOILS DERIVED FROM ULTRAMAFIC ROCKS AND TEPHRA IN SOUTHWESTERN BRITISH COLUMBIA

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES

DEPARTMENT OF SOIL SCIENCE

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

March, 1992

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June, 1992

ABSTRACT

Ultramafic rocks and soils are of interest because (1) they provide unique plant growth environments, (2) environmental hazards such as chrysotile asbestos may be present, and (3) valuable deposits of asbestos, and minerals containing Mg, Cr, Ni, Co and Pt may be present. Information on ultramafic soils is useful for alleviating environmental problems associated with ultramafic terrain, and for exploiting the opportunities associated with ultramafic mineral deposits.

This thesis presents new information on the weathering status of ultramafic soils that formed since the most recent advance of continental ice sheets in southwestern British Columbia. The effects of eolian and tephra additions on soil formation were also described, and soil processes in ultramafic- and tephra-derived soils were compared.

A total of 27 soil profiles were described and sampled at three areas in southwestern British Columbia. Brunisolic soils with composite profiles of tephra overlying serpentinite covered much of the Shulaps ultramafic complex. These soils developed in a dry environment and showed weak profile development. The Tulameen area was characterized by a moderately dry climate, and Brunisolic soils had developed in serpentinized peridotite and dunite. The soils of the Coquihalla serpentine belt had Podzolic profiles which resulted from intense weathering in a moist environment.

The weathering status of the soils was investigated using a variety of chemical and mineralogical techniques. Chlorite and mica weathering was observed in clay

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fractions for the Podzolic soils at the Coquihalla area, while profiles from the Shulaps area had similar clay mineralogy throughout the profiles, as determined by XRD.

Serpentine dissolution was indicated by chemical analysis of upland soil profiles. Weathering and leaching depleted Mg from B horizons relative to parent materials. Nickel and Co were redistributed to the C horizons in all but the driest environments, while Mn was less mobile. Chromium was retained in the B horizons of all profiles.

The influence of tephra on ultramafic paleosols was minimal, but the addition of colluvial and eolian ultramafic materials to the tephra-derived soils gave rise to soils with the cation exchange complex dominated by Mg, which is more typical of ultramafic soils. Lack of buried organic layers in ultramafic paleosols was interpreted as evidence that modern-day tephra soils in the Shulaps Range were more productive than the ancient ultramafic soils.

Weathering experiments showed that trace metals such as Cr, Mn, Co and Ni were preferentially released from serpentine to dilute citric acid solutions compared to major elements such as Mg, Si, and Fe. The results suggest that these potentially toxic trace metals may be released in significant amounts in the early stages of pedogenesis.

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ACKNOWLEDGEMENTS

I thank my research supervisor, Dr. L.M. Lavkulich for his guidance and encouragement throughout this study. Thanks also to Dr. T.M. Ballard and Dr. H. Schreier, who sparked my interest with their enthusiasm, and to Dr. K. Fletcher, who read the thesis and suggested improvements.

I received much help in the laboratory, and I thank the following people for their technical assistance during the course of my studies: Bernie von Spindler, Eveline Wolterson, Barb Cade, Laura Toerper, Martin Hilmer, Shaobing Yu, Graeme Spiers, Yvonne Douma, and Maureen Soon.

I also benefitted greatly from discussions with Dr. L.E. Lowe, Dr. J. de Vries, and Dr. A. Bomke, and from the stimulating environment in the Department of Soil Science reading room.

During the past few years, I have spent many happy hours with my friends, and their spirit and companionship helped me tremendously.

To my wife, Ruth, I give my love, and sincere appreciation for her strength, reassurance and perspective.

1. INTRODUCTION

1.1 WHY STUDY ULTRAMAFIC SOILS?

Soils derived from ultramafic rocks have attracted the interest of soil scientists for several reasons: (1) Ultramafic soils are commonly associated with poor plant growth which is attributed to various combinations of low fertility (N, P, K, Ca); nutrient imbalances (Ca:Mg); toxic concentrations of Ni, Cr, Co, and Mn; low water-holding capacity; and slope instability (Alexander et al., 1985; Alexander, 1988). (2) Environmental hazards associated with ultramafic parent materials include the presence of chrysotile asbestos in windblown materials and the potential release of toxic metals to natural water systems during mineral weathering (Schreier, 1989). (3) Economically important deposits of asbestos and minerals containing Mg, Cr, Co, and Ni are associated with ultramafic rocks, and information on soil properties and processes can be applied to activities such as geochemical exploration, mineral processing, and reclamation of mine wastes.

1.2 ENVIRONMENTAL ASPECTS OF ULTRAMAFIC ROCKS AND SOILS

1.2.1 Plant growth

Compared to associated soils, ultramafic soils often support an unusual plant community, characterized by a xeromorphic flora which is poor in species and individuals. Many investigations have been conducted to determine the factors affecting plant growth on ultramafic terrain. The literature on this topic was

reviewed by Proctor and Woodell (1975), and by Brooks (1987) who described the "serpentine factor"¹ as:

"the causal factor or factors (chemical or physical) related to the infertility of serpentine soils and to the nature of the vegetation colonizing them."

These authors discussed several chemical factors, and their conclusions are summarized in the following paragraphs:

(1) Toxic effects of Cr, Co and Ni;

High levels of Cr, Mn, Co, and Ni are often present in ultramafic soils. The potential for Ni^{2+} toxicity appears to be much higher than for Cr^{3+} or Co^{2+} , because of the low solubility of Cr^{3+} at neutral to slightly acid pH values, and due to the much lower total concentration of Co compared to Ni in ultramafic rocks. The Ni content of plants growing over ultramafic soils is usually much higher than for plants growing over other types of soils (e.g. Soane and Saunder, 1959), but the evidence supporting Ni toxicity as the main causal factor responsible for unhealthy plant growth on ultramafic soils is contradictory. For example, some plants endemic to ultramafic soils tolerate very high foliar Ni levels.

(2) Adverse Ca:Mg ratio in soils, Mg toxicity, and Ca deficiency;

^{1.} Many authors use the term serpentine to include all ultramafic soils. In this thesis, the term ultramafic will be used unless it is known that serpentine is the dominant mineral. "Serpentine" (in quotes) will be used when citing authors who use the term to describe all ultramafic rocks.

Many researchers have concluded that an exchangeable Ca:Mg ratio greater than one is necessary for healthy plant growth. Plants endemic to ultramafic soils are generally more tolerant of low Ca:Mg ratios than other plants.

Considerable evidence suggests that the unfavorable effect of Mg is the most important aspect of the "serpentine factor". The high Mg levels in ultramafic rocks and the relatively high plant availability of Mg contribute to excessive Mg uptake. The mechanism of Mg toxicity may partly relate to antagonism of other plant nutrients.

Many examples of improved plant growth on ultramafic soils amended with Ca have been reported. The mechanism of Ca infertility is unclear, but some evidence suggests that while Ca levels may be sufficient for physiological requirements, they may be too low to ameliorate the toxic effects of elevated Ni levels.

(3) Infertility due to low levels of plant nutrients;

Low N, P, and K levels in ultramafic soils contribute to deficiencies of these nutrient elements, and fertilizer applications usually result in improved plant growth. Nutrient deficiencies may be partly caused by competition from ions such as Mg^{2+} and Ni^{2+} .

Kruckeberg (1984, p. 24) discussed the problems associated with seeking a single factor responsible for the "serpentine phenomenon", and encouraged a multifactor approach investigating chemical, physical and biotic factors. He believed that feedback loops integrate the various factors as illustrated in the following hypothetical example: nutrient imbalances of Mg versus Ca, and the presence of

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toxic metals may elicit a biological response resulting in restricted cycling of N and P; the resulting sparse plant cover may lead to heat stress, and low soil organic matter levels restrict available water storage capacity (AWSC), possibly leading to moisture stress.

Alexander (1988) found that soils on peridotite were more productive than those on serpentinite, and that weathering and leaching of soils derived from peridotite improved their productivity. Higher fertility and AWSC were observed on the soils with better pedogenic development. Differences in timber site index were correlated with AWSC on shallow and deep Ochrepts (weak soil development). Small differences in AWSC from deep Ochrepts to Humults (moderate soil development) accompanied site index variations, suggesting that fertility was also an important factor controlling plant growth on these ultramafic soils.

The presence of species uniquely adapted to ultramafic soils and the formation of tolerant ecotypes represent evolutionary responses to the "serpentine syndrome" (Kruckeberg, 1984, p. 24). Other species which are outside of their normal geographic range may occur on ultramafic sites.

1.2.2 Water quality

Weathering releases major constituents and trace elements (elements present in concentrations less than one percent) associated with rock forming minerals to the soil solution and the aquatic environment. The concentration of metal ions in soil solutions and in streamwaters draining ultramafic terrain depends

on the nature of the mineral phases which are dissolving or precipitating, pH, Eh, and the concentration of complex forming ligands.

Cleaves et al. (1974) found that chemical weathering was the dominant process responsible for land surface reduction and denudation of serpentinite terrain in Maryland. Mechanical weathering was more important in schist terrain. Dissolved solids in a stream draining serpentinite were nearly ten times higher than for the schist terrain. Hydrologic factors such as increased flood flow discharge, greater fluctuation in seasonal base flow discharge, and pronounced seasonal fluctuations in total discharge were attributed to the presence of serpentinite.

Stream water from the serpentinite terrain in Maryland had high concentrations of Mg^{2+} , HCO_3^- , H_4SiO_4 , and SO_4^{2-} . The authors concluded that weathering of antigorite occurred via the following reaction:

 $Mg_3Si_2O_5(OH)_4 + 6CO_2 + 5H_2O - > 3Mg^{2+} + 6HCO_3^- + 2H_4SiO_4.$ Magnesium released from antigorite left the system with bicarbonate as the balancing anion. About half of the released silica left the system, and the remainder was incorporated into newly formed quartz, chalcedony, and clay minerals.

Schreier (1987) observed that streamwaters affected by asbestos-rich landslide materials had elevated Mg, Cr, Co, and Ni levels. Sediments as far as 20 km downstream were also enriched in these elements. Elevated levels of Ni and Mn were present in fish muscle tissue (Schreier et al., 1987b), indicating that transfer of trace metals from asbestos minerals to the biota had occurred.

Assessment of metal availability using dilute acid extractions provides insight into the potential release of toxic elements to natural waters. A comparison of data from ultramafic soils showed that less than five percent of total Ni was extractable with acetic acid (Schreier, 1989, p. 78), and a smaller proportion of Cr was available in acetic acid-extractable forms. Acidic conditions enhanced the availability and mobility of Ni in organic soils covered with a layer of serpentinitic sediment (Schreier et al., 1987a), but had less effect on Cr.

1.2.3 Asbestos

Chrysotile asbestos is often present in soils derived from ultramafic rocks (Hodgson, 1986, p. 150), and asbestos observed in drill cores from the Greenland ice-cap (Bowes et al., 1977) may have been carried from areas of eroding serpentinite in eastern Canada. Windblown dusts containing asbestos pose a health problem, and revegetation of exposed areas is desirable, including the stabilization and reclamation of tailings from asbestos mining and milling operations.

The carcinogenic properties of asbestos appear when the fibers are inhaled, and according to Bonneau et al. (1986), they may be associated with adsorption and stabilization of exogenous carcinogenic molecules on solid surfaces. A second possibility involves catalytic activity of the solid via participation in an electron transfer chain, with formation of free radicals. These authors observed that chrysotile dissolution in aqueous systems resulted in depletion of Mg from the surface layers of the mineral and the appearance of negatively charged sites associated with cationic vacancies on the compact lateral surfaces of the fiber. Surfaces associated with the ruptured octahedral layer at extremities acquired a

slight positive charge at low pH. The charge duality of the asbestos surface likely allowed the fibers to interact with nucleophilic and electrophilic molecules, and the ratio of donor sites to acceptor sites likely depended on the aspect ratio, or lengthto-width ratio of the fiber.

Bales and Morgan (1985a) showed that chrysotile freshly suspended in aqueous solutions had a positive surface charge below pH 8.9. Preferential leaching of the Mg hydroxide sheet induced charge reversal after two weeks. These authors predicted that adsorption of organic ligands in natural systems may induce a negative charge on the surface after one day. Ligands such as NO_3^- , $Cl^- HCO_3^-$, and SO_4^- were not adsorbed on the mineral.

Asbestos fibers may have negative effects on fish and other aquatic biota, but the presence of 10^7 to 10^{12} chrysotile asbestos fibers per liter in waters from the Sumas River, British Columbia had no obvious negative effects on fish health (Schreier, 1987). According to Schreier (1989), most evidence suggests that exposure to asbestos in drinking water is harmless to humans, and animal feeding studies indicate that ingestion of asbestos fibers is not a serious health problem. In addition, leaching of chrysotile asbestos fibers under acidic conditions reduced the incidence of cancer from asbestos inhalation in test animals (Morgan et al., 1987; cited by Schreier, 1989), and this process may occur to some extent in natural systems.

These investigations indicate that the structure of chrysotile fibers and the amphoteric nature of the surfaces may account for the carcinogenic properties. Some fibrous amphibole minerals are also considered to be carcinogenic. Non

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fibrous serpentine minerals (lizardite and antigorite) do not have these carcinogenic properties.

1.2.4 Economic minerals

Economically viable deposits of Ni in many areas of the world are associated with Ni-rich ultramafic rocks that have been subjected to lateritic weathering. Nickel displays limited mobility in laterites, and Ni ores occur as secondary Ni oxides or Nirich smectites which may have 10 times the Ni content of the parent ultramafic rocks (Ogura, 1981). Soil processes affecting Ni accumulation in residual ultramafic deposits are of interest to geologists engaged in mineral exploration, mining and ore processing.

Layered basic intrusions are a type of ultramafic rock association which host the world's largest deposits of chromite and Pt group minerals (Hancock, 1991). In the Bushveld complex, horizons of concentrated chromitite a few meters thick are localized within dunite layers and extend over many kilometers.

Ultramafic rocks rich in magnesite, brucite, and olivine are mined as a source of Mg (Grant, 1987). In addition, the high melting point of olivine accounts for its use as foundry sand and in refractory brick in the iron and steel industry.

Disruption of the landscape and accumulation of tailings during mining operations on ultramafic terrain create a need for understanding soil processes in order to minimize the detrimental environmental effects of resource development.

1.3 TEPHRA-DERIVED SOILS

Large areas of western North America received airfall tephra during the Holocene. Soil development in tephra and the extent of weathering of tephra deposits are of interest in the context of soil fertility, and because the weathering products of tephra may affect underlying soils (Dahlgren and Ugolini, 1989). In addition, alteration of tephra layers in paleosols may affect their interpretation for stratigraphic studies (King, 1986).

Tephra-derived soils generally have unique properties such as low bulk density and a surface exchange complex dominated by active Al which is associated with amorphous materials such as allophane. Coarse-textured volcanogenous Regosols with lower amounts of active Al have also been described (Otawa, 1986).

1.4 RESEARCH RATIONALE AND OBJECTIVES

Significant contributions to the understanding of soils derived from ultramafic rocks have been made through the investigation of highly weathered soils and deep weathering profiles in tropical and subtropical regions (Nahon et al., 1982), moderately weathered soils in temperate regions (Wildman et al., 1968a), and relatively unaltered soils in glaciated regions (Proctor and Woodell, 1975). Despite these efforts, many aspects of pedogenesis on ultramafic parent materials remain enigmatic. For example, parent material variation (degree of serpentinization) was an important factor influencing soil properties on ultramafic terrain in western North America (Alexander, 1988). Only recently has consideration been given to more detailed and rigorous classification of ultramafic

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soils in the United States (Alexander, et al., 1985; 1991), and classification of ultramafic soils in Canada remains problematic. These issues point to a need for more information on ultramafic soils in North America.

The Cordillera of western North America is a region of tremendous topographic and climatic diversity. The Canadian portions of the Cordillera were largely covered by continental ice sheets as recently as ca. 11,500 years ago. For these reasons, this area provides an excellent location for investigation of the early stages of ultramafic pedogenesis.

In regions where geomorphic and tectonic processes are active, soil parent materials usually consist of a mixture of the local bedrock types and eolian additions. This is the case in southwestern British Columbia, where glaciation was the main agent responsible for the deposition of soil parent materials and the shaping of landforms, but additions of various amounts of tephra have also had an influence. To fully understand the genesis of soils formed from ultramafic materials, these additions must be considered.

This research was conceived as an investigation of the ultramafic- and tephra-derived soils of the Shulaps Range, the largest ultramafic massif in southwestern British Columbia. Extensive reconnaissance of the Shulaps area, and subsequent laboratory investigations showed that the soils from this area were weakly developed, and that only slight changes in mineralogy could be attributed to pedogenesis during the Holocene.

The investigations were widened to include sites unaffected by Bridge River tephra, and sites in wetter climatic zones (higher weathering intensity) at the Coquihalla, Tulameen, and Twin Sisters areas. The addition of these sites provided a more comprehensive view of pedogenesis on ultramafic parent materials recently deposited by glaciers. In addition, these investigations have provided new information on ultramafic soils in similar geologic settings, but unique depositional and climatic regimes compared to the recent work on ultramafic pedogenesis in the western United States.

Finally, simulated weathering experiments were conducted to determine the rates of dissolution for some ultramafic- and tephra-derived parent materials under controlled conditions, and the nature of the solutions in contact with dissolving ultramafic parent materials. The information from the weathering experiments provided a framework for the interpretation of major and trace element behavior in the soils.

To summarize, the purpose of this thesis was to clarify the role of important soil forming processes on ultramafic parent materials in southwestern British Columbia, and to assess the effects of tephra on soil properties. Three investigations were performed and they form the subjects of Chapters 3, 4, and 5. The specific objectives of these investigations were:

- (1) to determine the weathering status of ultramafic soils at various locations in southwestern British Columbia and, for comparison, one soil in northwestern Washington State,
- (2) to describe the polygenetic soils of the Shulaps ultramafic complex in relation to the regional environment, topographic diversity and the presence of tephra, and

(3) to investigate the processes involved in the release and attenuation of environmentally important elements during pedogenesis using a laboratory weathering experiment.

1.5 RESEARCH DESIGN

Figure 1.1 provides an overview of the sites selected for the study, and shows the position of the sites along a transition from a dry, cold to a moist, cool climate. Figure 1.2 illustrates the design of the analytical portion of the work, and Figure 1.3 presents a flow diagram for the weathering experiments.

Site selection:



Figure 1.1. Environmental characteristics and parent materials of sites selected for investigation, showing the number of profiles examined in each category.

Sample preparation and analysis:

Profile description and horizon designation Horizon samples ·_____ Sieve through 2 mm coarse fragments -- thin sections fine earth fraction CEC, N, P, %C, pH DCB, AOD, PYRO -----Particle size separation -----, Pretreat: remove organics, oxides Sonication Calgon Hydrometer v.f.s. clay -----DCB, AOD, PYRO --------- total elemental analysis (XRF) - sequential extraction SEM silt sand clay ----- mineralogy (XRD)------

Figure 1.2. Diagram illustrating the sequence of laboratory investigations undertaken to characterize the ultramafic and tephra derived soils. Details of analytical work are presented in Section 3.3.2.



Figure 1.3. Flow diagram of the procedures used during column and batch weathering experiments on serpentine and tephra derived parent materials.

2. LITERATURE REVIEW

2.1 OVERVIEW OF ULTRAMAFIC ROCKS

Ultramafic rocks have greater than 70 percent content of mafic (dark colored) minerals (Wyllie, 1967, p. 1). Figure 2.1 (after Best, 1982, p. 169) shows the mineralogy of important ultramafic rocks. The dominant minerals present in these rocks are olivine, pyroxene, amphibole, biotite, and their hydrothermal alteration products serpentine (existing as one or more of the three polymorphs chrysotile, lizardite, and antigorite), talc, chlorite and brucite.

Table 2.1 (after Brooks, 1987) shows that ultramafic rocks such as dunite and peridotite are enriched in Mg and first row transition metals such as Cr, Fe, Mn, Co, and Ni, relative to other rock types. The high concentrations of Cr in ultramafic rocks result from substitution of Cr^{3+} for Fe^{3+} in crystal structures, while Co^{2+} and Ni^{2+} readily substitute for Mg^{2+} in olivines and pyroxenes. Table 2.1 also shows that ultramafic rocks contain relatively low levels of Al, Ca, Na, and the major plant nutrients N, P, and K.

The mineral group and chemical formula of some minerals present in ultramafic rocks and soils are given in Table 2.2. In general, the degree of hydration is highest for soil minerals, less for serpentine minerals and lowest for the igneous ultramafic minerals.

Serpentinization involves the circulation of hot fluids through igneous ultramafic rocks. Several hydration reactions may occur during serpentinization,



Figure 2.1. Compositional diagram showing olivine, orthopyroxene and clinopyroxene content of ultramafic rocks (after Best, 1982).

	ULTRAMAFIC	C GRANITE	BASALT	SANDSTONE
SiO ₂ (percent)	40.5	70.2	48.2	79.7
Al ₂ O ₃	0.6	14.5	17.9	5.8
FeO	4.8	1.8	6.0	0.3
Fe ₂ O ₃	6.0	1.6	3.2	1.6
MgO	37.4	0.9	7.5	1.7
CaO	0.7	2.0	11.0	6.5
Na ₂ O	0.2	3.5	2.6	0.4
K ₂ O	0.1	4.1	0.9	1.3
TiO ₂	0.6	0.3	1.0	0.2
H ₂ O	8.2	0.8	1.4	2.3
Cr (mg kg ⁻¹)	1600	13	170	35
Mn	1620	470	1500	100
Co	150	4	48	0.3
Ni	2000	10	130	2
P	220	100	760	170
N	6	20	20	

Table 2.1. Average composition of some rock types.

Sources:

major elements: trace elements: Krause (1958), cited by Brooks (1987). Green (1972).

Mineral	Group	Chemical Formula ¹
In igneous roo	cks ² :	
forsterite	olivine	Mg ₂ SiO ₄
fayalite	olivine	Fe ₂ SiO ₄
enstatite	pyroxene	$Mg_2Si_2O_6$
hypersthene	pyroxene	$(Mg,Fe)_2Si_2O_6$
hornblende	amphibole	(Na,K) ₀₋₁ Ca ₂ (Mg,Fe,Al) ₅ (Si,Al) ₈ O ₂₂ (OH) ₂
chromite	spinel	(Mg,Fe)Cr ₂ O ₄

Table 2.2. Composition of some minerals present in ultramafic rocks and soils.

In serpentinized rocks²:

chlorite	phyllosilicat	e (Mg,Al,Fe) ₁₂ [(Si,Al) ₈ O ₂₀)](OH) ₁₆
talc	phyllosilicat	$Mg_{6}[Si_{8}O_{20}](OH)_{4}$
serpentine: lizardite antigorite chrysotile	phyllosilica	te Mg3[Si2O5](OH)4
brucite	hydroxide	Mg(OH) ₂
magnetite	spinel	(Mg,Fe)Fe ₂ O ₄
In soils ³ :		

magnesite	carbonate	MgCO ₃
montmorillonite smectite		$(M^{+}_{y}nH_{2}0)(Al_{2-y},Mg_{y})[Si_{4}O_{10}](OH)_{2}$
nontronite	smectite	$(M_{x}^{+}nH_{2}^{0})Fe^{3} + {}_{2}[(Si_{4-x}^{-},Al_{x}^{-})O_{10}^{-}](OH)_{2}$
saponite	smectite	$(M_{x-y}^{+}nH_{2}^{0})(Mg_{3-y}^{-}(Al,Fe)_{y})[(Si_{4-x}^{-}Al_{x}^{-})O_{10}](OH)_{2}$

1 [] denotes composition of the tetrahedral sheet.

Sources:

² Deer, Howie, and Zussman (1982)
³ Brindley and Brown (1980)

including the conversion of forsteritic olivine to serpentine and brucite through the addition of water:

 $2Mg_2SiO_4 + 3H_2O ---> 2Mg_3Si_2O_5(OH)_4 + Mg(OH)_2$. The compositional changes (loss of MgO, increased SiO₂ and H₂O) that accompany this hydration reaction are illustrated in Figure 2.2 (after Coleman, 1977, p. 99), which also shows the changes which occur during the formation of talc from enstatite.

Compositional variations are observed among the three forms of serpentine (Coleman, 1977, p. 98), but the pressure and temperature of the hydrothermal environment largely determine which products form. O'Hara (1967) described the temperature relationships of mineral facies associated with hydrothermal alteration of ultramafic rocks, indicating that chlorite forms at temperatures greater than 650 °C; talc forms from pyroxene at temperatures between 450 °C and 650 °C; and serpentines form at temperatures below 450 °C. According to Coleman (1977, p. 99), antigorite forms at temperatures in excess of 300 °C, and perhaps as high as 550 °C, while chrysotile and lizardite form at temperatures below 350 °C.

According to Moody (1976), the following compositional variations occur:

- (1) antigorite has a relatively high SiO₂ content, relatively low MgO and H_2O^+ ,
- (2) chrysotile has a relatively low Al_2O_3 content,
- (3) lizardite has a relatively high Fe_2O_3 content and is relatively low in FeO,
- (4) lizardite has greater substitution of Fe and Al than chrysotile, and
- (5) substitution of Fe and Al in antigorite extends over the range of the other minerals.



Figure 2.2. Composition of minerals in the system SiO_2 -H₂O-MgO (after Coleman, 1977), The forsterite hydration path passes through an assemblage of serpentine plus brucite. Enstatite hydration path passes through serpentine plus talc.
Leech (1953) observed that olivine was more readily altered than pyroxene during serpentinization of the Shulaps ultramafic complex in southwestern British Columbia.

Serpentinization also affects the distribution of Fe, Cr, and other metals present in ultramafic rocks. For example, the Fe originally present in olivine or pyroxene redistributes during serpentinization and enters in solid solution in serpentine minerals or brucite, or forms an opaque phase such as secondary magnetite (Moody, 1976). Chromite may be entirely replaced by secondary magnetite, or relict chromite grains may be surrounded by a rim of ferrite-chromite, a spinel with composition intermediate between chromite and magnetite (Springer, 1975; cited by Moody). Leech (1953) observed ferrite-chromite in association with chlorite in serpentinized rocks, and Moody (1976) observed that minerals commonly associated with ferrite-chromite indicate high temperature and pressure during serpentinization.

Residual chromites present in a lateritic deposit in Greece had an inner chromite zone, an intermediate ferrite-chromite zone, and a magnetite rim (Michailidis, 1990). The content of MgO and Al_2O_3 decreased, and Fe_2O_3 increased from the chromite core to the magnetite rim. The author attributed high MnO concentrations in the ferrite-chromite zone to serpentinization in the presence of Mn rich fluids.

Kimball (1990) also reported that hydrothermally altered chromites were enriched in Cr relative to Al, and in Fe^{2+} relative to Mg, indicating that Cr was preferentially retained over Al in the presence of hornblende and chlorite, and Fe^{2+}

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was preferentially retained over Mg in the presence of serpentine. Another process of Cr redistribution which may occur during serpentinization involves the transfer of Cr from hornblende to chlorite (Kimball, 1990, p. 344).

2.2 OCCURRENCE OF ULTRAMAFIC ROCKS

Although ultramafic rocks occupy less than one percent of the land surface of the earth, they are the dominant rock type in the crust under the ocean basins (Best, 1982, p. 146). Ultramafic rocks are exposed on every continent and occur in a variety of rock associations (Wyllie, 1967, p. 3). The general features of layered basic intrusions, ophiolite ultramafic complexes, and Alaskan type ultramafic-mafic complexes are described in the following paragraphs, which were paraphrased in part from Hancock (1991).

The Bushveld complex in South Africa, the Great Dyke in Zimbabwe, the Muskox layered complex in the Northwest Territories, the Bird River complex in Manitoba, and the Stillwater complex in Montana are all examples of layered basic intrusions, also known as stratiform complexes. These bodies are usually located in tectonically stable landmasses, or cratons, and formed by intrusions of ultramafic magma. Single intrusions give rise to sills (Stillwater, Bird River), while multiple intrusions give rise to funnel shaped bodies (Bushveld, Great Dyke, Muskox). The stratigraphy of each intrusive phase consists of a basal dunite layer overlain by orthopyroxenite, clinopyroxenite, and an upper gabbroic layer.

Ophiolite ultramafic complexes, also known as alpine-type peridotiteserpentine associations, represent fragments of oceanic lithosphere which were

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obducted (thrust over) onto continents at consuming plate margins (Coleman, 1977, p. 149). The term ophiolite refers to an assemblage of ultramafic and mafic rocks in the following arrangement: an ultramafic mantle sequence consisting of variably serpentinized dunite, harzburgite and lherzolite is overlain by a gabbroic complex of crustal origin, which is overlain by a sheeted dike complex, a mafic volcanic complex, and pelagic sediments. Ophiolites are commonly associated with chromite bodies and felsic intrusives (Nicolas, 1989, p. 5). The distribution of ophiolites is closely related to the location of tectonic plate boundaries, and important examples include the Troodoos massif in Cyprus, the Sumail ophiolite complex in Oman, and the Zambales massif in the Philippines.

Alaskan type ultramafic-mafic complexes occur in orogenic belts and have features which suggest they formed by intrusion of ultramafic magmas into subvolcanic magma chambers. These complexes often display a crude zonation where ultramafic lithologies in the "core" are surrounded by gabbroic rocks. The classic locality at Duke Island in southeastern Alaska consists of a typical rock suite of dunite, olivine clinopyroxenite and clinopyroxenite, hornblende clinopyroxenite, gabbro, and felsic to mafic pegmatites.

2.3 SOIL FORMING FACTORS

Pedology is the study of soil properties in relation to the processes which created them. Soil genesis (pedogenesis) was defined by Joffe (1936, p. 67) as:

"The evolution of the complex constitution and habitus, or general appearance, of the soil body in relation to the natural laws responsible for its origin."

Jenny (1941, p. 7) contributed to the theoretical foundation of pedology by describing soils as open systems characterized by properties which are functionally related to each other, and to the factors of soil formation. Jenny considered the factors of soil formation as independent variables which completely defined a soil in the following way:

SOIL = f (parent material, climate, organisms, topography, time) This approach involved the quantitative description of the effects of one or more factors while other factors were held constant. The challenge was to quantitatively describe the factors of soil formation and to functionally relate them to measurable soil properties. Although the pedogenic functions are difficult to quantify because soil forming factors can seldom be completely separated, Jenny's factorial approach has been used successfully to study pedogenesis.

Soils inherit important properties such as mineralogy, chemical composition and texture from parent materials, and this influence is particularly important near the beginning of pedogenesis, when mineral weathering reactions are the dominant soil chemical processes. The early stage of pedogenesis gives way to intermediate stages where soil processes controlled by vegetation (e.g. organic matter production) and climate (e.g. leaching) dramatically alter the soil properties. Eventually the soil may reach a mature state characterized by a rather constant suite of soil properties maintained by a dynamic equilibrium of chemical, physical and biological processes. In the mature stage, vegetation and climatic factors have a relatively large influence on soil properties, and parent material influences are reduced.

2.4 PEDOGENESIS ON ULTRAMAFIC PARENT MATERIALS

Studying the rate of pedogenesis on ultramafic rocks is problematic for a number of reasons. The competing effects of (1) easily weathered parent materials, (2) inhibited biological activity, and (3) susceptibility to erosion have contributed to much confusion, and pedologists lack a unifying concept of pedogenesis on ultramafic parent materials.

According to published stability sequences (Goldich, 1938 cited by Rai and Kittrick, 1989; Jackson and Sherman, 1953), mafic minerals are among the least stable minerals in the weathering environment, yet Proctor and Woodell (1975) cited several authors who described ultramafic rocks as resistant to weathering. The confusion results partly from variations in lithology of ultramafic rock massifs, and also because serpentinitic landscapes are easily eroded, exposing bedrock. Proctor and Woodell concluded that the rate of weathering of "serpentine" parent materials was variable.

The initial conditions present on a recently exposed ultramafic outcrop are severe for plants and microorganisms. These conditions may persist, placing a restriction on pedogenic processes until high concentrations of Mg and Ni are reduced, and soil organic matter accumulation provides for increased plant nutrient pools and improved soil physical properties.

Denudation and mass wasting, as described by Cleaves et al. (1974) and Schreier (1989) contribute to the presence of weakly developed soils on serpentinite terrain, while Alexander (1988) showed that unserpentinized ultramafic rocks such

as peridotite were more resistant to erosion, and may support well developed soils. These results emphasize that an important difference exists between serpentinized and unserpentinized ultramafic rocks.

Early investigations of ultramafic soil focussed on the botanical aspects of the unusual plant communities, and on plant growth factors (reviewed by Proctor and Woodell, 1975; and by Brooks, 1987). Other geological work concentrated on the economic potential of ultramafic rocks. Information on the mineralogy of ore deposits and the mechanisms of alteration of ultramafic materials was useful for improving techniques in mineral exploration, recovery and processing (e.g. Sahu and Venkateswaren, 1980).

2.4.1 Weathering processes of ultramafic rocks

Many studies of mineral weathering were initiated in the 1970's and 1980's, in part to improve our understanding of the capacity of geologic materials to neutralize inputs of acidic precipitation (Johnson, 1983). Much excellent work was produced during this period, providing information on weathering reactions of many minerals, including olivine (Eggleton, 1984) and pyroxene (Scott et al., 1981), as well as phyllosilicates such as serpentine (Lin and Clemency, 1981) and chlorite (Kodama et al., 1983).

The stability of minerals depends on the composition of fluids bathing them, and the temperature and pressure of the environment. Minerals are most stable in their environment of formation, and they tend to dissolve with formation of a new equilibrium phase when the environmental conditions change. The rate of alteration

depends on kinetic factors, which may be, but are not necessarily, affected by the composition of the system. The rate of dissolution of unstable minerals ultimately controls the occurrence of primary minerals in soils. Three important processes affecting mineral weathering are hydrolysis, oxidation and complex formation.

One of the most powerful weathering agents in nature is the hydrolytic dissolution of minerals. Hydrolysis reactions are enhanced at low pH values. Because the pH of natural waters is buffered at about 5.5 due to the absorption of CO_2 and the dissociation of H_2CO_3 , acid decomposition of minerals has been used to simulate their behavior in natural weathering environments.

The oxidation of Fe^{2+} to Fe^{3+} is accompanied by a considerable decrease in the ionic radius, and this process may enhance the dissolution of many minerals containing Fe^{2+} by disrupting the crystal structure. In contrast, the presence of Fe hydroxide coatings on mineral grains may inhibit the transfer of reactants and products between the solution and the mineral surface.

The rates of processes occurring at oxide - water interfaces depend on the coordinative interactions between oxygen donor atoms on the mineral surface and protons and ligands in the soil solution (Stumm, 1986). The detachment of metal ions from lattice sites is enhanced when O atoms at the extremities of mineral structures are replaced by water or other ligands which form soluble complexes with metal ions.

The following sections describe investigations of mineral weathering in ultramafic rocks. Information on the stability of mafic minerals, the rates and

mechanisms of weathering, and the nature of alteration products provides an understanding of processes which may be important in ultramafic soils.

2.4.1.1 stability relations

Olivine was considered the least stable mineral in Goldich's (1938; cited by Rai and Kittrick, 1989) stability sequence for coarse grained minerals. Delvigne et al. (1979) considered the instability of olivine to be a consequence of the crystal structure where SiO_2 tetrahedra are linked together by readily soluble (Mg^{2+}) or oxidizable (Fe^{2+}) bivalent cations. In addition, the increasing stability of olivine < pyroxene < amphibole appears to be related to increasing Si polymerization in these minerals (Huang, 1989). The initial weathering products of olivine frequently consist of a mixture of Fe hydroxide and hydrated Mg silicate known as iddingsite. The silicate phase is smectite if sufficient Mg and Si are present, while opal is formed if Mg is removed.

The mineral weathering sequence presented by Jackson and Sherman (1953) for particles finer than two microns differs from established sequences for coarse grained particles because the large specific surface exposes unstable fine grained minerals to more rapid weathering. Olivine appeared at stage three of the thirteen-stage weathering sequence, along with hornblende and pyroxene. Magnesium chlorite and antigorite were placed at stage four (same stage as biotite and nontronite), and thus were considered more stable in the fine fractions. The presence of any of these minerals in the clay fraction (< 2 microns) indicates a soil in the early stages of weathering (Jackson and Sherman, 1953).

Using X-ray diffraction (XRD), Faust and Nagy (1967) showed that chrysotile was the least stable form of serpentine under strongly acidic conditions. Chrysotile was decomposed by reaction with 1 M HCl at 95 °C for one hour, while lizardite and antigorite endured this treatment.

Wildman et al. (1971) used solubility data to determine a value for the free energy of formation for California serpentines. Variations in Fe content appeared not to affect the value, but one sample with higher Al content had a lower free energy of formation. Figure 2.3 shows the stability field for serpentine obtained by Wildman et al., along with pH values and log $[Mg^{2+}]$ commonly found in soil solutions (Sposito, 1989) and streams (Freeze and Cherry, 1979; Schreier, 1987; Cleaves et al., 1974). This diagram shows that serpentine minerals occupy a small stability range at high pH values and Mg²⁺ concentrations.

Wildman et al. (1971) also attributed the presence of Fe-rich montmorillonite (current terminology would describe this mineral as nontronite; Borchardt, 1989) in serpentine-derived soils to the combination of Fe, Al, and Si released during serpentine weathering. Free energy relations (Figure 2.4) indicated that trivalent Fe- and Al-hydroxides would be more stable than Mg-hydroxides when in contact with serpentine soil matrix solutions in the neutral pH range. Assuming that similar free energy relations govern the formation of the octahedral sheet of a layer silicate, this analysis provided a thermodynamic explanation for the formation

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Figure 2.3. Stability field for serpentine (after Wildman et al., 1971), and pH and Mg²⁺ content of 1. acid soil solutions (Sposito, 1989, p 78); 2. serpentine affected river waters (Schreier, 1987; Cleaves et al., 1974, Figure 3); and 3. streams and rivers from igneous terrain (Freeze and Cherry, 1979; Table 7.5, entries 1,3 9).



Figure 2.4. Stability fields for metal hydroxides present in ultramafic soils, showing the dominant soluble species (ions) and insoluble species (inside boxes) present at various solution compositions (after Wildman et al., 1971).

of nontronite in well drained soils in preference to Mg-rich smectite (saponite). The dissolving serpentine would likely maintain Si at sufficient concentrations to nucleate the 2:1 phyllosilicate.

These studies show that ultramafic rocks contain primary minerals which are unstable and are expected to weather rapidly under the conditions present in soils. The extent of mineral weathering and the mechanisms responsible for alteration under laboratory conditions have been the subject of numerous investigations, some of which will be discussed in the next sections.

2.4.1.2 mineral weathering studies: serpentine

Pedro and Bitar (1966) used a soxhlet apparatus to study weathering processes of antigorite-bearing serpentinite and observed that under free drainage, preferential release of Si occurred in the presence of pure water and CO_2 charged water at pH 4.5. Leaching with acetic acid at pH 3.5 resulted in preferential removal of Mg. The release of Mg and Si was strongly influenced by the drainage regime, with Mg release favoured over Si for all treatments at low drainage. Iron was strongly retained relative to Si and Mg for all treatments.

Wildman et al. (1968a) also studied the dissolution of serpentinite as a function of CO_2 partial pressure. In agreement with the findings of Pedro and Bitar, solutions with low CO_2 partial pressure extracted more Si, while solutions with high CO_2 partial pressure (lower pH) had higher Mg and Si concentrations. There was no consistent relation between the Si:Mg ratio of the California serpentines and the weathering solutions at higher pH values, but after long time periods, the solutions

tended towards congruent dissolution. The results suggested that soil water, which generally has elevated CO_2 levels, preferentially removes Mg from serpentine minerals.

In contrast to the results of Pedro and Bitar for antigorite, Bales and Morgan (1985b) found that the ratio of molar Si to Mg released from chrysotile at constant pH values between 7 and 10 was about 0.5, compared to about 0.69 in the solid. The surface therefore became more silica-like over time, compared to the original $Mg(OH)_2$ composition. Magnesium was released at a constant rate after one day, and Si was released at a constant rate from the beginning of the dissolution experiments. At pH values near 10, less Mg and more Si were released. The dissolution rate also showed a slight dependence on pH, which was attributed to a surface reaction involving proton attachment to high energy sites at crystal edges or dislocations. Reaction rates for the more abundant low energy sites along the Mg(OH)₂ sheet were less dependent on pH.

Gronow (1987) also showed that dissolution of chrysotile asbestos in water occurred with preferential release of Mg. Very slow rates of dissolution were observed in solutions maintained at a constant pH of 7.0, removing less than one atomic layer of Mg surface after 1024 hours. Dissolution occurred faster at pH 4.0, removing the equivalent of 8.8 atomic layers of Mg surface after 170 hours, and surface analysis by X-ray photoelectron spectroscopy (XPS) indicated a nearly 10fold depletion of Mg relative to Si. Increasing temperatures and longer reaction times promoted congruent dissolution. Congruent dissolution was evident at an earlier stage under acid conditions, perhaps because the initially faster removal of Mg ions exposed a large area of the tetrahedral silica sheet to hydrolytic attack.

In summary, serpentine dissolution is generally incongruent, and the release of Mg over Si is favored at low pH values. Comparison of the results from these four studies suggests that Si release from antigorite is favored at neutral to slightly alkaline pH values, but this was not observed for chrysotile. These studies also suggest that congruent dissolution may occur at some intermediate or late stage of weathering.

2.4.1.3 mineral weathering studies: chlorite

The weathering of chlorite occurs primarily through the destruction of the interlayer hydroxide sheet of the 2:2 structure (Barnhisel and Bertsch, 1989). An important consequence of the weathering process was observed by Jones (1981), who found that unaltered chlorite had a low cation exchange capacity (CEC), but removal of the positively charged octahedral sheet in laboratory experiments and during weathering may result in the formation of a negatively charged mineral similar to montmorillonite or vermiculite.

Ross and Kodama (1973) found that destruction of the hydroxide layer of a Mg-chlorite was possible if the sample was heated to $610 \,^{\circ}$ C and then suspended in 0.2 M HCl. Analysis with XRD, differential thermal analysis (DTA), and infrared spectroscopy (IR) showed that the residue had properties similar to vermiculite. The authors suggested that oxidation of Fe²⁺ played a major role in the initiation of structural disorder that was required for the selective removal of the hydroxide sheet during the pedogenic alteration of chlorite to vermiculite.

The role of oxidation was further clarified by Senkayi et al. (1981). They used solutions containing Br to oxidize Fe^{2+} and convert chlorite to smectite. The amount of Fe^{2+} and its location within the chlorite structure determined the rate and direction of alteration. In general, the results indicated that if significant amounts of Fe^{2+} occurred in the interlayer hydroxide sheet, oxidation and alteration of the chlorite was rapid. If the Fe^{2+} was present in low amounts or was present primarily in the 2:1 layer, then oxidation would occur more slowly. In addition, oxidation of Fe^{2+} within the 2:1 layer would result in charge reduction, and smectite would form rather than vermiculite.

In an experiment designed to more closely mimic natural environments, Kodama et al.(1983) showed that dissolution of chlorites by fulvic acid solutions was incongruent, with preferential dissolution of octahedral ions such as Al, Mg and Fe. The rates of dissolution were initially rapid, then declined exponentially in a closed system, while in an open system the rate of dissolution reached a steady state after about 35 days.

To summarize, these studies emphasize the importance of the interlayer hydroxide sheet in chlorite weathering. Dissolution may be enhanced by oxidation of Fe^{2+} . Alteration proceeds via transitional phases to produce expanding minerals similar to vermiculite or smectite which have much higher CEC than the original chlorite. The composition of the chlorite, the distribution of charge between the octahedral and tetrahedral sheets, and the distribution of Fe^{2+} affect the mechanism of alteration and the nature of the weathering products.

2.4.1.4 mineral weathering studies: olivine, pyroxene, and amphibole

Oxidation and hydrolysis are important weathering mechanisms for these minerals. The role of Fe^{2+} oxidation in the weathering process is contradictory, however, as Siever and Woodford (1979) found that fayalite dissolution at pH 4.5 to 5.5 occurred much faster under N₂ gas than in air. Incongruent dissolution was observed, and involved a preferential replacement of Fe^{2+} by H⁺ in the mineral structure, followed by oxidation of the Fe^{2+} to Fe^{3+} in solution, and subsequent precipitation of $Fe(OH)_3$ on the mineral surface. The results indicated that an Fehydroxide coating on the mineral grains scavenged Si and other cations from the solution, acted as a surface armor, and slowed the dissolution reaction.

Grandstaff (1986) observed congruent dissolution of natural sand-sized forsterite at pH values between 3.0 and 5.0. The use of natural materials eliminated the rapid release of weathering products in the initial stages of the experiment caused by dissolution of fine residues from grinding. Dissolution occurred at a constant rate for more than 50 days. The rate law was first-order with respect to H⁺ activity.

The use of transmission electron microscope (TEM) and electron microprobe (EM) analysis has provided direct information on the mechanisms of weathering. For example, Eggleton (1984) observed that the initial breakdown of olivine to a mosaic of needle-shaped units with a diameter of about 5 nm was followed by formation of a hexagonal phase (probably consisting of metal octahedra) and the opening of solution channels parallel to the olivine y-axis. Laths of smectite nucleated from the metastable phase and began to fill in the channels,

partially inheriting the structure of the metastable phase, but the solution channels remained open. Goethite also formed in the channels.

Schott et al. (1981) showed that Fe-free pyroxene (enstatite) and amphibole dissolved with preferential release of Mg and/or Al relative to Si. Incongruent dissolution persisted for the duration of a 40-day experiment at pH 1.0 and 6.0. Surface analysis by X-ray photoelectron spectroscopy (XPS) indicated that H⁺ had substituted for Ca^{2+} and Mg^{2+} in a cation-depleted layer which was only a few atoms thick. Enstatite experienced the greatest cation depletion at high temperature and low pH, and a surface precipitate of pure silica was formed under these conditions. These results, along with the observation of etch pits indicated that enstatite dissolution was controlled by a surface chemical reaction.

Eggleton and Boland (1982) showed that the conversion of enstatite to talc plus oxide occurred via sequential mineral reactions without the development of a non-crystalline phase. Enstatite initially weathered by vacancy diffusion with the formation of biopyriboles (I beam units consisting of chains of Si tetrahedra linked by dioctahedral cations; these units may act as the building blocks for tetrahedral and octahedral sheets in secondary minerals). The biopyriboles eventually coalesced into a talc-like layer silicate which had a high degree of structural correspondence with the enstatite. Upon nucleation of these initial products into talc units larger than several tens of nm, the structural correspondence with the enstatite was lost. Talc formed in association with smectite, and the later stages of weathering were dominated by talc or smectite, apparently depending on the release of SiO₂ and MgO from the pyroxene.

In summary, Siever and Woodford showed that Fe(II) oxidation does not always enhance the weathering of primary minerals in ultramafic rocks. Congruent dissolution of forsterite was observed by Grandstaff (1986), but enstatite dissolved incongruently (Schott et al., 1981). These results may reflect the lack of Si polymerization in the olivine structure, but the factors governing congruent versus incongruent dissolution of mafic minerals are still not resolved. Structural inheritance exerts considerable control over olivine and pyroxene weathering rates, and this aspect will be discussed further in the next section.

2.4.1.5 comparison of mineral weathering rates

Comparison of weathering rates, along with information on mineral stability, provides a framework for interpreting mineral assemblages within soils. Luce et al. (1972) found that rates of dissolution decreased in the order forsterite > lizardite > enstatite. Dissolution involved a rapid replacement of surface Mg^{2+} by H⁺, and a subsequent extraction of internal Mg and Si. A Mg-depleted surface layer formed during incongruent dissolution under acidic conditions, and the authors presented diffusion coefficients for Mg and Si through the depleted surface layer as a measure of the dissolution rate. The results were interpreted on the basis of polymerization of Si in the mineral structures, but the rapid dissolution of lizardite compared to enstatite was problematic. These authors did not consider the effects of hyperfine particles produced by grinding.

Lin and Clemency (1981) observed that the rate of incongruent dissolution of Mg-containing minerals decreased in the order brucite > antigorite > phlogopite > talc. The initial pH of the CO₂ buffered systems was 4.0. For brucite, the pH

reached 9.2 within 20 minutes, while the antigorite system reached pH 6.9, and talc reached pH 5.0 after one hour. Loss of Mg was greater than Si, and the overall dissolution rates for these phyllosilicates were controlled by the destruction of silicate sheets. After 1000 hours, 50 percent of the brucite, five percent of the antigorite, and 0.5 percent of the talc had dissolved.

A comparison of later results from a number of authors by Bales and Morgan (1985b) indicated that dissolution rates of mafic silicates were highly pH-dependent, and did not follow the expected pattern of minerals with higher degrees of Si polymerization dissolving more slowly. In particular, they observed that forsterite (isolated Si tetrahedra), dissolved at about the same rate as enstatite (chain structure), and that serpentine minerals (phyllosilicates) dissolved at about the same rate or faster. Chrysotile dissolved faster at pH 7 to 10 than antigorite did at pH 6.3, or talc at pH 5.0. These results suggest that the nature of octahedral sites has an important effect on dissolution rates of mafic silicates.

Eggleton (1986) concluded that the rate of alteration of mafic silicates also depended on the degree of structural inheritance in the alteration products, and on the size of diffusion avenues created during mineral dissolution. Olivine weathered very rapidly because cracks developed faster than alteration products filled them, providing for uninhibited diffusion of reactants and products. The situation for enstatite was different because it altered to talc with a high degree of lattice coherence. Silicate chains from the pyroxene structure became an integral part of the phyllosilicate tetrahedral sheet and the initially formed talc-like units had almost identical dimensions to the enstatite structure, so diffusion avenues were smaller

than one nm. The weathering process for enstatite was restricted at a slow rate by the diffusion of products and reactants to reaction sites.

In summary, both chemical and physical factors affect dissolution rates of mafic silicates. Properties of octahedral and tetrahedral sites are important. The presence and nature of alteration products, particularly the degree of structural coherence and filling of solution channels determines the importance of transport processes and surface reactions.

2.4.1.6 mineral transformations in ultramafic rocks and deep weathering profiles

Lateritic weathering represents an extreme example of rock alteration, and investigations of deep weathering profiles provide information on the changes in mineralogy and geochemistry that accompany rock dissolution and secondary mineral formation in the surficial environment.

Many investigations of highly altered ultramafic rocks have observed vermiculite and smectite in association with primary minerals. For example, Gilkes and Little (1972) observed alteration of chlorite to randomly interstratified chlorite/vermiculite at depths as great as ten meters in a section of phyllite in Australia. The proportion of vermiculite increased near the surface of the section, and the loss of Mg from the chlorite structure was strongly correlated with oxidation of Fe^{2+} .

Fontanaud and Meunier (1983) found that rock porosity governed the weathering reactions observed in a lherzolite consisting of orthopyroxene-

clinopyroxene-chrysotile-picotite. The earliest stage of weathering was observed in intragranular and intergranular microsystems, where pyroxenes were altered to Ferich talc and Fe oxides, with loss of Al^{3+} , Mg^{2+} , Ca^{2+} and Na^+ to solution. A plasmic microsystem represented an intermediate stage of weathering with increased rock porosity, where the talc-oxide assemblage and chrysotile were both unstable and reverted to saponite. Fissure microsystems were also described where argillization caused a complete restructuring of the rock, and saponite was replaced by nontronite.

Few studies have reported that serpentine minerals may form in the surficial environment, but Craw et al. (1987) observed chrysotile associated with lizardite, magnetite and pyrite in debris flows of an ophiolite complex in New Zealand. These authors considered the chrysotile to be an authigenic replacement of lizardite, which formed under alkaline, reducing conditions in the near surface environment at low temperature.

The distribution of trace elements during lateritic weathering is also of interest. Nahon et al. (1982) found that smectite which had formed from pyroxene in the Western Ivory Coast had 30 times as much Ni, and twice as much Cr as the pyroxene. The later stage of pyroxene alteration was characterized by the formation of a Ni- and Cr-containing ferrihydrite-like mineral at the expense of the phyllosilicate phase. Finally, the ferrihydrite-like mineral altered to goethite via a series of in situ dissolution/recrystallization reactions, where each successive stage developed from the one formed earlier. A portion of the Ni and Cr was released to solution at each stage, and a relatively pure goethite was the final product.

In summary, these investigations confirm that the common products of serpentinization include chlorite, talc and serpentine. Observation of vermiculite as an alteration product of chlorite, and the alteration of serpentine and talc to smectite suggests that these reactions may also be important in soils. Nahon et al. (1982) observed differential redistribution of Ni and Cr from primary to secondary minerals, illustrating that different mechanisms are responsible for retention of these two metals during ultramafic weathering.

2.4.2 Morphological, chemical and mineralogical properties of ultramafic soils.

Ultramafic parent materials may be affected by any soil process, including podzolization, brunification, laterization, lessivage or the formation of gley. The intensity of soil forming processes, and the resulting soil properties and classification are mediated by the climate, topography, time of formation, and vegetation.

Kruckeberg (1984), in a short literature review observed that ultramafic soils reflect the composition of the rocks from which they are derived, having Mg as the dominant exchangeable cation, while Ca levels are lower than for non-ultramafic soils. In addition, levels of N, P, and K are suboptimal for normal growth of crop plants in ultramafic soils, and Cr and Ni are present in high concentrations.

In comparison to soils derived from granite, basalt and andesite in Japan, Miura et al. (1988a, 1988b) observed that a serpentinitic soil had low Ca:Mg ratios, higher pH and lower exchangeable Al in the subsoil, and very high dithionitecitrate-bicarbonate (DCB) extractable Fe (Fe_d). The serpentinitic soil had over 50

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percent heavy mineral content in the fine sand, consisting mostly of chlorite and opaque minerals such as magnetite.

Weakly and moderately developed ultramafic soils contain detrital minerals such as serpentine, chlorite, olivine and pyroxene. The extent of alteration of these minerals is closely related to the degree of pedogenic development.

Rabenhorst et al. (1982) found that weakly expressed argillic horizons in moderately weathered serpentinitic soils (Hapludalfs) from Maryland had clay fractions dominated by chlorite and vermiculite, while serpentine was more common in the parent materials. In addition, the content of serpentine minerals was much lower in fine fractions than in coarse fractions. These authors found evidence for alteration of chlorite to vermiculite via regularly interstratified intermediates. Smectite in the fine clay was interpreted as an alteration product of serpentine.

The surface horizons of the Maryland soils were depleted in Mg relative to the parent materials, and the B horizons had high levels of Fe_d . The Ni content of the soil materials increased with depth, while the distribution of total Cr was more variable.

Three important processes of ultramafic pedogenesis are illustrated by these results: (1) alteration of serpentine and chlorite to vermiculite and smectite, (2) transfer of Fe from ultramafic silicate minerals to secondary sesquioxides, and (3) redistribution of Mg and Ni within the profile. Rabenhorst et al. (1982) proposed a model of pedogenesis for the Maryland ultramafic soils which suggested that the formation of a podzolic B horizon would precede the formation of a Bt horizon.

This mode of pedogenesis is distinct for easily weathered ultramafic parent materials, and reflects the importance of serpentine dissolution in the early stages of pedogenesis.

The extensive release of Fe during serpentine weathering was also observed by Sasaki et al. (1968), who described a Podzol developed on serpentinized pyroxenite in Japan. Although this soil had a distinct leached horizon (Ae2), the Bf horizon had only slightly higher levels of acid ammonium oxalate (AOD) extractable Fe, Al, and Si (Fe_o, Al_o, and Si_o) than the Ae2. Goethite is an important mineral that forms in soils after release of Fe from ultramafic silicate minerals (Mizota et al., 1982).

Ducloux et al. (1976) investigated three serpentinitic soils from an unglaciated region in southern France. A well developed hydromorphic soil contained a mixed-layer chlorite-vermiculite clay mineral and dioctahedral smectite (nontronite) which replaced chlorite and antigorite present in the parent material. The more weakly developed soils contained more chlorite, detrital antigorite and talc, and lesser amounts of smectite. The evolution of the clays was represented by

antigorite + magnesian/aluminous chlorite soil chlorite + ferric smectite + Fe oxides + Mg²⁺.

Soil chlorite formed early, and had a composition similar to the serpentine, while the later formed smectite was relatively distant from the original composition. These authors also observed that the fine earth fractions near the surface of the soils were depleted in Mg, and Fe sesquioxides were an important product of mineral weathering during pedogenesis. Eswaren and Sys (1973) found that topographic position (as it influenced water balance) strongly controlled soil profile features in ultramafic terrain in Borneo. The clay mineralogy of an Inceptisol (weak pedogenic development) did not change with depth in the profile. An Alfisol (moderate pedogenic development) contained nontronite which had formed in saprolite, along with chlorite and kaolinite. The surface horizons contained accumulations of kaolinite and goethite. An Oxisol (strong pedogenic development) had antigorite, talc, nontronite, and traces of kaolinite and goethite in the saprolite zone, while the oxic zone contained goethite (50 percent) and gibbsite (20 percent) which had formed from nontronite, along with lesser amounts of kaolinite and nontronite.

The formation of smectite as a weathering product of ultramafic rocks is closely linked with topographic position. Istok and Harward (1982) found that smectite formation from serpentine and chlorite in the Klamath Mountains, Oregon occurred mostly in poorly drained landscape positions. Examination with TEM showed that the amount of amorphous coatings on chrysotile fibers declined with depth. The coatings were thought to be an integral part of the process of smectite formation in these soils.

A further aspect of topographic control of mineral transformations during ultramafic pedogenesis is illustrated by the work of Wildman et al. (1968b), who observed that Fe-rich montmorillonite (nontronite) was the predominant mineral in the fine clays from the B horizons of well drained serpentinitic soils in California. The coarse clay and silt fractions contained only trace amounts of smectite. Incongruent dissolution and leaching of Mg^{2+} left the soil clays enriched in Fe and Al relative to the parent rock. In poorly drained landscape positions of the

California serpentine terrain, Senkayi (1977) observed a Mg-rich smectite (saponite). The saponite formed by neosynthesis in an environment with higher pH, and where Mg and Si had accumulated by subsurface flow of soil water.

Dirven et al. (1974) studied a toposequence of serpentinitic soils in Cuba and observed that a poorly drained Gleysol had a mineralogical composition which closely matched the predictions of a mass transfer model. Weathering reactions at high CO_2 concentrations led to the formation of siderite, magnesite, smectite and amorphous silica from chrysotile, spinel, and magnetite. Well drained upland soils contained more kaolinite and goethite than the Gleysol. All of the soils in the ultramafic toposequence contained large amounts of Fe sesquioxides.

The pedogenic behavior of the three serpentine polymorphs has not been investigated in detail. Smectite has been reported as an alteration product of antigorite (Ducloux et al., 1976), lizardite (Veniale and van der Marel, 1963), and chrysotile (Istok and Harward, 1982). Other types of parent material variation, especially the extent of serpentinization may also have a profound influence on ultramafic pedogenesis.

Alexander (1988) showed that soils on unstable serpentinite terrain in the Klamath Mountains, Oregon were weakly developed compared to soils on more stable peridotite parent materials. The Ca:Mg ratio of a serpentinitic Ochrept (weak pedogenic development) was less than 0.4, while a Humult (moderate pedogenic development) derived from peridotite had a Ca:Mg ratio near 4.0. The Ochrept had over 10 percent Fe_d in the B horizon, while the Humult and a Humox (advanced stage of pedogenesis) had maximum Fe_d levels of 15 and 23 percent. Olivine and

serpentine were abundant in the fine sand fraction of the Ochrept, while serpentine was sparse, and olivine absent from the sola of the older soils. Nitric acid extracted more Ni and less Cr from the Ochrept than from the older soils, indicating that Ni was leached from the sola of the older soils, while Cr was retained and transferred to acid soluble phases during weathering.

Vegetation factors also play an important role in ultramafic pedogenesis. In Scotland, Bain (1977) found that Fe-rich chlorite was more highly altered in podzols with high organic matter content in the B horizons. Dissolution of chlorite was likely enhanced by the presence of complex forming organic acids in the soils, since similar soils with lower levels of organic matter had the same chlorite content throughout the profile. The only weathering product of chlorite in the podzol was goethite.

The chemical evolution of ultramafic soils is governed by two major groups of processes: (1) dissolution of primary minerals containing Mg, Si, Fe and trace metals such as Cr and Ni, and (2) incorporation of the released elements into secondary minerals. The release of Mg is generally followed by the depletion of this element from surface horizons. Nickel is also relatively mobile in ultramafic soils. In contrast, Fe is strongly retained in B horizons.

Gough et al. (1989) studied the processes influencing Cr and Ni mobility and uptake by plants in an ultramafic landscape in California. In well developed, stable soils from gently sloping areas the Cr content was higher for surface horizons, while the highest Ni concentrations were found in B horizons. For eroded soils from steep sites, the content of these elements was more uniform with depth. In general, plants grown on stable soils with high Ni levels had higher foliar Ni content, but foliar Cr was not so well correlated with total soil Cr. These results indicate that Cr has very limited mobility during pedogenesis.

Lateritic weathering also emphasizes differences in elemental mobility. Beinroth (1982) described a serpentinitic Oxisol (Nipe series) in Puerto Rico as a product of lateritic weathering, where the loss of SiO₂, CaO, MgO, Na₂O, and K₂O, and the concentration of hydrated forms of Fe and Al led to a residual deposit rich in Fe, Al, and elements with ionic potentials between 3.0 and 9.5 such as Ti, Ni, Cr, and Zr. In general, the formation of lateritic material is enhanced in areas with humid conditions, free internal drainage, long term geomorphic stability, and the strong weathering intensities associated with continually high temperatures (Beinroth, 1982). Since desilication and removal of bases occurs near the rock surface in the early stages of weathering, laterization may be considered a geochemical process rather than a pedogenic one.

The Nipe soil was developed in lateritic materials which had been transported over short distances and redeposited in a sedimentary environment. The solum and parent material of the Nipe soil had very similar chemical composition, suggesting that previous geologic weathering had produced a parent material which was in quasi-equilibrium with the environment. One important chemical difference between the soil and the parent material was the addition of up to 10 percent organic matter, and the most important translocation process was nutrient cycling by the vegetation. Soils derived from andesite on surfaces of similar age in Puerto Rico were classified as Ultisols, indicating that ultramafic materials weather more rapidly than andesitic rocks.

Jones et al. (1982) also presented chemical and mineralogical data for the Nipe soil. The levels of total Ni were slightly lower in the surface horizons, suggesting that pedogenic processes acted to deplete the surface horizons in Ni. The content of Cr was highest in the B1 horizon. Minerals present in significant amounts were gibbsite, goethite, and hematite, while lesser amounts of quartz, kaolinite, and chlorite were present, particularly in the surface horizons.

To summarize the information reviewed in this section, mineral weathering reactions which may occur during ultramafic pedogenesis are illustrated in Figure 2.5. Alteration of primary minerals to vermiculite and smectite occurs with some degree of structural inheritance. Silicon, Mg, and Fe released during weathering may be incorporated in these alteration products along with lesser amounts of trace elements. The largest pathway for Fe involves precipitation of sesquioxides from solution. Iron and Cr show limited mobility while Mg, Si and Ni show greater mobility.

A conceptual model of ultramafic pedogenesis is presented in Figure 2.6. In the early stages of pedogenesis, mineral weathering results in the rapid release of Mg from serpentine minerals, and even poorly developed ultramafic soils (Regosols; Entisols) have higher Ca:Mg ratios in the surface horizons than in the parent materials. Organic matter accumulation also occurs in these poorly developed soils.

In slightly weathered ultramafic soils (Brunisols; Inceptisols), release and translocation of Co, Ni, Mn, and finally Fe from the primary minerals is observed. This stage is characterized by slight increases in Fe_d for the B horizons, and the



Figure 2.5. Mineral weathering and pathways of element redistribution in ultramafic soil materials. The solid lines represent reactions which may occur with a high degree of structural inheritance, while the dashed lines represent reactions occuring via a soluble intermediate phase.



Figure 2.6. Conceptual model of ultramafic pedogenesis, showing the important properties and processes of ultramafic soils at various pedogenic stages.

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presence of small amounts of Co_d , Ni_d , and Mn_d may indicate redistribution of these mobile elements. Redistribution of Cr is not evident at this stage.

As weathering proceeds, depletion of primary minerals occurs. Olivine depletion likely precedes the loss of serpentine, and chlorite alteration may precede the loss of serpentine or talc. The formation of secondary alteration products from chlorite occurs with a very high degree of structural inheritance. Some structural inheritance occurs during formation of smectite from olivine and pyroxene, but the mechanism of smectite formation from serpentine, widely considered to be an important process is enigmatic. The formation of clay minerals, and the reduction in particle size due to weathering are important processes during the intermediate stages of pedogenesis. If sufficient clay is present, lessivage becomes an important soil forming process (Luvisols; Alfisols, Ultisols). This process appears to be more likely in poorly drained landscape positions.

Well drained soils experience loss of Mg and Si by leaching without the formation of secondary minerals in the intermediate stages of pedogenesis. Negative enrichment of Fe and Cr at the soil surface, and illuviation of organic complexes of Fe and Al are important processes under these conditions. Soils at this stage of development (Podzols; Spodosols) are characterized by high levels of Fe_d, Fe_o and Fe_p in B horizons, although the presence of Ae horizons is not necessary. Plant growth on these soils is better than on poorly developed soils, partly because of larger nutrient pools and lower levels of toxic metals such as Ni.

The late stages of ultramafic pedogenesis are characterized by the disappearance of serpentine minerals, and the presence of very high Fe_d levels (20

percent or more of the soil mass). In this stage (Oxisols), significant quantities of Fe, Al, and Cr may be present in the surface horizons due to negative enrichment, and Co and Ni may be enriched in a subsurface zone well below the solum.

2.5 PEDOGENESIS OF TEPHRA-DERIVED SOILS

Tephra is a general term for pyroclastic fall and flow materials produced by volcanoes. Tephra includes various particle sizes such as ash (< 2 mm) and lapilli (2 to 64 mm). Tephra may have variable chemical compositions as well, including rhyolite (> 70 percent SiO₂), dacite (64 to 70 percent SiO₂), and basalt (< 50 percent SiO₂) (Shoji, 1986).

The nature of volcanic soils depends largely on the distribution and properties of the tephra from which they are derived. Tephra often occurs as composite deposits due to intermittent periods of volcanic activity. Lateral variations in particle size and mineralogy also occur because large, heavy particles fall close to the source, while smaller and lighter particles are carried further away by winds. The most important constituent of tephra is volcanic glass, which is an amorphous aluminosilicate that is very susceptible to weathering. Feldspar, amphibole, pyroxene and other minerals may also be present as phenocrysts, but the small amounts and relative stability of these minerals compared to volcanic glass limit their importance in pedogenesis of tephra-derived soils.

Otowa (1986) described two main groups of volcanic soils in Japan. Volcanogenous Regosols and Ando soils are differentiated based on the degree of development of the A horizon. Volcanogenous Regosols are tephra-derived soils

with weakly developed A horizons, having low levels of organic carbon, and low phosphate absorption coefficient (indicating low levels of short range order materials such as allophane). Ando soils are tephra-derived soils having high organic carbon content, low bulk density, high phosphate absorption coefficient and very high cation exchange capacity (CEC).

Ando soils form when volcanic glass alters rapidly in the presence of soil organic matter (Mizota and van Reeuwijk, 1989). Iron and Al released during weathering are bound into stable organic complexes, and Al may precipitate with Si to form allophane and imogolite. Soil organic matter is stabilized against decomposition by the presence of Al, even if the Al is part of allophane associated with organic matter in a clay-organic complex. Ando soils only form in environments where the soil is continuously moist because the clay-organic complex and short range order clays are irreversibly altered upon drying.

For soil classification, the unique features of Ando soils are defined in terms of Andic soil properties, which specify an upper limit for bulk density, as well as minimum values for Al_0 and Fe_0 , phosphate retention, and presence of volcanic glass in the less than 2 mm fraction of the soil material (Mizota and van Reeuwijk, 1989).

While the Volcanogenous Regosols and Ando soils described by Otowa represent two extremes of soil development on tephra, slightly weathered tephra soils (Brunisols; Inceptisols) have been described in North America. Sneddon (1973) described a Dystric Brunisol derived from Bridge River tephra (2350 years old). This soil had a weak granular structure, low bulk density, and low clay content

indicating that minimal weathering of the tephra had occurred in the cold, continental climate. The CEC of the tephra-derived Brunisol was primarily associated with soil organic matter, and Andic properties associated with the weathering products of volcanic ash were poorly expressed.

Fosberg et al. (1979) described Inceptisols developed in Mazama ash (6600 years old) with moderate expression of Andic soil properties such as high CEC, organic C, and estimated allophane (based on high pH in NaF). The presence of fragipans in soils buried by volcanic ash or loess was observed in these soils, but no evidence linking the development of the fragipans to the presence of volcanic ash was obtained.

The Canadian System of Soil Classification (Agriculture Canada, 1987) distinguishes tephra-derived soils at the family level of soil classification. Ashy and Cindery soil families have at least 60 percent content of volcanic ash (< 2 mm) and/or cinders (> 2 mm). Recent proposals (ICOMAND, 1988) for the establishment of the Andisol order in Soil Taxonomy (Soil Survey Staff, 1975) provide for classification based on the presence of Andic soil properties.

2.6 CLASSIFICATION OF ULTRAMAFIC SOILS

Ultramafic soils may be found classified as Regosols (Entisols), Brunisols (Inceptisols), Luvisols (Alfisols, Ultisols), Gleysols, and Podzols (Spodosols), as well as various types of laterites (Oxisols). They are thus widely distributed. Despite their unique properties, only recently has consideration been given for improved

classification at higher (Alexander, 1991) and lower (Alexander, 1985) levels of classification.

At the order level, the criteria for Spodosols require that they have $(Fe_p + Al_p)/Fe_d$ greater than 0.5, which eliminates most ultramafic soils because they generally have high levels of Fe_d. Alexander (1991) recommended changes to Soil Taxonomy (Soil Survey Staff, 1975) which would allow the classification of ultramafic soils as Spodosols. This restriction does not affect Podzolic soils in the Canadian System of Soil Classification (Agriculture Canada, 1987), and Podzolic ultramafic soils occur in Canada.

Soil Taxonomy (Soil Survey Staff, 1975, p. 387) recognizes a serpentinitic mineralogy class which includes all soils with greater than 40 percent serpentine and talc in the < 2 mm fraction. Serpentinitic families are separated after carbonatic, ferritic, gibbsitic, and oxidic classes in the key to mineralogy classes.

Alexander et al. (1985) considered low fertility to be the most important characteristic of ultramafic soils from the perspective of soil classification, and these authors recommended the expansion of the serpentinitic mineralogy class to include all ultramafic soils. The proposed changes to the serpentinitic mineralogy class include: (i) renaming the serpentinitic class the ultramafic class and adding olivine, orthopyroxene, brucite, magnesite, hydromagnesite, and lithogenic chlorite to the list of diagnostic minerals, (ii) changing the determinant size fraction to the coarse silt and sand fractions (0.02 to 2 mm) only, (iii) decreasing the percentage of diagnostic minerals required in the coarse silt and sand fraction to 15 percent, (iv) adding an exchangeable Ca:Mg ratio criterion which must be less than 0.7, and (v)
changing positions in the key to mineralogical classes to include ultramafic soils that now fall in the oxidic class in the ultramafic class. These authors suggested that the presence of olivine versus serpentine may be used as a series criterion.

Soils containing more than 40 percent serpentine and talc in the less than 2 mm fraction are classified in the serpentinitic class at the family level in the Canadian System of Soil Classification (Agriculture Canada, 1979; p 119). Serpentinitic families are separated after carbonatic families in the key to mineralogy classes.

3. WEATHERING STATUS AND GEOCHEMISTRY OF ULTRAMAFIC SOILS IN SOUTHWESTERN BRITISH COLUMBIA AND NORTHWESTERN WASHINGTON STATE

3.1 INTRODUCTION

Ultramafic soils have been studied in diverse climate regions, but few studies have attempted to correlate their weathering status and geochemical properties with medium range differences in the regional climate. In British Columbia there is tremendous climatic diversity among areas which occur relatively close to one another, and numerous ultramafic rock associations are present, partly because the province is constructed of many small microcontinents with various geological origins (Yorath, 1990). For these reasons, southwestern British Columbia offers excellent opportunities to investigate ultramafic soils at an early stage of development in areas of diverse climate.

The objectives of this portion of the thesis research were to compare the weathering status and geochemistry of ultramafic soils developed along a transition from relatively wet-cool to relatively dry-cool climate. In addition, the partitioning of major pedogenic elements, Cr, Mn, Co and Ni in the soil materials was investigated in order to gain information on the processes affecting element mobility and retention in weakly and moderately developed ultramafic soils.

3.2 COMPARISON OF STUDY AREAS

Figure 3.1 shows the location of the four study areas. The Shulaps, Coquihalla and Tulameen areas are located within southwestern British Columbia, while the Twin Sisters area is located in northwestern Washington State. Within the Coast Mountain area, the Shulaps Range is included among the Chilcotin Ranges, part of the Coast Mountains, and the Coquihalla serpentine belt is located within the Hozameen Ranges, part of the Cascade Mountains (Holland, 1976). The Twin Sisters area is located in the Cascade Mountains of Washington State. The Tulameen ultramafic complex is included within the Thompson Plateau, part of the Interior Plateau of the Southern Plateau and Mountain Area.

3.2.1 Environmental setting

3.2.1.1 climate.

Table 3.1 provides precipitation and temperature data for the four study areas (Lloyd et al., 1990; Meidinger and Reynolds, 1990; Douglas, 1969). The regional climate is characterized by mild and dry summers with a northwesterly flow associated with high pressure systems that dominate the northeastern part of the Pacific Ocean. In winter, cyclonic storms embedded in the atmospheric flow across the Pacific deliver large amounts of precipitation (Jackson, 1985). Climatic diversity is largely attributable to the Coast Mountains in southwestern British Columbia and the Cascade Mountains in northern Washington State. These mountain ranges create an east-west moisture divide and isolate the high elevation interior of the region from the moderate temperatures of the Pacific Ocean. Precipitation and



Figure 3.1. Location of the study areas within southwestern British Columbia and Washington State.

Climate		Twin Sisters	Coqui- halla	Olivine Mt.	Grass- hopper	Shulaps (high)	Shulaps (low)
Mean annual precipitation (mm):		2800	2023	839	606	766	438
Growing se precipitatio	ason on (mm):			296	267	251	193
Annual sno	wfall (cm):				307		155
Mean annu temperatur (^O C):	al e	4.5	5.3	-0.2	2.8	0.8	3.4
Mean grow temperatur	ing season e (⁰ C):			8.0	10.2	7.9	11.1
Mean minit temp (^o C):	mum January			-14.1	-12.5	-14.9	-13.1
Mean frost (days):	free period				85	9	86
Site elevati	on (m.a.s.l.):	970	950	1730	1260	2150	1410
Biogeoclimatic unit: ¹			CWH ms	ESSF dc2	MS dm2	ESSF dv	IDF dk1
Sources:	Twin Sister Coquihalla Olivine Mt	'S: : .:	D M L	ouglas (19 leidinger a loyd et. al.(69) from 1 nd Reyno (1990), p 6	Mt. Baker. Ids (1990). 57.	

Table 3.1: Environmental characteristics of study areas.

Sources:Twin Sisters:Douglas (1969) from Mit. Baker.Coquihalla:Meidinger and Reynolds (1990).Olivine Mt.:Lloyd et. al.(1990), p 67.Grasshopper Mt.:Lloyd et. al.(1990), p 53.Shulaps high elevation:Lloyd et. al.(1990), p 67.Shulaps low elevation:Lloyd et. al.(1990), p 47.

1 Lloyd et al. (1990) gives descriptions of the biogeoclimatic units.

temperature gradients are also induced along the steep slopes of the Cascades and the Coast Mountains, and site microclimates are strongly associated with topographic position.

The Twin Sisters and Coquihalla areas have coastal climatic regimes, with winter maximum precipitation, mild winters and cool summers. The Tulameen and Shulaps areas are transitional to a continental climate, with more extreme summer maximum and winter minimum temperatures, lower annual precipitation, and a smaller proportion of the total precipitation occurring in the winter months.

The climatic characteristics presented for the Twin Sisters site were derived from a compilation of 30 years of data (1920's to 1950's) from a climate station at approximately 1250 m.a.s.l. on Mount Baker (Douglas, 1969). The soil profiles investigated in this study were at 970 m.a.s.l., so the site microclimate may be slightly warmer and drier than the climate at the weather station. This area has the highest mean annual precipitation of the study areas, and much of the precipitation occurs as snow.

Climate data for the Coquihalla site were obtained from a short term climate station operated by the B.C. Ministry of Environment on Ogilvie Mountain., approximately 15 km south of the sampling area (Meidinger and Reynolds, 1990). The elevation of the study site and the climate station were similar, and these data are considered representative of conditions at the study site. The Coquihalla area has the highest mean annual precipitation of the study areas within British Columbia. Orographic enhancement of precipitation occurs as cyclonic storms move eastward and the associated airmasses rise to cross the Hozameen Ranges. Large

Weathering Status and Geochemistry of Soils

accumulations of snow are received in the Coquihalla area during the winter season. The Coquihalla area also has the warmest mean annual temperature of all of the study areas, largely due to the moderating influence of the Pacific air masses in winter.

Climate data for the Tulameen and Shulaps areas were extracted from information on biogeoclimatic units established by the B.C. Ministry of Forests (Lloyd et al., 1990). These data represent approximate values based on climate data from various regional sources which were adjusted to account for the effects of elevation and aspect. The Tulameen ultramafic complex is located 30 km east of the Coquihalla area, in the rainshadow of the Hozameen Ranges. The Tulameen area has a drier, cooler climate than the Twin Sisters and Coquihalla areas. Site aspect and topography strongly influence the soil environment. The Grasshopper Mountain site was located at a lower elevation than the Olivine Mountain site and had a south aspect, accounting for the lower annual precipitation and slightly higher mean annual temperature.

The major features of the climate of the Shulaps area are the tremendous topographic variation and the generally dry conditions, particularly at the lower elevations. The Shulaps Range occurs in the rainshadow of the Coast Mountains. The low elevation Shulaps site is the driest of the four areas investigated in this study. Valley bottoms in the Shulaps area have high summer maximum temperatures.

3.2.1.2 vegetation.

A brief description of the major tree species and some associated species was recorded at each sampling location, but no detailed vegetation surveys were carried out during this study.

The Twin Sisters and Coquihalla sites were both occupied by forests of yellow cedar (<u>Chamaecyparis nootkatensis</u>), Amabilis fir (<u>Abies amabilis</u>) and western hemlock (<u>Tsuqa heterophylla</u>). The Tulameen area was covered by forests of lodgepole pine (<u>Pinus contorta var. latifolia</u>) and Douglas fir (<u>Pseudotsuga menziesii</u>) at the lower elevations, with whitebark pine (<u>Pinus albicaulis</u>) and subalpine fir (<u>Abies lasiocarpa</u>) at higher elevations. The Shulaps area was covered with forests of Douglas fir, ponderosa pine (<u>Pinus ponderosa</u>) and associated species at the lower elevations, which gave way to subalpine fir, lodgepole pine, whitebark pine, and Engelmann spruce (<u>Picea engelmannii</u>) at the mid elevations, and alpine tundra above the treeline. Treeline occurred at approximately 2300 m over most of the Shulaps area.

3.2.2 Geological setting

Ultramafic soils are found in several areas associated with the Fraser fault system of British Columbia. Many of these occurrences are very small, and/or the surficial materials are the mixed products of recent glaciation, especially at the lower elevations. Soils derived only from ultramafic parent materials were more common at higher elevations, where ice cover was thinner and glacial transport tended to be more localized.

The Twin Sisters ultramafic body in northwestern Washington State consists of dunite and peridotite. The area was affected by recent glaciation, and close inspection of the sand fraction revealed that the surficial material had mixed lithology.

In the southern portion of the Fraser fault system, the Coquihalla serpentine belt follows the Hozameen fault system for over 50 km, and includes a continuous unit approximately 15 km long and as wide as 2 km in outcrop. (Ray, 1986). The ultramafic rocks are part of a tectonically disrupted ophiolite complex. The lithology consists of dark, highly sheared and massive serpentinites presumably derived from peridotite and dunite. The serpentinite was dominantly lamellar antigorite and massive lizardite, with trace amounts of chrysotile.

The Tulameen ultramafic complex is an example of an Alaskan-type ultramafic deposit, and displays a crude zonation with a dissected dunitic core (Olivine Mountain and most of Grasshopper Mountain) surrounded by concentric shells of olivine clinopyroxenite, hornblende clinopyroxenite, and gabbroic rocks (Nixon and Rublee, 1987). The degree of serpentinization observed in the Tulameen complex was lowest near the summit of Olivine Mountain, while materials from Grasshopper Mountain consisted of approximately 80 percent serpentine (White, 1986). Surficial materials on Grasshopper Mountain included a blanket of till and colluvium. The summit area of Olivine Mountain had features typical of old weathering surfaces, and appeared to have escaped deposition of exotic materials during the most recent glaciation.

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The geology of the Shulaps range was investigated by Leech (1953), who delineated the Shulaps ultramafic complex and described the dominant rock type as serpentinized harzburgite, with associated dunite and enstatite pyroxenite. The degree of serpentinization of the Shulaps rocks was relatively uniform, and the common products were fibrous serpentine and serpophite combined in mesh textures, along with bastite. The mesh-textured serpentines were thought to be forms of chrysotile, while the bastite may be a form of antigorite which formed by pseudomorphic replacement of olivine (Leech, 1953). Schiarizza et al. (1988) described the ultramafic rock association as part of a dismembered ophiolite complex.

The Shulaps Range is located 80 km east of the source of the Bridge River tephra at Mt. Meager. Mathewes and Westgate (1980) dated the eruption at 2350 years ago. The tephra deposited on the Shulaps Range consisted of pea-sized pumice and sand-textured ash. The tephra was of dacitic composition, and was redistributed by wind and water after deposition. It presently comprises the parent material for modern soils varying from less than 15 cm to greater than 75 cm in thickness, overlying most of the ultramafic paleosols of the Shulaps Range.

3.3 MATERIALS AND METHODS

3.3.1 Site descriptions and Profile characteristics

Table 3.2 gives site and profile information for the six soils used in the study. Complete profile descriptions for these and some associated soils are presented in Appendix 1. The rationale used for field site selection is described in Appendix 2.

Table 3.2 Ho	orizon dept	hs (cm), parent materials, and descriptions: ultramafic soils.				
TWIN SISTERS (Profile 20): till with mixed lithology.						
LFH	7 - 0	moder forest floor				
Ae	0 - 4	light gray; loam				
Bf1	4 - 10	light yellowish brown; sandy loam.				
Bf2	10 - 25	very pale brown; sandy loam; 40% coarse frags.				
BC	25 - 33	light yellow brown; sandy loam; 40 % coarse frags.				
COQUIHAI	LLA (Profi	le 34): ultramafic till.				
FH	1 - 0	mor humus form				
Bf1	0 - 10	brown; loam; 20 % coarse frags.				
Bf2	10 - 30	light yellow brown; sandy loam; 20 % coarse frags.				
Bf3	30 - 45	very pale brown; sandy loam; 25 % coarse frags.				
BCc	45 - 70	light yellow brown; sandy loam; 30 % coarse frags.				
TULAMEE	N (Olivine	Mt., Profile 13): dunitic residuum.				
Bm1	0 -15	dark reddish brown; sandy loam.				
Bm2	15 - 20	dark brown; sand.				
BC	20 - 26	dark yellowish brown; sand.				
R	26 +	dark yellowish brown; weathered dunite.				
TULAMEE	N (Grassho	opper Mt., Profile GMDRY): ultramafic till.				
Bm	0 - 17	dark grayish brown; loamy sand; 20 % coarse frags.				
BC	17 - 26	dark grayish brown; loamy sand; 20 % coarse frags.				
С	26 +	grayish brown; sandy loam.				
SHULAPS H	ULAPS HIGH ELEVATION (Profile 3): tephra and ultramafic till.					
LF	2 - 0	fibrous leaf litter.				
Bm1	0 - 15	olive brown; sand; tephra.				
C1	48 - 55	olive; loamy sand; tephra.				
IIBm1b	62 - 66	dark yellowish brown; silt loam; 5 % coarse frags.				
IIBm2b	66 - 85	dark yellowish brown; silt loam; 50 % coarse frags.				
IIC	100 +	olive; loam; 50 % coarse frags.				
SHULAPS LOW ELEVATION (Profile 31): tephra and ultramafic till.						
LF	15	forest floor.				
H	.5 - 0	dark gray humic material.				
Bm	0 - 6	light brownish gray; loamy sand; tephra.				
С	6 - 20	light gray; loamy sand; tephra.				
IIBm1b	20 - 28	yellowish brown; loam; 10 % coarse frags.				
IIBm2b	28 - 40	light olive brown; sandy loam; 30 % coarse frags.				
IIC	40 - 100	olive; sand; 95 % ultramafic coarse frags.				

The Twin Sisters soil had well developed Ae and Bf horizons, typical of Podzolic soils in the Coast Mountains. The soil was classified as an Orthic Humo-Ferric Podzol (Agriculture Canada, 1987).

The Coquihalla soil had a well developed Podzolic B horizon, but lacked an Ae horizon. Lewis (1976) observed that Podzols developed in fine grained basic parent materials such as andesite and basalt on Vancouver Island generally lacked Ae horizons. Where coarse grained quartz was present in the Vancouver Island parent materials, Ae horizons were frequently present, although disruption of Ae horizons by biotic pedoturbation, slope processes and biocycling was widespread. Lewis attributed the formation of Fe- and Al-rich B horizons to negative enrichment via loss of Si and base cations.

Indurated BCc and Cc horizons (duric horizons) were observed in the Coquihalla soil. Duric horizons are impermeable to roots and have very low hydraulic conductivity. The Coquihalla soil was classified as a Duric Humo-Ferric Podzol (Agriculture Canada, 1987).

The profiles from the Tulameen area had reddish brown Bm horizons, and were underlain by shallow transitional horizons. Discontinuous forest floors were present over a small proportion of the surface at both study sites, but were not sampled. These soils did not show the depth of profile development observed in the Twin Sisters and Coquihalla soils. The Grasshopper Mountain soil was sampled during a study of Pt geochemistry (Cook, 1991; profile 65). Weakly developed soils were commonly observed and formed in till and colluvium parent materials derived from partly serpentinized dunite. The soils on Grasshopper Mountain and on

Olivine Mountain were classified as Orthic Eutric Brunisols (Agriculture Canada, 1987).

The Shulaps soils had composite profiles consisting of 60 cm (high elevation site) and 20 cm (low elevation site) of tephra over serpentinized peridotite. The modern-day soils and the underlying ultramafic-derived paleosols both had weakly developed Bm or Bfj horizons with slight accumulations of organic C near the surface. The two Shulaps soils included in this portion of the study were classified as Orthic Dystric Brunisols (Agriculture Canada, 1987).

3.3.2 Sample preparation and Methodology

Samples were air dried, and material finer than 2 mm was separated with a stainless steel sieve and used for analysis. The following methods were used (method numbers from McKeague, 1978): particle size by sieve analysis (> .053 mm) followed by hydrometer on < .053 mm fraction, without removal of Fe oxides (2.121); total C by Leco induction furnace (3.611); exchangeable cations by ammonium acetate at pH 7 (3.32 modified); exchangeable acidity by KCl and titration with NaOH, and determination of Al by atomic absorption spectroscopy (AAS) (modified from Thomas, 1982); pH in H₂O (modified from MacLean, 1982); extractable Fe, Al, etc. with dithionite-citrate-bicarbonate (DCB; reported as Fe_d, Al_d, etc.) on unground samples (3.51), acid ammonium oxalate in the dark (AOD; reported as Fe_o, Al_o, etc.) on samples ground to pass 100 mesh (3.52), and Na-pyrophosphate (PYRO; reported as Fe_p, Al_p, etc.) on samples ground to pass 100 mesh. Solutions were analyzed for metals and Si by AAS or inductively coupled plasma atomic emission spectroscopy (ICP-AES).

Clay separations for mineralogical analysis with X-ray diffraction (XRD) were performed after treatment with DCB to remove free Fe oxides. Samples high in organic matter were treated with H_2O_2 . Mineralogy of the clay fractions was determined using a Philips X-ray diffractometer operating at 40 kV and 20 mA and providing Cu K alpha radiation. XRD patterns were obtained for Mg- and Ksaturated clay samples smeared onto glass slides as a paste (McKeague, 1981, method 5.22). Mineralogy of some silt and fine sand fractions was also determined by XRD, using powder mounts. Semi-quantitative estimations of relative abundance of clay minerals were based on peak height.

The use of both ethylene glycol (EG) and glycerol (GLY) solvation treatments of Mg-saturated clays aids in distinguishing high-charge smectite (transitional to vermiculite) from low-charge smectite (montmorillonite). Highcharge smectite may not form a two-layer complex with glycerol (1.8 nm spacing), but will form a two-layer complex with ethylene glycol (1.7 nm spacing). Low-charge smectite forms two-layer complexes with both glycerol and ethylene glycol (MacEwan and Wilson, 1980). K-saturated clays were analyzed at ambient conditions (K), after heating to 300 °C for 4 hours (K300), and after heating to 550 °C for two hours (K550).

Diffractograms of soil clays were interpreted as follows: serpentine (0.73 nm peak for all treatments), chlorite (1.4 nm peak for all treatments, and 0.71 nm peak for all treatments except reduced height for K550 treatment); expanding chlorite (1.7 nm peak for EG treatment, and 1.4 nm peak for K550 treatment); talc (0.94 nm peak for all treatments); low-charge smectite (1.8 nm peak for GLY treatment, broad 1.2 nm peak for K treatment, and 1.0 nm peak for K550 treatment); hydroxy-

interlayered (HI) vermiculite (1.4 or 1.7 nm peak for EG treatment, 1.4 nm peak for GLY treatment, broad 1.2 nm peak for K300 treatment, and 1.0 nm peak with broad tail for K550 treatment): high-charge smectite (1.4 nm peak for GLY treatment, 1.7 nm peak for EG treatment, and 1.0 nm peak for K550 treatment).

For geochemical analyses, the fine earth (< 2 mm) was dispersed using ultrasonic dispersion, and the clay (< .002 mm) and very fine sand fractions (.05 to .10 mm) were separated by gravity sedimentation and sieving. Samples for geochemical analysis were not subjected to any chemical pretreatments, except for the flocculation of clays using NH_4Cl .

Total elemental analysis of oven dried (105 °C) clay and very fine sand fractions was determined by X-ray fluorescence spectroscopy (XRF) using the following ultramafic materials as standards (Abbey, 1983): PCC-1; peridotite from Sonoma County, California, USA (US Geol Survey), UB-N; serpentinite from France (ANRT), NIM-P; pyroxenite from the Bushveld complex, South Africa (NIM), DTS; dunite from Hamilton, Washington, USA (US Geol. Survey).

XRF analyses were performed in the Dept. of Oceanography at UBC according to the procedure of Calvert et al. (1985). The method involved preparation of fused glass disks for major elements, while pressed pellets were used for minor elements. The disks and pellets were analyzed on an automated Philips PW 1400 X-ray fluorescence spectrometer.

Estimated loss on ignition (LOI) values were also obtained during the preparation of fused glass disks for the XRF analysis. LOI was based on the weight loss of the oven dried sample (0.6 gram) plus flux (3.6 grams) mixture after heating to 1100 $^{\circ}$ C, assuming that the weight loss came from the sample only (i.e. that the flux mixture lost no weight). Comparison of the resulting LOI values with the expected values for the ultramafic standards (based on H₂O and CO₂ content from Abbey, 1983) indicated that this method resulted in a consistent overestimation of four to six percent in LOI. As the LOI values were not used in further calculations, and the element oxide percentages determined by XRF closely reproduced the expected values for the standard materials (Abbey, 1983), the results for LOI were considered to be sufficiently accurate for this work.

Density separation of very fine sand grains was achieved with the non-toxic heavy liquid Na-polytungstate, adjusted to a density of 2.90 Mg m⁻³ by either diluting the liquid (maximum specific gravity near 3.20 Mg m^{-3}) with water, or concentrating it by evaporation. About 20 ml of heavy liquid and 5 grams of washed very fine sand were added to a 50 ml conical centrifuge tube, and the tube was shaken by hand to suspend the sand grains. The tube was then centrifuged at 200 g for five minutes to separate the light and heavy fractions. Liquid nitrogen was used to solidify a plug of Na-polytungstate containing the heavy minerals at the bottom of the tube, and the light mineral fraction was decanted from the top.

Selective dissolution analysis was performed on clay and very fine sand fractions with DCB, AOD, and PYRO and the solutions were analyzed for Fe, Al, Si, Cr, Mn, Co and Ni. A sequential extraction technique was also applied to some of the clay samples selected for geochemical analysis. This procedure involved

extraction of a known weight of sample with PYRO followed by extraction of the residue with AOD. The residue from the AOD extraction was dried and a subsample was then extracted with DCB. The weight loss of the sample after PYRO extraction was calculated from the weight loss of duplicate samples. The weight of sample used for calculation of elements extracted with AOD and DCB was corrected to account for the weight loss during the previous extractions. Since XRD analysis indicated that chlorite was a dominant clay mineral, a subsample of the DCB residue was heated to 600 °C for 4 hours (Ross and Kodama, 1974) and then extracted with 0.2 N HCl to destroy the interlayer hydroxide sheet of the chlorite structure. The solution was analyzed for Fe, Al, Si, Cr, Mn, Co, and Ni by AAS to determine the composition of the interlayer hydroxide sheet.

3.4 RESULTS AND DISCUSSION

3.4.1 Particle size analysis

Results of particle size analysis for the soil materials are presented in Figures 3.2, 3.3, and 3.4. All of the soils had low clay content (< 20 percent), and no evidence for clay translocation was found. For these soils in the early to mid stages of pedogenesis, the particle size characteristics were largely inherited from the parent materials.

A common feature of the particle size distributions for the soils was a higher silt and clay content in the surface horizons compared to the parent materials, which may be attributed to mineral weathering and/or eolian additions. Particle size reduction by mineral weathering would be indicated by a gradual increase in the content of finer fractions from the parent materials to the surface horizon. In contrast, tephra additions would increase the silt and very fine sand content for the surface horizon only.

The overall form of the particle size distribution curves for the Twin Sisters soil (Fig. 3.2) was typical for locally derived glacial till materials (poorly sorted), and the low clay content indicates that these parent materials were relatively . unweathered prior to transport and comminution by glacier ice. Weathering likely resulted in particle size reductions in the solum, and eolian additions were also received in the surface horizon.

The particle size distribution curves for the Coquihalla soil materials were very similar to those for the Twin Sisters soil. The silt and clay content declined from the Bf1 to the Bf2, Bf3 and BC, indicating that breakdown of mineral grains by weathering had occurred to a greater extent in the upper solum. The similar shape of the particle size distribution curves in the upper solum indicates that this soil developed in a uniform parent material.

The Olivine Mountain soil materials had lower silt content than the Twin Sisters and Coquihalla soils, and consisted primarily of sand with minor amounts of silt and clay in the surface horizons. Mineral weathering and eolian additions likely resulted in the higher silt content in the upper solum.

Figure 3.3 shows that soil materials derived from the Bridge River tephra consisted mostly of sand. In contrast, the particle size distribution curves for ultramafic materials from the Shulaps high elevation site at Blue Creek had a



Figure 3.2. Particle size distribution for ultramafic soil materials.



Figure 3.3. Particle size distribution for tephra derived soil and ultramafic paleosol from Shulaps high elevation site at Blue Creek.

sigmoidal shape, which indicates a normal distribution of particle sizes around a mean diameter of about 0.04 mm. The material consisted of glacial rock flour produced from the intense grinding of a uniform source rock during transport by glacier ice. In addition, the similar sand content of samples from the IIBm1b, IIBm2b and IIBm3b horizons indicates that there was very little mixing of serpentinitic materials and the coarse-textured tephra.

Figure 3.4 shows that the tephra-derived soil at the low elevation Shulaps site (Barren Valley) also consisted of sand, while the ultramafic materials had a similar particle size distribution to the till-derived materials in the Coquihalla soil. This profile had a discontinuity below one meter, where coarse-textured ultramafic materials derived from fractured bedrock were present.

In this study, particle size analysis was performed without removal of iron oxides. The DCB pretreatment dissolves Fe oxide cementing agents, enhancing the dispersion of clay-sized particles (Jackson, 1956). Particle size analysis without DCB pretreatment provided data which are representative of natural soil conditions, providing more reliable insights into properties such as soil drainage and aeration.

3.4.2 Soil chemical properties

Table 3.3 presents selected chemical properties for the soils. The amounts of exchangeable K⁺ and Na⁺ were very low for all mineral soil samples. Additional



Figure 3.4. Particle size distribution for tephra derived soil and ultramafic paleosol from Shulaps low elevation site at Barren Valley.

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HORIZON	SAMPLE	EXCHANGEABLE CATIONS (cmol kg ⁻¹)				pН	ORG	
	NO.	Ca	Mg H ⁻	$+ + Al^{3+}$	SUM	Ca:Mg	H ₂ O	C%
TWIN SIST	ERS:							
LFH	(110)	11.3	10.7	8.0	30.0	1.06	4.4	35.5
Ae	(111)	0.3	0.6	10.9	11.8	0.54	4.2	1.4
Bf1	(112)	0.1	0.3	6.4	6.8	0.42	4.9	3.5
Bf2	(113)	0.0	0.1	4.2	4.4	0.33	4.9	1.7
BC	(114)	0.1	0.1	0.4	0.5	1.21	5.4	0.7
С	(115)	0.1	0.0	0.3	0.4	1.82	5.4	0.2
COQUIHA	L LA:							
LFH	(201)	2.5	2.2	1.0	5.7	1.11	5.4 ·	27.1
Bf1	(202)	0.6	4.8	0.2	5.6	0.12	5.7	2.1
Bf2	(203)	0.4	4.8	0.3	5.5	0.09	5.9	1.3
Bf3	(204)	0.4	4.2	0.1	4.7	0.10	6.0	0.7
BCc	(205)	0.4	3.9	0.1	4.4	0.10	6.2	0.4
Cc	(206)	0.4	4.8	0.0	5.2	0.09	6.6	0.1
TULAMEE	N (Olivine	Mountair	n):					
Bm1	(92)	1.0	5.3	0.1	6.3	0.18	6.3	1.5
Bm2	(93)	0.4	2.6	0.0	3.0	0.14	6.2	0.6
BC	(94)	0.1	1.3	0.0	1.4	0.07	6.6	0.2
TULAMEE	N (Grassh	opper Mo	untain):					
Bm	(5)	1.7	5.1	n.d	7.0	0.34	6.2	1.6
BC	(6)	0.5	7.3	0.2	8.0	0.07	6.7	0.5
С	(7)	0.7	14.5 ^{°°}	0.1	15.3	0.05	6.8	0.4
SHULAPS (Blue Cree	k):						
LFH	(19)	14.4	21.4	4.0	39.8	0.67	4.8	39.0
Bm1 tephra	(20)	0.3	1.7	0.1	2.1	0.20	5.9	0.5
Bm2 tephra	(21)	0.1	0.6	0.0	0.7	0.17	6.1	0.1
C1 tephra	(22)	0.1	0.4	0.0	0.5	0.29	6.1	0.1
C2 tephra	(23)	0.1	0.2	0.0	0.3	0.36	6.2	0.0
IIBm1b	(24)	0.7	6.4	0.0	7.1	0.11	6.2	0.6
IIBm2b	(25)	0.6	7.1	0.0	7.7	0.09	6.3	0.3
IIBm3b	(26)	0.6	8.1	0.0	8.7	0.07	6.6	0.2
IIC	(27)	0.5	6.7	0.0	7.2	0.07	0.8	0.1
SHULAPS (Barren Va	alley):						
LF	(189)	3.0	2.7	1.9	7.6	1.10	5.1	35.6
H	(190)	1.4	1.4	0.9	3.7	1.04	5.3	17.4
Bm tephra	(191)	1.4	2.9	0.1	4.4	0.48	0.0	0.9
C tephra	(192)	0.7	0.8	0.2	1.7	0.85	5.9	0.4
IIBm1b	(193)	1.2	16.3	0.0	17.5	0.08	0./	0./
IIBm2b	(194)	0.7	20.2	n.d	21.1	0.04	0.8	0.5
IIC	(195)	0.5	15.8	0.0	16.4	0.03	0.0	0.3
IIIC	(196)	0.2	6.1	n.d	0.3	0.03	1.5	0.2

Table 3.3 Chemical properties of ultramafic soils.

chemical information for these soils, and for some associated soils is presented in Appendix 1.

Soil samples from the Coquihalla and Tulameen areas, and from the ultramafic paleosols at the Shulaps area had low exchangeable Ca:Mg ratios, which is typical for soils derived from ultramafic parent materials (Alexander et al., 1985). The Twin Sisters profile had very low levels of exchangeable Ca²⁺ and Mg²⁺ in the lower solum, making interpretation of the Ca:Mg ratio difficult.

Exchangeable acidity in the form of H⁺ and Al³⁺ comprised insignificant amounts of the sum of exchangeable cations for the ultramafic-derived soils from the Coquihalla, Tulameen, and Shulaps areas. Forest floor samples had higher levels of exchangeable acidity, accounting for up to 25 percent of the sum of exchangeable cations. In contrast, exchangeable acidity accounted for up to 95 percent of the sum of cations in the Twin Sisters soil, and over 85 percent of the exchangeable acidity in the Twin Sisters Ae and Bf1 horizons occurred in the form of Al³⁺. Graham et al. (1990) observed that exchangeable Al³⁺ levels were higher for soils of non-ultramafic origin than for ultramafic soils.

In this study, exchangeable acidity was determined using unbuffered KCl, representing the acidity which is released at the "natural" soil pH. Higher levels of exchangeable acidity, reflecting the total "potential" acidity would probably be measured using the $BaCl_2$ triethanolamine method (Thomas, 1982), which is buffered at pH 8.2.

The ultramafic parent materials had near-neutral pH values. The pH values in the upper solum were moderately acid for the Coquihalla soil, while the Barren Valley soil had a near-neutral pH in the IIBm1b horizon, reflecting the lower intensity of weathering and leaching in the dry environment at the Shulaps low elevation site.

The Twin Sisters soil had pH values about one unit lower than those for the Coquihalla soil throughout the solum, which may reflect parent material differences between these two soils from high intensity leaching and weathering environments.

The organic C content of the B horizons also reflected the soil environment, with the Twin Sisters and Coquihalla soils having higher levels than the Shulaps soils, and the Tulameen soils were intermediate.

3.4.3 Very fine sand mineralogy

3.4.3.1 density separation

Results of heavy liquid separations for selected samples are presented in Table 3.4. The density of the Na-polytungstate liquid was 2.90 Mg m⁻³. Deer, Howie, and Zussman (1982) list mineral densities which indicate that quartz (2.65 Mg m⁻³), serpentine (2.55 Mg m⁻³), talc (2.58-2.83 Mg m⁻³), and some chlorites (2.80-3.06 Mg m⁻³; Mg-rich chlorites have densities in the lower portion of this range) should float in the liquid. Heavy minerals such as enstatite (3.21 + Mg m⁻³), forsterite (3.22 + Mg m⁻³), chromite (4.00 + Mg m⁻³) and magnetite (4.00 + Mg m⁻³) should sink.

	LIGHT %	HEAVY %
COOLIHALLA		
Bf1	84	16
Cc	91	9
TULAMEEN (Olivine Mountain):		
Bm1	11	89
BC	1	99
TULAMEEN (Grasshopper Mountain): Bm	55	45
SHULAPS (Blue Creek):		
IIBm1b	53	47
IIC	57	43
SHULAPS (Barren Valley):		
Bm (tephra)	87	13
IIBm1b	74	26
IIC	89	11

Table 3.4: Results of heavy liquid separation of very fine sand fractions from ultramafic soils.

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In general the minerals found in the light fraction are the products of serpentinization, along with quartz and feldspars introduced as eolian additions or present in porphyritic bodies within ultramafic massifs. Unserpentinized minerals characteristic of ultramafic rocks, and magnetite are found in the heavy fraction.

The very fine sands from the Coquihalla and Barren Valley sites consisted mostly of light minerals, indicating that these ultramafic parent materials were highly serpentinized. The samples from Blue Creek and Grasshopper Mountain had about equal amounts of light and heavy minerals, indicating a moderate degree of serpentinization. The very fine sands from Olivine Mountain consisted predominantly of heavy minerals, which is consistent with studies of the degree of serpentinization of the Tulameen ultramafic complex. White (1986) observed that the extent of alteration was lowest for dunite in the central portion of the Tulameen complex near Olivine Mountain, while the rocks on Grasshopper Mountain were more heavily serpentinized.

Within the profiles, variation in the proportion of light minerals may reflect differential weathering rates for the light and heavy mineral fractions, or eolian addition of light minerals. Compared to the parent materials, the light mineral content was lower in the surface horizons for the Coquihalla soil and the Shulaps paleosols, suggesting that more rapid weathering of ultramafic light minerals resulted in their depletion from surface horizons of these soils developed in partially serpentinized parent materials. Heavy minerals such as olivine, enstatite, and particularly chromite and magnetite may have higher resistance to weathering and accumulate at the surface by negative enrichment during pedogenesis.

Cook (1991) found that the vertical distribution of light and heavy minerals within ultramafic soils of the Tulameen complex depended on parent material variation and pedogenic processes. Till stratigraphy associated with dispersion plumes arising in the vicinity of bedrock margins gave rise to irregular variations in light and heavy mineral content within soil profiles. For two profiles developed in more uniform dunitic till on Grasshopper Mountain (Cook, 1991; soil sites 69, 73), the weight percent of light minerals (S.G. < 3.3) in the very fine sand fraction was lower in the surface horizons than the parent materials.

In the current study, the soil developed in dunitic residuum at Olivine Mountain had a higher content of light minerals in the surface horizon relative to the parent material, reflecting eolian additions or a reduction in the density of olivine grains during pedogenesis. Alexander (1988) observed a similar enrichment of the light mineral fraction near the surface of a weakly developed soil (Inceptisol) derived from dunite in the Klamath Mountains, Oregon.

These results illustrate the variation that may occur among ultramafic parent materials from different geological units, and within the same complex. Heavy liquid separation provided a rapid method for estimating the extent of serpentinization of these ultramafic soil materials.

Variations in light mineral content within profiles may reflect the combined influence of eolian and tephra additions, variations in the stratigraphy of the till deposits, and mineral weathering. The relative importance of these competing processes can be determined by detailed investigation of soil profiles which will be discussed in the next sections.

3.4.3.2 XRD and SEM analysis: very fine sand fractions.

The light mineral fractions of very fine sands from the ultramafic B horizon samples contained serpentine, talc, and chlorite, along with considerable amounts of quartz and feldspar, as illustrated by X-ray diffractograms presented in Figure 3.5, and data from cursory grain counts using SEM-EDS which are presented in Table 3.5. Non-ultramafic minerals in the Blue Creek parent materials were likely derived from small porphyritic bodies within the ultramafic massif. The amount of tephra shards, quartz and feldspar was lower for BC and C horizons than for B horizons, indicating that eolian additions were likely received at the surface of these soils. Eolian additions of feldspar to ultramafic soils were also observed by Rabenhorst et al. (1982).

For the Bm horizon of the Olivine Mountain soil, tephra grains comprised about half of the light fraction, although the light fraction accounted for only 10 percent of the very fine sand. The origin of the tephra at this site was likely Mazama or St. Helens Y, because the Tulameen area is located south of the major plume of the Bridge River tephra (King, 1986).

The ultramafic parent materials contained varying amounts of serpentine, talc and chlorite, likely reflecting different conditions during hydrothermal alteration as well as geochemical differences in the original rocks. The Coquihalla soil contained similar amounts of serpentine, talc and chlorite, while the Olivine Mountain soil contained only serpentine in the light fraction.



Figure 3.5. XRD patterns for light mineral fraction of very fine sands, indicating feldspar (F), quartz (Q), serpentine (S), talc (T), and chlorite (C).

Table 3.5: Lithology of	of very fine sa	and grains de	etermined by	SEM-EDS		
		SERPENTINE				
	QUARTZ	FELDSPAR	R SHARDS	TALC	MICA	
			(CHLORITE		
		NUMBER OF GRAINS				
COQUIHALLA:						
Bf	4	11		9	4	
Cc	6			10	12	
TULAMEEN (Olivin	e Mountain)	:				
Bm1		11	15	7		
BC			1	21		
TULAMEEN (Grass	hopper Mou	ntain):				
Bm	9	8	6	12		
SHULAPS (Blue Cre	ek):					
IIBm1b	9	8	6	12		
IIC	6	10	-	17		
SHULAPS (Barren V	/alley):					
IIBm1b	4	10	3	16		
IIC		1		17		

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The XRD patterns for the heavy mineral separates (Fig. 3.6) indicate the presence of olivine, enstatite, amphibole and magnetite. The highly serpentinized materials from Coquihalla and Barren Valley contained mostly magnetite and amphibole in the heavy mineral separate. In contrast, the dominance of olivine in the materials from Olivine Mountain, and of enstatite with olivine at Blue Creek illustrate the lower degree of serpentinization for these parent materials. Analysis with SEM-EDS showed that the olivine present in the Olivine Mountain soil contained both Mg and Fe.

In summary, analysis with XRD and SEM-EDS reinforces the conclusions drawn in the previous section regarding the extent of serpentinization of the parent materials. The variation in mineralogy of light and heavy separates of very fine sand fractions also emphasizes the diversity of ultramafic parent materials in southwestern British Columbia. The very fine sands were mixtures of minerals characteristic of ultramafic and non-ultramafic rocks. Eolian additions of quartz and feldspar were received by these soils, and small to moderate amounts of these nonultramafic minerals were also present in the parent materials.

Although the data presented for the very fine sand fractions in this section and in section 3.4.3.1 is drawn from a limited number of samples and profiles, information relevant to pedogenesis was obtained. For example, the relative proportion of light minerals declined in the B horizons of the Coquihalla soil and the Shulaps ultramafic paleosols relative to the parent materials (Table 3.4). In these same light mineral fractions, the proportion of ultramafic light minerals decreased (Table 3.5). These results are consistent with a considerable loss of ultramafic light minerals (i.e. serpentine, talc and chlorite) from the very fine sand



Figure 3.6. XRD patterns for heavy mineral fraction of very fine sands, indicating magnetite (MT), amphibole (A), forsterite (FO), and enstatite (E).

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fractions of B horizons during pedogenesis. The results are also consistent with a variation in the till composition between the B and C horizons, however and this possibility will be explored in the next sections.

Sequeira (1968) concluded that serpentine minerals weathered by dissolution in moderately developed ultramafic soils in Portugal. Dissolution of serpentine minerals may also be an important pedogenic process in southwestern British Columbia.

3.4.4 Clay mineralogy

The formation of clays in soil weathering environments depends on parent material composition, soil texture and the soil moisture regime. Clay neoformation is enhanced when parent materials release the necessary elements, in fine-textured materials where percolation of clay forming constituents occurs slowly, and in areas of poor drainage where mineral forming elements can be concentrated (Birkeland, 1974). Because of the high Mg content, weathering of mafic and ultramafic rocks is more favorable to the neoformation of smectite clays than is the weathering of more felsic rocks.

Clay mineral alteration will be observed using XRD only if detectable secondary products are formed or if one or more mineral from an assemblage dissolves at a significantly different rate than the others. Analysis with XRD will not detect simple dissolution, which may be an important process in ultramafic soils from southwestern British Columbia.

3.4.4.1 Twin Sisters.

XRD results for fine clays (< .0002 mm) from the Ae, Bf1, and C horizons for the Twin Sisters soil are presented in Figure 3.7. The Ae horizon fine clay consisted almost entirely of smectite. There was partial expansion with EG and GLY treatment, indicating that these clays had properties transitional between highcharge and low-charge smectite. The Bf1 fine clay contained smectite, HI vermiculite and a small amount of chlorite, while the C horizon fine clay consisted of chlorite, HI vermiculite, and muscovite or phlogopite mica. The clay fraction of the Twin Sisters soil did not contain serpentine.

The coarse clays from the Twin Sisters soil had XRD patterns very similar to those observed for the fine clays, although the peaks were sharper, and a small amount of talc was present in the C horizon.

The major weathering pathways for the Twin Sisters soil involved (1) the formation of smectite from chlorite via an HI vermiculite intermediate; and (2) the disappearance of mica with possible transformation to smectite. The Ae horizon clays represent the most advanced and the C horizon clays the least advanced stage of weathering, while the clays from the Bf1 horizon were intermediate.

Kodama (1979) discussed the disappearance of chlorite and mica, and the enhancement of expandable minerals such as vermiculite and smectite in the surface horizons of Podzolic soils in various regions of Canada. The degree of chlorite alteration correlated well with the development of Podzolic characteristics. The Twin Sisters soil represents a moderate weathering stage on a global scale of


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pedogenesis, but weathering was more advanced than for the majority of Canadian soils.

3.4.4.2 Coquihalla.

XRD patterns for fine clays from the Bf1 and Cc horizons of the Coquihalla soil are presented in Figure 3.8. The fine clays from the Bf1 horizon contained about equal proportions of HI vermiculite, chlorite, serpentine and talc. The fine clays from the C horizon contained expanding chlorite, talc, mica (muscovite or phlogopite) and serpentine in approximately equal proportions.

The major weathering process indicated by XRD analysis of fine clays involved the disappearance of mica from the surface horizons, and the conversion of expanding chlorite to HI vermiculite. The coarse clays followed a similar trend. The extent of chlorite alteration was much less than that observed at the Twin Sisters site.

In laboratory weathering experiments using fulvic acid solutions, Kodama et al. (1983) showed that the rate of biotite weathering was about three times faster than the rate of chlorite weathering. Results of XRD analysis on clays from the Coquihalla soil also show that mica altered more rapidly than chlorite, although the mica was not biotite.

The persistence of talc and serpentine in the fine clay fractions throughout the profile suggests that these minerals may have considerable stability in this high



Figure 3.8. XRD patterns for fine clays from Coquihalla soil.

intensity leaching and weathering environment. Little is known about the stability of talc relative to other minerals in soils (Allen and Hajek, 1989), but some studies (e.g. Rabenhorst et al., 1982; Maoui, 1966) have observed depletion of talc from the fine clays of ultramafic soils relative to coarse clays. For the Coquihalla soil, there is more talc in the coarse clays, but this mineral represents an important constituent of the fine clay as well.

3.4.4.3 Tulameen.

Figure 3.9 presents XRD patterns for fine clays from the Bm1 and BC horizons of the Olivine Mountain soil. The fine clays from the Bm1 horizon consisted of serpentine and a 1.4 nm mineral like expanding chlorite or low-charge smectite. The BC horizon fine clays contained serpentine only. The coarse clays followed a similar trend, and the 1.4 nm mineral in the coarse clays from the Bm1 horizon was expanding chlorite.

The mineral weathering processes which occurred in the Olivine Mountain soil appear to involve the formation of smectite or chlorite from serpentine. The extent to which additions of tephra influenced this process is not known.

Figure 3.10 presents XRD patterns for the less than .002 mm fraction of the Grasshopper Mountain soil. The Bm horizon clays contained chlorite, serpentine and talc in approximately equal proportions, while the C horizon contained chlorite and serpentine, with less talc and a small amount of mica. Weathering of mica occurred in this soil. The apparent increase in talc content in the surface horizon relative to the parent material may reflect negative enrichment of this mineral.



Figure 3.9. XRD patterns for fine clays from Olivine Mountain soil.



Figure 3.10. XRD patterns for clays from Grasshopper Mountain soil.

3.4.4.4 Shulaps.

The mineralogy of several soils from the Shulaps area is discussed in Chapter 4. For most of these weakly developed soils, the clay mineralogy did not vary significantly with depth. Chlorite and serpentine were the dominant minerals in the coarse clay fraction at the Blue Creek site, while the fine clay contained chlorite, expanding chlorite, and serpentine. The clay mineralogy of the low elevation site was not examined, but nearby soils contained serpentine, talc and chlorite, with minor amounts of smectite in the fine clays, and serpentine, talc and chlorite in the coarse clays.

To summarize, mineralogical transformations were well expressed in soils from the Twin Sisters, Coquihalla, and Tulameen areas. The weathering status of the soils, as illustrated by mineralogical analysis was closely related to climate, with the Twin Sisters soil showing the greatest amount of alteration of the parent materials, and the weakly developed soils from the Shulaps area the least. Weathering processes indicated by XRD for the ultramafic soils were the dissolution of mica and chlorite and the formation of smectite and HI vermiculite.

3.4.5 Geochemistry

3.4.5.1 total elemental analysis (XRF).

Table 3.6 presents results of total elemental analysis for major elements, and loss on ignition (LOI) for soil clays (less than .002 mm) and very fine sands (.05 to .10 mm) from the Coquihalla, Tulameen and Shulaps areas. The Twin Sisters soils

W	eathering	Status	and	Geochemistry	of	Soil	S
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		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	ÇaO	Na ₂ O	к ₂ о	TiO ₂	LOI1	SUM
COOLUE		-			· · · · · ·	percer	nt				
		24.0	10.9	10.2	12.0	07	0.8	0.5	1 2	247	105.0
DI	ciay	54.9	10.0	19.5	5.2	29	0.0	0.5	1.2	120	107.0
	sand	01.0	11.8	8.9	5.2	2.8	5.4	0.9	0.9	12.0	107.0
Cc	clay	43.8	15.7	13.7	12.3	0.6	1.5	1.4	0.6	15.7	105.4
	sand	60.3	10.7	6.6	10.7	1.9	3.3	1.0	0.8	10.5	105.8
TULAM	EEN (O	livine	Mountai	n):							
Rm	clav (C	20.2	8.4	26.5	8.4	0.2	0.2	0.2	0.6	34.3	99.0
ЫШ	cand	30.6	2.0	12.0	41 0	0.9	0.6	0.2	0.3	5 5	103.0
	Sana	57.0	2.0	12.7	41.0	0.2	0.0	0.2	0.5	5.5	105.0
BC	clay	32.0	1.3	17.9	25.7	0.1	0.2	0.1	0.3	25.8	103.4
	sand	39.2	0.1	11.2	48.3	0.3	0.0	0.0	0.1	5.2	104.3
TULAM	EEN (G	rassho	pper Mo	untain):							
Bm	clav	38.2	12.9	13.7	14.2	0.5	1.7	1.1	0.8	22.7	105.7
	sand	51.4	11.6	12.8	11.4	5.1	2.9	0.8	1.0	8.7	105.7
		Creat	···								
SHULAI	-S (Blue):	26.5	0.6	0.5	1 0	0.0	1 1	21.5	105.9
IIBm10	ciay	33.1	11.4	20.5	9.0	0.5	1.2	0.0	1.1	21.5	103.0
	sana	60.1	9.7	8.1	15.5	3.9	2.1	0.0	0.4	1.0	107.9
IIC	clav	41.9	12.6	16.1	12.0	0.5	0.5	1.0	0.8	20.3	105.6
	sand	50.4	5.4	7.7	27.8	1.7	1.4	0.5	0.2	9.8	105.0
SHIII AI	PS (Barr	en Val	ev).								
Bm	clav		15.6	11.0	85	0.6	0.9	1.0	0.8	24.3	108.8
tophra	cand	65 /	14.6	6.8	37	3.1	4.0	2.0	0.0	8.0	108.5
tepnia	Sanu	05.4	14.0	0.0	5.7	5.1		2.0	0.0	0.0	106.6
IIBm1b	clay	43.2	8.2	14.8	18.9	0.5	0.2	0.5	0.4	20.0	106.6
	sand	49.0	8.8	16.1	13.0	3.1	1.8	0.7	0.7	12.0	105.2
нс	clav	46.4	7.7	12.8	19.2	0.6	0.3	0.4	0.3	18.5	106.3
	sand	44 3	37	8.8	29.7	1.8	0.7	0.2	0.3	17.2	106.5
	MAEIC	OT A M		AVED	ACES	0E20	וס 2 סו	INC).			
DCC 1	MARIC	51 AN		(AVER	AGES			0.0	0.0	10.4	105 5
PCC-1		42.0	0.0	8.5	43.2	0.0	0.1	0.0	0.0	10.4	105.5
STD DE	v	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
UB-N		39.5	2.8	8.5	35.0	1.3	0.1	0.0	0.1	17.3	104.7
STD DE	v	0.4	0.1	0.0	0.1	0.0	0.0	0.0	0.0		
				4.0	05.0	• •		0.1	0.2	4.2	100 6
NIM-P		50.6	4.0	12.9	25.5	2.8	0.4	0.1	0.2	4.3	100.0
STD DE	V	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
EXPEC	CED VA	LUES	2 _:								
PCC-1		41.7	0.7	8.3	43.4	0.5	0.0	0.0	0.0	4.9	
UB-N		39.4	2.9	8.3	35.2	1.2	0.1	0.0	0.1	11.3	
NIM-P		51.1	4.2	12.8	25.3	2.7	0.4	0.1	0.2	0.4	

Table 3.6: Total elemental analysis of ultramafic soils by XRF.

¹ LOI values are consistently overestimated by about 5 percent. Please see text sections 3.3.2 and 3.4.5.1 for discussion.

² Abbey, 1983.

were not included for geochemical analysis of individual particle size fractions because of the mixed lithology observed in sand fractions, and because very low levels of Cr, Mn, Co, and Ni were extracted from the soil materials with DCB and AOD (please see Table 3.8). Results of several determinations of some ultramafic standards, and the expected values for the standards are also presented in Table 3.6. The clays and very fine sands were separated after ultrasonic dispersion of the samples. No chemical pretreatments were performed, so the samples contained free Fe oxides and poorly crystalline products of weathering.

The average value for the sum of oxides plus LOI was near 105 percent. Analysis of the expected values for the standard materials revealed that LOI was overestimated by four to six percent, and that the results for the major element oxides were in close agreement with expected values (Abbey, 1983). The method used to obtain the estimate of LOI was described in section 3.3.2.

For all soil samples, LOI was higher for clay than for very fine sand fractions, and LOI was higher for B horizon clays than for C horizon clays, which is an indication of the higher organic matter content of the clay fractions near the surface. In addition, the Coquihalla and Olivine Mountain soils had more expanding clay minerals such as HI vermiculite and smectite in the surface horizons compared to the parent materials. These clay minerals absorb large quantities of water which may contribute to LOI.

The results for LOI and for MgO content of the C horizon very fine sands reflect the degree of serpentinization of the parent materials. Relatively unaltered dunite (Olivine Mountain) contained the highest amount of MgO and had the

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lowest LOI for C horizon very fine sands. Moderately serpentinized parent materials (Blue Creek, Grasshopper Mountain) had intermediate levels of MgO and LOI, while highly serpentinized parent materials from Coquihalla and Barren Valley had high LOI and low MgO. The very low levels of MgO observed for the Coquihalla parent materials suggests that loss of Mg²⁺ by leaching likely occurred in this wet environment.

Very fine sands and clays from ultramafic surface horizons contained less MgO than the corresponding C horizon fractions, likely reflecting the loss of Mg during pedogenesis. Juchler (1988; cited by Gasser, 1990) analyzed the fine earth (< 2 mm) of moderately weathered serpentinitic soils in Switzerland with XRF. He observed that surface horizons were depleted in Mg, Si, and Ni, while Al, Fe, Ca, Na, K, and Cr levels were higher for surface horizons. Similar results were obtained by Sequeira (1968) for moderately weathered ultramafic soils in Portugal.

The levels of SiO_2 in the Coquihalla, Tulameen, and Shulaps soils reflected the parent material geochemistry (including ultramafic and non-ultramafic components). In general, very fine sand fractions with high MgO content (e.g. Olivine Mountain) had low SiO_2 , and those with low MgO content (e.g. Coquihalla) had high SiO_2 . Total SiO_2 was lower for clays than for very fine sands, although the differences were small for the samples from the Barren Valley soil, which formed in a dry climate. The SiO_2 content of clay fractions was generally lower for the surface horizons than for parent materials. This may reflect a loss of SiO_2 during weathering, as was reported by Juchler (1988) for the ultramafic soils in Switzerland.

The Fe₂O₃ and Al₂O₃ content of clay fractions was generally higher than for the corresponding very fine sand fractions. Wildman et al. (1971) showed that Fe³⁺ and Al³⁺ were preferentially retained in clays formed from serpentine in well drained soils. In the current study, the clays from surface horizons contained large accumulations of Fe₂O₃ in particular, which has lower mobility than either Mg²⁺ or H₄SiO₄ in weathering environments. The highest Fe₂O₃ levels were present in the clay fractions from the dunite-derived soil at Olivine Mountain and from the soil at Blue Creek derived from serpentinized peridotite. The very large difference between the Fe₂O₃ content of clays and very fine sands in the Blue Creek soil coincides with a much higher content of chlorite and serpentine in the clays relative to quartz and feldspar in coarser fractions (Fig. 4.4).

The low CaO, K_2O , and Na_2O content in the very fine sands reflects the low abundance of these element oxides in ultramafic rocks. The levels of CaO and NaO in particular were higher for B horizons than for C horizons, indicating the extent of eolian additions of plagioclase feldspars received by the soils. Negative enrichment and nutrient cycling by the vegetation may also account for higher Ca, Na, and K levels in surface horizons.

Table 3.7 lists the minor element composition of the soil materials. For all ultramafic samples, the very fine sand fraction contained more Cr than the clay fraction. Ferrite-chromite and chromite were common accessory minerals in ultramafic rocks from all three areas, and these minerals are resistant to weathering. Chromium in the clay fractions was likely present in silicate structures and in secondary Fe hydrous oxide minerals, where it may substitute for Fe (Schwertmann et al., 1989).

		V	Cr	Mn	Со	Ni	Zn	Rb	Sr	Zr
	_					- mg kg	1			
COQUIH	IALLA:				-					-
Bf	clay	388	1410	805	78	699	275	23	63	78
	sand	101	2151	942	29	296	13	17	209	119
Cc	clay	262	629	2178	180	2255	147	36	129	102
	sand	121	839	831	33	631	62	16	185	119
TULAM	EEN (O	livine N	(ountain)):						
Bm	clay	70	110	1770	163	590	128	6	12	43
	sand	16	5526	2038	148	1082	72	3	73	29
BC	clay	40	36	2071	144	1084	61	2	0	26
DC	sand	-10	2202	1933	146	1181	57	1	5	11
			2202		2.10			-	•	
TULAM	EEN (G	rasshop	per Mou	ntain):	150	1544	1.40	4.1	67	01
Bm	clay	107	180	1307	159	1544	148	41	57 205	91
	sand	187	2707	1287	0/	528	89	19	393	92
SHULAI	PS (Blue	Creek):								
IIBm1b	clay	238	1194	1095	192	1312	234	42	50	94
	sand	159	5746	1021	58	605	92	13	217	69
IIC	clay	163	763	1619	116	1654	124	19	48	96
	sand	55	1665	952	67	1621	53	10	144	37
SHIII AT	DS (Barr	an Valla	v)·							
Bm	clav	158	507	1461	88	1100	183	28	42	76
tephra	sand	97	563	1021	21	159	75	36	414	169
IID 1h	.1	100	1001	1200	127	2174	07	27	10	68
IIBm10	clay	120	1021	2008	103	21/4	07 110	18	200	68
	Sanu	147	5709	5090	1)5	1411	110	10	200	
IIC	clay	99	859	937	133	2163	67	18	16	45
	sand	75	1860	975	63	1739	44	4	58	33
ULTRA	MAFIC	STAND	ARDS (A	AVERAG	GES OF	2 OR 3	RUNS):			
PCC1		28	2835	1098	105	2298	45	2	1	13
STD DE	V	1	81	28	2	48	1	1	4	2
UBN		76	2784	1233	98	1977	86	4	10	16
STD DE	v	6	183	101	7	87	6	2	0	2
D	·		0000	1110	101	0414	40	1	4	10
DTS OTD DE	1 <i>r</i>	-3	3866	1149	131	2411	48	1	4	10
SID DE	v	Z	60	32	U	19	2	U	T	U
EXPECT	ED VA	LUES:								_
PCC1		31	2730	929	112	2380	42	0	0	10
UBN		75	2300		100	2000	85	6	10	8
DTS		11	3990		137	2360	46	U	U	

Table 3.7: Minor element content of ultramafic soils by XRF.

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The distribution of Cr within the profiles provides evidence that the till deposits forming the soil parent materials were relatively free of stratigraphic variation. In contrast to the data for Mg and Ni, which are also a characteristic element in ultramafic rocks, the levels of Cr in clay and very fine sand fractions were higher for B horizon samples than for C horizons. The opposing trends for Mg and Ni versus Cr within the profiles are best explained on the basis of their mobility in the weathering environment. Magnesium and Ni were depleted (leached) as mineral weathering occurred in B horizons, while Cr accumulated in B horizons by negative enrichment during pedogenesis.

The clay fractions from the Tulameen complex were much lower in Cr than those from the Shulaps and Coquihalla soils, even though the very fine sands from Olivine Mountain had high levels of Cr. The very low Cr content of serpentine minerals in the clay fraction of the Olivine Mountain parent material relative to the very fine sands indicates that Cr was strongly retained in the very fine sands, probably as chromite.

All of the ultramafic soils had similar Mn content. The clay fractions from the C horizon of the Coquihalla soil had 2.5 times more Mn than the Bf1 horizon clays, even though the very fine sand fractions had similar Mn content. The results suggest that Mn was released from the Bf1 horizon during mineral dissolution and transported to the lower solum in leaching waters. There, Mn may have been incorporated into clay minerals and Fe hydrous oxides in the C horizon, held on the cation exchange complex, or leached from the profile. A similar Mn distribution pattern, but less dramatic was observed for the Tulameen and Blue Creek profiles. The Barren Valley site had a IIBm1b horizon with more Mn than the underlying IIC

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in both the clay and very fine sand fractions, indicating that Mn was immobile in the dry environment.

Redistribution of Co was also indicated in the Coquihalla profile, where the C horizon clays had the highest Co content. For the Olivine Mountain profile, Co levels were similar in the very fine sands and the clays from the Bm and C horizons. There were higher levels of Co in the clays than in the very fine sands from the Blue Creek paleosol, and the IIBm1b clays had slightly higher Co levels than the IIC, indicating that Co was immobile at this site.

The Blue Creek and Barren Valley paleosols generally had higher levels of Ni than soils from the other sites. In the Coquihalla soil, the B horizon was depleted in Ni relative to the C horizon, which was attributed to redistribution of this mobile element during pedogenesis, likely via a process similar to that described for Mn. In the Barren Valley soil, the IIBm1b and IIC horizons from the ultramafic paleosol had similar Ni content, suggesting that little redistribution occurred in the dry environment.

The results are in general agreement with the findings of Juchler (1988). In addition, the redistribution of elements among particle size fractions, along with variations in the light and heavy mineral content between soil horizons suggests that elements more strongly associated with light minerals such as Mg, Co, and Ni are more easily leached than elements such as Fe and Cr which are more strongly associated with the heavy mineral fraction.

In summary, increased concentrations of Cr in B horizon samples relative to the parent materials provides the best evidence so far that weathering of ultramafic minerals and redistribution of mobile elements within soil profiles was an important process during pedogenesis. Eolian additions and stratigraphic variation in till deposits are likely less important sources of within profile variation in composition.

Changing concentrations of Mg, Fe, Si, Cr, Co, Mn, and Ni within particle size fractions and between B and C horizons can be partly explained by mineral dissolution during pedogenesis and subsequent redistribution of soluble weathering products or negative enrichment of insoluble residues. Redistribution of mobile elements which are characteristic of ultramafic soils occurred to varying degrees in the soils from different weathering environments in southwestern British Columbia.

3.4.5.2 selective dissolution analysis.

This section describes the results of selective dissolution analysis of whole soils (< 2 mm) by DCB and AOD, and clay and very fine sand fractions by DCB, AOD, and PYRO. The use of these three extractants aids in distinguishing different forms of elements within soil materials, and provides a test for the concepts presented in the previous section regarding element mobility and redistribution.

According to Jackson et al. (1986), the DCB method was designed to remove free Fe oxides, and elements such as Al, Si, and Mn, which are associated with them. Aluminum-substituted goethite and hematite are dissolved by the DCB treatment, but magnetite and ilmenite are not affected. Some reduction of structural Fe(III) in vermiculites and nontronites may lead to dissolution of these minerals, and Fechlorites may also be affected. The AOD procedure extracts most non-crystalline and paracrystalline materials, including allophane, imogolite, and short-rangeordered oxides and hydroxides of Fe, Al, and Mn. The AOD procedure generally dissolves very little < 0.2 mm hematite and goethite, and less than 10 percent of < 0.2 mm magnetite, but finely divided materials are more susceptible than coarse grains (McKeague et al., 1971). In addition, some decomposition of biotite and chlorite may occur during AOD extraction (Jackson et al., 1986; Arshad et al., 1972). The PYRO reagent extracts organically bound elements and acts as a dispersing agent for soil organic matter at high pH. The selectivity of all of these reagents may vary for different soil types, so interpretations must be made with caution (Borgaard, 1985).

A unique aspect of the current work was the analysis of DCB, AOD, and PYRO extracts for trace metals associated with ultramafic soil materials. Selective dissolution analysis of natural soils for trace metals has not been extensively performed because of the low levels of these elements present in most soils, and the difficult techniques required to concentrate the solutions to detection limits of AAS analysis (Jenne et al., 1974). Gasser (1991) used ammonium acetate-EDTA, AOD, and DCB to extract Cr and Ni from ultramafic soils in Switzerland. In the current study, the high levels of total Cr, Mn, Co and Ni which characterized the ultramafic soils in southwestern British Columbia were also partially extracted with the three extractants.

Fine earth (< 2 mm):

Results of DCB extraction on unground soils, and of AOD extraction of soils ground to pass 100 mesh are summarized in Table 3.8.

The ultramafic soils from southwestern B.C. had lower levels of Fe_d than ultramafic soils from unglaciated regions (Rabenhorst et al., 1982; Alexander, 1988), reflecting the shorter time span for pedogenesis. The levels of Fe_d and Fe_o extracted from the C horizons of the Olivine Mountain soil were in close agreement with Fe_d levels of 0.7 percent and Fe_o levels of 1.3 percent extracted from unaltered olivine (McKeague and Day, 1966). Levels of Fe_d and Fe_o were highest for B horizons, and declined with depth.

There was no consistent trend between the levels of Fe_d in B horizons and either the climatic regime or the degree of serpentinization of the parent materials, but Fe_o levels were higher for B horizons from the Twin Sisters and Coquihalla areas than for those from the Shulaps. These results indicate that Fe_o provides a better estimate than Fe_d of pedogenic development for serpentinized and partially serpentinized parent materials from the Coquihalla and Shulaps areas.

Levels of Al_d were about an order of magnitude lower than Fe_d for all sites except Twin Sisters. Ultramafic parent materials generally have low Al content which is reflected in the Al_d levels. For the Twin Sisters soil, the higher levels of Al_d indicate that the parent materials contained a significant proportion of nonultramafic materials.

SAMPLE	Fed	Ald	Sid	Crd	Mn _d	Cod	Nid	Feo	Cr ₀	Mn _o	Coo	Nio
		percent	t		== mg	kg ⁻¹ -		%		== mg	kg ⁻¹ =	
TWIN SIS	TERS	5:			-	-				-	-	
Ae	0.2	0.1	0.0	8	< 43	< 3	< 5	0.1	n.d	3	n.d	n.d
Bf1	1.5	1.1	0.1	31	< 43	< 3	7	0.9	n.d	10	n.d	n.d
Bf2	1.3	0.8	0.1	26	< 43	< 3	11	1.1	n.d	37	n.d	n.d
BC	0.7	0.4	0.1	18	75	4	12	0.6	n.d	86	n.d	n.d
С	0.5	0.2	0.0	11	138	6	12	0.4	n.d	143	n.d	n.d
COQUIH	ALLA	. :	2									
Bf1	2.9	0.2	0.1	209	278	11	55	1.5	41	276	15	36
Bf2	1.8	0.3	0.1	161	332	27	75	1.2	44	319	30	65
Bf3	1.0	0.2	0.1	93	393	35	109	0.7	39	393	39	93
BCc	0.9	0.1	0.1	63	362	33	94	0.8	32	429	46	132
Cc	0.8	0.1	0.1	28	340	29	138	0.6	17	468	44	157
TULAME	EN (Olivine	Mou	ntain):								
Bm1	1.8	0.2	0.1	7	593	33	67	1.6	7	593	37	64
Bm2	1.7	0.2	0.1	5	353	22	58	1.3	8	346	26	55
BC	0.8	0.0	0.1	3	220	21	76	1.2	8	320	24	183
С	0.7	0.0	0.2	3	260	22	128	n.d	n.d	n.d	n.d	n.d
SHULAPS	S (Blu	e Cree	ek):									
Bm1 tephra	a 0.4	0.1	0.1	. 19) 100	6	37	0.8	15	135	10	75
Bm2 tephra	a 0.1	0.0	0.0	5	5 < 43	< 3	14	0.4	6	51	. 6	33
C1 tephra	a 0.1	0.1	0.0	< 3	3 < 43	< 3	< 5	n.d	n.d	n.d	n.d	n.d
C2 tephra	a 0.0	0.0	0.0	< 3	3 < 43	< 3	< 5	n.d	n.d	l n.d	n.d	n.d
IIBm1b	3.1	0.3	0.1	127	7 253	21	100	0.6	15	5 162	. 14	36
IIBm2b	2.1	0.2	0.1	106	5 188	21	114	0.6	22	2 144	18	86
IIBm3b	1.2	0.1	^a 0.1	. 58	3 258	20	122	0.5	20	218	3 22	147
IIC	0.9	0.1	0.1	. 27	7 248	19	102	0.5	19	214	22	204
SHULAP	S (Bai	ren Va	alley):									
Bm tephra	a 0.4	0.1	0.1	. 14	4 360) 6	34	0.6	5 8	364	8	32
C tephi	a 0.2	0.1	0.0) (5 < 43	3 < 3	6	0.4	12	2 30) (6
IIBm1b	2.2	0.1	0.2	2 138	3 982	2 64	277	0.6	32	2 975	5 58	307
IIBm2b	1.2	0.1	0.2	2 79	9 575	5 57	261	0.4	22	663	57	435
IIC	0.7	0.0	0.2	2 50) 280	38	145	0.3	5 9	391	50	225
IIIC	0.5	0. 0	0.2	23	3 288	69	128	n.d	n.d	l n.c	l n.d	n.d

Table 3.8. DCB and AOD extractable elements for soil samples from the four study areas.

The compact BCc and Cc horizons from the Coquihalla soil had nearly the lowest Si_d levels of all the soil samples. Low Si_d and Si_o levels (near 0.13 percent) were also reported for a hardpan from an ultramafic soil in the Cleveland Peninsula, Alaska (Alexander et al., 1991). These authors concluded that Si may have been an important element in the cement of the Alaskan hardpan. McKeague and Sprout (1975) described gray, cemented subsoils which commonly occurred at depths of 50 to 75 cm below the surface in Podzols of southern British Columbia as duric horizons. They concluded that a cementing agent consisting of various proportions of amorphous and poorly crystalline products containing Fe, Al, and Si was likely responsible for the formation of duric horizons, which were most often observed in well developed soils on moderately coarse-textured, dense basal till.

Measurable levels of several first row transition elements were extracted from these soils with DCB and AOD. Of particular interest, the distribution of Cr_d and Cr_o within the profiles imitated Fe_d and Fe_o , where levels were generally highest for B horizons and declined with depth. Gasser (1990) observed a similar distribution pattern for Cr in ultramafic soils in Switzerland. These results suggest that Cr released from primary minerals during weathering may be incorporated into secondary Fe hydrous oxides. Soil samples derived from dunitic parent materials at Twin Sisters and Olivine Mountain had low levels of Cr_d , as did tephra-derived samples from the Shulaps soils.

The amount of Cr_d extracted from the serpentinitic parent materials of the Coquihalla, Blue Creek and Barren Valley soils were similar. Within this group, Cr_d levels for the Bf1 horizon from the Coquihalla soil (humid environment) were much higher than for the IIBmb horizons at Blue Creek and Barren Valley (drier

environment). The results for Fe_o were similar, suggesting that a crude relationship may exist between Cr_d and Cr_o levels and expected weathering status of the ultramafic soils based on soil climate.

Levels of Mn_d and Mn_o within the soil profiles did not follow the trends observed for Fe and Cr. For the Twin Sisters and Coquihalla soils, Mn_d and Mn_o levels were low in surface horizons and increased with depth in the profile, . indicating that Mn was partially mobilized to the lower solum of these moderately weathered soils. The Mn_d content of ultramafic samples from the Blue Creek soil was similar at all depths. In contrast, the ultramafic soils at Olivine Mountain and Barren Valley had the highest levels of Mn_d in surface horizons, indicating that redistribution of Mn in these profiles was limited.

The levels of Co_d and Co_o were highest for the Barren Valley soil. Very low levels of Co_d were present in the Twin Sisters soil, and for the soil materials derived from Bridge River tephra. The distribution of Co_d and Co_o in the soil profiles was broadly similar to the trend for Mn.

The behavior of Ni in the ultramafic soils from the four areas reflected the leaching intensity of the sites. Very low levels of Ni_d were present in the samples from the Twin Sisters soil. The Coquihalla and Olivine Mountain soils had low levels of Ni_d and Ni_o in surface horizons and higher levels in the lower solum, suggesting that Ni was subject to leaching deep into the solum or beyond the C horizon. The Blue Creek paleosol had similar levels of Ni_d at all depths, suggesting that in this profile a balance was achieved between release of Ni by weathering, immobilization of Ni and leaching. For the Barren Valley site, Ni_d levels were

highest for surface horizons. The data indicate that Ni was more easily leached than Mn and was redistributed at all sites except Barren Valley, where the dry environment did not provide enough excess water to leach this soluble element.

The trends observed for Mn_d , Mn_o , Ni_d and Ni_o varied slightly. The maximum concentration of Mn_d and Ni_d , was generally higher in the solum than the maximum for Mn_o and Ni_o . These results reflect the greater extent to which AOD extracts elements such as Fe and Al (and presumably Mn and Ni) from primary minerals such as olivine, hornblende, magnetite, and chlorite (McKeague and Day, 1966; McKeague et al., 1971; Arshad et al., 1972). These primary minerals are more abundant in the C horizon.

The results of this study are best summarized by examining the extremes along the soil environment sequence, along with the extremes of trace element behavior. The retention and accumulation of Cr in B horizons in association with high Fe_d was observed in all soils. In contrast, the behavior of Ni was sensitive to the soil environment. In the soils from wet environments, Ni was leached to the lower solum and below, while very little redistribution of Ni was observed in the dry environments. The behavior of Mn and Co was intermediate between these two trends.

Clays and very fine sands:

Results of selective dissolution analysis for clay and very fine sand fractions from the Coquihalla, Tulameen and Shulaps areas are presented in Table 3.9. Higher levels of all elements were generally extracted from clay fractions than from

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rama	Alp	rcen		0.4	0.1	0.1	0.0		0.4	0.0	0.2	0.0		0.2	0.0		0.2	0.0	0.1	0.0		0.3	0.0	0.1	0.0	0.1	0.0	
fractions from ultr	Fep	ь Ре		1.7	0.2	0.2	0.0		0.6	0.0	0.7	0.0		0.2	0.0		0.6	0.0	0.2	0.0		0.5	0.0	0.3	0.0	0.2	0.0	
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ind fr	Mn _O	, mg k		275	188	1300	218		006	174	1275	110		425	248		525	122	800	123		200	185	650	1800	275	255	
ne sa	cr _o			170	30	20	80		20	\$	< 20	6		< 20	9		52	14	8	80		4	6	2	12	35	8	
s of clay and very fin	Sio	== - percent -		0.1	0.0	0.3	0.0		0.3	0.2	0.6	0.2		0.2	0.1		0.3	0.0	0.5	0.1		0.2	0.0	0.3	0.0	0.2	0.0	
	Alo			0.7	0.1	0.5	0.1		1.0	0.1	0.5	0.0		0.7	0.1		0.7	0.1	0.7	0.1		1.0	0.1	0.5	0.1	0.3	0.1	
	Feo			3.6	0.6	1.6	0.2		2.3	0.6	2.7	0.5		1.1	1.4		2.2	0.5	1.6	0.3		1.7	0.7	1.2	0.3	0.6	0.2	
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on an	PuW	mg k		391	241	1281	221		1611	156	1021	105	: (1	621	256		841	175	881	146		691	171	641	1631	241	211	
oluti	crd			218	53	89	ø	ਂ : (u	38	4	53	4	intair	23	4		412	8	143	11		53	11	135	38	<u>98</u>	19	
e disso	Sid	1		0.2	0.0	0.3	0.1	untai	0.1	0.0	0.2	0.1	r Mou	0.2	0.0	••	0.2	0.1	0.3	0.1	еу):	0.2	0.0	0.3	0.1	0.4	0.1	
ctive	Ald	rcent		0.8	0.1	0.3	0.0	ne Mo	1.7	0.1	0.2	0.0	hoppe	0.6	0.1	reek)	1.2	0.1	0.5	0.0	L Vall	0.5	0.0	0.3	0.1	0.1	0.0	
Sele	Fed	- pe		8.2	1.5	3.0	0.6	olivi	14.2	0.5	4.9	0.4	Grass	4.9	1.2	lue C	12.4	1.5	4.7	0.6	arren	2.2	0.4	3.1	1.7	1.5	0.5	
3.9.			HALLA	clay	vfs	clav	vfs	EEN (clay .	vfs	clay	vfs	IEEN (clay	vfs	APS (B	clay	vfs	clay	vfs	NPS (E	clay	vfs	clay	vfs	clay	vfs	
Table			COQUI	Bf1		CC	;	TULAM	Bm1		BC		TULAN	Ba		SHULZ	IIBm1b		IIC		SHULZ	Bm	tephra	11Bm1b		IIC		ci.

very fine sands. For relatively immobile elements like Fe, Al and Cr, B horizons contained higher levels than C horizons. The distribution of elements such as Mn, Co, and Ni between B and C horizons was more variable and depended on the soil environment, in most cases reflecting the trends already described in the previous sections.

The amount of Fe_p and Fe_o extracted from ultramafic B horizon clays approximated the expected pattern for the climosequence, where Coquihalla samples had the highest weathering intensity and Barren Valley the least. The highest levels of Fe_o were obtained for the Coquihalla Bf1 horizon, and the Barren Valley IIBm1b horizon contained the lowest levels.

The levels of extractable Fe increased in the order $Fe_p << Fe_o < Fe_d$. The results indicate that a large proportion of the Fe released during weathering was present in well crystallized Fe hydrous oxides which accumulated in the clay fractions. For the Coquihalla soil, Fe_p accounted for 21 percent of Fe_d in the B horizon clays, indicating that organically complexed Fe was an important component of the free Fe in this Podzolic soil. For the Brunisolic soils, Fe_p constituted a very small fraction of Fe_d .

For Cr, Mn, Co and Ni, the results provide more information on the weathering processes within these ultramafic soils. For example, AOD and DCB extracted about equal amounts of Cr, Mn, Co, and Ni from Cc horizon clays from the Coquihalla soil. For the B horizon clays, DCB extracted much higher amounts of these transition metals. These results reflect the enhanced extraction of metals from silicates by AOD compared to DCB in the Cc horizon (Arshad et al., 1972;

McKeague and Day, 1966). In the B horizon, transfer of metals from silicates to Fe hydrous oxides occurs during weathering, and these phases are more readily extracted with DCB.

Very high levels of Mn_o and Mn_d were extracted from very fine sands in the Barren Valley IIBm1b horizon. More detailed investigation revealed that similar levels of Mn, along with high levels of Co were extracted from the light mineral fraction, which contained substantial amounts of chlorite and serpentine. For the clay fractions, Mn_p accounted for up to 46 percent of Mn_d . These results indicate that organically complexed Mn, and Mn associated with AOD soluble components (including phyllosilicates) form important pools of Mn in this soil.

Figure 3.11 presents element ratios between DCB extractable trace elements and Fe_d for clays from the ultramafic B and C horizons of the Coquihalla and Barren Valley soils, representing the wet and dry extremes of the climosequence. The element ratios may be interpreted as a comparison of the trace element behavior with the behavior of Fe.

The Cr_d/Fe_d ratio was nearly the same for B and C horizons from both profiles, indicating that Cr and Fe were conserved to a similar extent during pedogenesis. Gasser (1990) synthesized goethite containing 10 mole percent of Cr, which indicates that Cr may be retained in association with Fe in DCB extractable minerals.

The Mn_d/Fe_d ratio for the Coquihalla B horizon was much lower than for the Cc horizon, indicating that less Mn was associated with Fe hydrous oxides near



Figure 3.11. Element ratios for DCB and AOD extractable Cr, Mn, Co, and Ni compared to Fe_d and Fe_o .

the surface; i.e. that Mn was subject to redistribution in the wet environment while Fe was not. These results may reflect preferential complexation of Mn^{2+} by soluble organic matter. The clays from the Barren Valley B and C horizons had similar Mn_d/Fe_d ratios, indicating that Mn was not preferentially redistributed to the C horizon in the dry environment.

The data indicate that Co and Ni were redistributed to the C horizon to a greater extent than Fe at the Coquihalla site. Ratios of Co_d/Fe_d and Ni_d/Fe_d ratios were similar for B and C horizons in the Barren Valley soil.

Figure 3.11 also presents element ratios for the AOD extraction, which displayed similar patterns to those discussed for the DCB. The ratios for Mn_o/Fe_o and Ni_o/Fe_o were slightly higher than for Mn_d/Fe_d and Ni_d/Fe_d , suggesting that AOD soluble phases are less restrictive in the amount of trace element substitution allowed. Elements rejected from the structure as poorly crystalline Fe minerals age may be available for incorporation into freshly precipitating materials, enhancing the difference between ratios of DCB and AOD extractable trace elements with Fe_d and Fe_o.

The behavior of Cr, Mn, Co and Ni in comparison to Fe may be explained partly on the basis of the first hydrolysis constants for the metals (Baes and Messmer, 1976):

Cr ³⁺	+	H ₂ 0	>	CrOH ²⁺	+	н+	pK	=	3.4
Mn ²⁺	+	H ₂ 0	>	MnOH ⁺	+	H+	pK	=	10.54
Fe ³⁺	+	H ₂ 0	>	FeOH ²⁺	+	H+	pK	=	2.5
Co ²⁺	+	н ₂ 0	>	СоОн+	+	H+	pK	=	9.8

$Ni^{2+} + H_2O --> NiOH^+ + H^+ pK = 9.5$

The very low pK value for the first hydrolysis reaction of Fe^{3+} , and the very low solubility of Fe hydrous oxides means that Fe^{3+} is present in the soil solution at very low concentrations, restricting its mobility. The low pK value for the first hydrolysis reaction of Cr^{3+} indicates that this metal will be specifically adsorbed to oxide surfaces at low pH values (James and Healy, 1972), and may form $Cr(OH)_3$ at neutral pH values (please see Section 5.1.1.2). The pK values of hydrolysis constants for Mn^{2+} , Co^{2+} , and Ni^{2+} are much higher, indicating that these metals are not specifically adsorbed to oxide surfaces at low pH values, and exist as soluble cations over a wide range of pH in soils. After release of Mn, Co and Ni from primary minerals in acidic surface horizons, these metals behave as exchangeable cations, and may be subject to leaching.

3.4.5.3 sequential extraction.

Table 3.10 compares the results of the sequential extraction analysis for soil clays with the selective dissolution results. The left side of the table shows the levels of the elements extracted with DCB from a sample which had previously been extracted with PYRO and AOD. These values are thought to represent elements associated with well crystallized Fe hydrous oxides present in the sample. The right side of the table shows the difference between DCB and AOD extractable elements using separate subsamples (e.g. $Fe_d - Fe_o$), which is also a measure of the well crystallized Fe hydrous oxides.

If the assumptions are correct that DCB extracts all of the free Fe, and that AOD extracts only poorly crystalline and organically complexed Fe, then the two

		SEQUI (af	ENTIA ter PY	AL EX (RO a)	TRAC	CTION D)	1	SELECTIVE DISSOLUTION (El _d - El _o)								
	Fe	Al	Si	Cr	Mn	Со	Ni	Fe	Al	Si	Cr	Mn	Со	Ni		
	1	percen	t	==== mg kg ⁻¹ ====				percent			==== mg kg ⁻¹ ====					
Coquiha	lla:															
Bf1	4.2	0.2	0.2	254	136	18	112	4.6	0.1	0.1	48	116	28	157		
Cc	1.4	0.1	0.2	34	112	<11	282	1.4	-0.2	0.0	-2	- 19	32	15		
Tulamee	en (G	rassho	pper l	Mounta	ain):											
Bm	3.9	0.3	0.2	14	199	20	223	3.8	-0.1	0.0	23	196	44	230		
Shulaps	(Blue	Creel	k):													
IIBm1b	9.7	0.7	0.2	377	362	73	364	10.2	0.5	-0.1	337	316	112	313		
Shulaps	(Barı	en Va	lley):													
IIBm1t	2.2	0.1	0.2	133	105	<11	310	1.9	-0.2	0.0	65	-9	63	30		
IIC	1.1	0.1	0.3	75	59	<11	224	0,9	-0.2	0.2	62	-34	27	90		

Table 3.10: Amount of Fe, Al, Si, Cr, Mn, Co and Ni associated with well crystallized Fe hydrous oxides in soil clays, using two methods.

results should be the same. Apart from experimental error, any differences may indicate that (1) AOD extracts Fe from a phase that was not dissolved with DCB (e.g. from chlorite), resulting in a low estimate of crystalline Fe by selective dissolution, or (2) the prior removal of AOD extractable Fe enhances the extraction of some constituents with DCB, resulting in an overestimate of crystalline Fe by sequential extraction. The two methods did give similar results for Fe, but there were some discrepancies in the trace element results.

Explanation (1) is favoured where selective dissolution provided negative results. For example, in the Barren Valley clays, Mn_o exceeded Mn_d , but after sequential extraction with PYRO and AOD, some Mn was extracted with DCB. These results suggest that AOD extracted a Mn-containing phase which was not removed by DCB. A similar situation likely exists for Ni in the Barren Valley clays.

For the Coquihalla soil, Cr extracted with DCB after sequential extraction exceeded Cr_d from selective dissolution. Explanation (2) applies to this situation, where some Cr released from a silicate phase such as chlorite or serpentine by AOD was likely adsorbed by Fe hydrous oxides in the sample, enhancing the Cr content of the well crystallized Fe minerals. Sequential extraction results likely overestimate Cr associated with crystalline Fe hydrous oxides in this sample.

The sequential extraction results for soil clays are expressed as a proportion of the total elemental content from XRF in Figures 3.12, 3.13, and 3.14. The proportion of total Al (Figure 3.12) that was present in extractable forms was very low for all clay samples. The Al present in these clays was likely present in chlorite and serpentine.





Figure 3.12. Sequential extraction of soil clays with DCB, AOD and PYRO for Fe and Al, expressed as a proportion of total Fe and Al determined by XRF.

Figure 3.12 also shows that less than half of the total Fe in the clay fraction of the Coquihalla Bf1 horizon was present in the residual fraction (not extractable with PYRO, AOD, or DCB), while the clays from the Cc horizon contained a large residual Fe fraction. A large proportion of the Fe present in the Blue Creek paleosol was extractable with DCB. For the IIBm1b horizon from the Barren Valley soil, approximately 25 percent of the total Fe in the clays was present in an extractable form, while the IIC clays had less than 15 percent of the total Fe present in an extractable form. These data provide further evidence that soils from the wetter Coquihalla and Blue Creek sites were more highly weathered than those from the Barren Valley site, and that secondary Fe minerals accumulated in the B horizons.

Figure 3.13 shows that residual Cr as a proportion of total Cr was higher than the proportion of residual Fe for all samples. The Coquihalla Bf1 and Blue Creek IIBm1b horizon clays had the highest proportion of Cr extractable with the three reagents. The limited mobility of Cr occurs because (1) primary minerals containing Cr are resistant to weathering, and (2) Cr accumulates in B horizons in association with DCB extractable Fe minerals.

The Coquihalla Cc horizon clays had higher total Mn, residual Mn and extractable Mn than the Bf1 horizon clays. These results indicate that Mn was dissolved from primary minerals and lost from the Bf1 horizon. It is more difficult to determine whether the high Mn levels in the Cc horizon reflect the original parent material composition or enrichment with Mn redistributed from the upper solum. The AOD extraction removes some Fe, and presumably other metals from primary minerals such as chlorite as well as from poorly crystalline weathering products.





Figure 3.13. Sequential extraction of soil clays with DCB, AOD and PYRO for Cr and Mn, expressed as a proportion of total Cr and Mn determined by XRF.

For the Barren Valley clays, residual Mn formed a higher proportion of total Mn than for the Coquihalla site. The dry conditions at the Barren Valley site likely resulted in slow release of Mn from primary minerals. The dry climate of the Barren Valley site also resulted in less leaching, so higher levels of extractable Mn were observed for the IIBm1b horizon than for the IIC.

The results of the sequential dissolution analysis for Co and Ni (Figure 3.14) were similar to the results for Mn. These soluble elements were depleted from the Coquihalla Bf1 horizon, and significant quantities were present in extractable form in the Cc horizon. In contrast, the Barren Valley clays had very similar residual and extractable levels of Co and Ni in the IIBm1b and IIC horizons, indicating that leaching of these soluble elements was not an important process in the soil from the dry extreme of the climosequence.

The first stage of chlorite weathering involves dissolution of the interlayer hydroxide sheet. A heat treatment and acid dissolution procedure developed by Ross and Kodama (1974) simulates this process, allowing an evaluation of the release of elements during chlorite weathering. Table 3.11 presents the results of heat treatment of clays after sequential dissolution analysis. The results show that large amounts of Mg, and lesser amounts of Si, Fe, Al, and other elements were released following the heat treatment. Acid extraction of samples without the heat treatment released about one third of the amount extracted by the heat treatment.

The results indicate that considerable Al resides in the chlorite structure, as the amount of Al extracted was similar to the amount of Fe extracted. The amounts of Cr and Ni released represent about 10 percent of the total Cr, Mn and Ni present





Figure 3.14. Sequential extraction of soil clays with DCB, AOD and PYRO for Co and Ni, expressed as a proportion of total Co and Ni determined by XRF.

chlorite.								
	Mg _{ht}	Fe _{ht}	Al _{ht}	Si _{ht}	Cr _{ht}	Mn _{ht}	Co _{ht}	Ni _{ht}
				==== mg	kg ⁻¹ ===			
Coquihal	la:							
Bf1	14200	4100	3280	6600	145	45	< 5	75
Cc	10300	4100	3750	5000	85	45	< 5	95
Tulameer	n (Grassho	pper Mou	untain):					
Bm	18500	3000	5150	8200	15	46	10	120
Shulaps (Blue Cree	k):						
IIBm1b	13500	3600	3560	6400	80	30	< 5	85
Shulaps (Barren Va	lley):						
IIBm1b	26600	5200	2730	9000	80	36	10	130

IIC

Table 3.11: Release of metals from clays after sequential dissolution (PYRO + AOD + DCB) and heat treatment to destroy interlayer hydroxide sheet of chlorite.

in the clays, indicating that chlorite weathering may be an important process affecting trace metal behavior during pedogenesis in the future.

3.5 SUMMARY

The particle size characteristics of these upland soils were largely inherited from the parent materials, and reflected comminution of relatively fresh ultramafic rocks during transport by glacier ice.

Profiles from the Coquihalla and Tulameen areas, and paleosols from the Shulaps area were characterized by very low Ca:Mg ratios, indicating that they were derived primarily from ultramafic parent materials. In contrast, chemical and mineralogical analyses revealed that the Twin Sisters soil contained large amounts of non-ultramafic material. The degree of serpentinization of the parent materials was greatest for the Coquihalla and Barren Valley soils and least for the Olivine Mountain soil.

Soil chemical properties such as pH and organic matter content reflected the soil environment. The soils developed in wetter climates had lower pH values and higher organic matter content in the B horizons than the soils developed in the dry climate at the Shulaps area.

The Twin Sisters and Coquihalla soils were classified as Podzols (Agriculture Canada, 1987), while the ultramafic soils from the Tulameen and Shulaps areas were classified as Brunisols. The soil classification reflected the climatic regime, and also broadly characterized the weathering status of the soils.
Weathering Status and Geochemistry of Soils

The Twin Sisters and Coquihalla soils were moderately weathered on a global scale of pedogenesis. X-ray diffraction analysis showed that the clay mineral assemblage of these soils was altered by pedogenesis, with conversion of chlorite to HI vermiculite and smectite, along with disappearance of mica in the upper solum. These weathering processes are near the maximum expression of pedogenic alteration observed for Canadian soils.

Geochemical analyses indicated that dissolution of serpentine minerals, talc and chlorite was likely an important process in all of the soils, even though XRD evidence for this was equivocal. Release of Mg, Fe, and other metals associated with dissolving minerals, and the extent of redistribution of these weathering products was strongly controlled by the climatic regime. For example, while Cr was strongly retained in the B horizons of all soils, Mn, Co, and Ni were depleted from the B horizons of the soils from the wetter end of the climosequence. In the soils from the drier sites, redistribution of soluble elements such as Co and Ni was limited. These elements were excellent pedogenic indicators during the early stages of soil development.

These investigations have shown that weathering processes in weakly developed ultramafic soils produce trace element distribution patterns which can be observed using well established soil analytical procedures. Trace element distribution patterns provide useful insights into ultramafic pedogenesis which deserve increased attention in future investigations.

4. GENESIS OF SOILS DERIVED FROM ULTRAMAFIC MATERIALS AND TEPHRA IN THE SHULAPS RANGE: SOUTHWESTERN BRITISH COLUMBIA.

4.1 INTRODUCTION

Several pedological investigations have provided evidence that alteration of serpentine minerals occurred in soils from some locations in the U.S.A. (Wildman et al. 1968a,b; Rabenhorst et al. 1982, Maoui, 1966). In contrast, other ultramafic soils show little evidence for alteration of silicate clays (Ducloux et al., 1976) and the literature on ultramafic soils in glaciated regions generally describes soils at an early stage of pedogenic development with little evidence for mineral alteration.

Roberts (1980) described serpentinitic Regosols in Newfoundland with loam to sandy loam texture, very low Ca:Mg ratios, and sparse vegetation cover. These soils had very similar levels of Fe_p for all horizons. Horizon development in the Newfoundland soils was inhibited by extensive cryoturbation, attributed in part to a lack of insulating vegetation cover.

Schreier et al. (1987a) observed translocation of clays and Mg, Cr, Mn, and Ni into non serpentinitic soils which had been inundated and covered with a layer of asbestos rich serpentinitic sediment in northwestern Washington State. Serpentine and montmorillonite were present in the clay fractions of these materials. A weathering experiment showed that significant amounts of Mg, Cr and Ni were released from the sediments under acid conditions.

While many soils in western Canada have been influenced by additions of tephra, soils derived principally from tephra are of limited extent in British Columbia. In humid climates, weathering of tephra occurs rapidly, and the resulting soils typically have unique ion exchange characteristics owing to the presence of allophane, imogolite, and amorphous Al in combination with soil organic matter. Pedogenesis on tephra parent materials in cooler and drier climates may result in soils where these distinctive characteristics are weakly expressed or absent (Sneddon, 1973).

In some locations in southwestern British Columbia, tephra and ultramafic rocks are found together to give rise to polygenesis and polymorphism. This portion of the thesis reports on soils developed from tephra and ultramafic materials in a relatively cool, dry climate. The objectives of the study were to describe the soils in relation to the climatic setting and topographic position, determine the weathering status and the mineralogy, and investigate the polygenesis of ultramafic soils influenced by tephra.

4.2 STUDY AREA

One of the larger occurrences of ultramafic rocks in southwestern British Columbia is the Shulaps ultramafic complex, located at the eastern edge of the Coast Mountains. Leech (1953) delineated a ca. 25000 ha massif consisting of variably serpentinized harzburgite and dunite. The mineralogical composition of the rocks before serpentinization was approximately 85 percent forsterite with 12 percent enstatite. Other minerals present included fayalite, diopside and chromite.

The Shulaps ultramafic rocks were emplaced during the Triassic period, and were considered to be part a dismembered ophiolitic suite (Schiarizza et al. 1988).

Southwestern British Columbia was covered by a Cordilleran glacier complex which attained a maximum size approximately 15,000 years ago (Clague, 1981). Large parts of the southern Coast Mountains were ice-free 11,500 years ago (Souch, 1989), and soil development on exposed parent materials in mountain valleys began at about that time.

Bridge River tephra (ca. 2350 years old; Mathewes and Westgate, 1980) was deposited over the entire Shulaps complex and formed a veneer approximately 20 cm thick. The tephra consisted mostly of sand- and pea-sized pumice with 95 percent cellular groundmass (dacitic), four percent plagioclase phenocrysts and one percent hornblende phenocrysts (Leech, 1953). The tephra was redistributed by wind and water, resulting in exposure of the underlying ultramafic materials on steep sided gullies and small ridge tops, while small depressions were sites of accumulation.

Figure 4.1 shows the physical features of the study area. The Shulaps range consists of a branched ridge system, which is oriented in a northwest-southeast direction and separates the Marshall Creek and Yalakom River valleys. The rugged landscape of the Shulaps Range was shaped by alpine glaciation. The Yalakom tributary streams (Burkholder Creek, Retaskit Creek, Blue Creek) flow from well developed cirques and glacial troughs on the northeast side of the highest divide were carved by tributary glaciers, and large quantities of ultramafic materials were transported to the broad bench in the main Yalakom Valley. Most of this material

Shulaps Soil Genesis



Figure 4.1. Location of the Shulaps ultramafic complex, bounded by the Yalakom fault zone and the high ridge system of the Shulaps Range. The sampling locations are indicated by the profile numbers.

Shulaps Soil Genesis

was gravel and sand but considerable quantities of silty "rock flour" were also present.

The presence of sinuous meltwater channels running parallel to the Yalakom River, and cutting across the drainages of Burkholder and Retaskit Creeks was observed by Leech (1953). These prominent features were attributed to erosion of the ultramafic bedrock by meltwaters associated with stagnant ice which occupied the Yalakom valley during retreat of the Fraser ice sheet. The distribution of soil parent materials at the edge of a typical meltwater channel is shown in Figure 4.2, along with the positions of representative soil profiles. The morphology of these soils illustrates a common theme which was observed in the Shulaps soils; that soil development had progressed further for ultramafic paleosols buried under tephra layers than for ultramafic soils not affected by tephra. This observation likely indicates that the locations where tephra layers remained in place were the stable portions of the landscape, and that steep slopes suffered erosion of tephra- and serpentine-derived soils.

The serpentinitic rocks were very soft and fractured easily along numerous slip planes; as a result many of the parent materials in the valley were unstable, and earthflows were a common feature of the mid valley bench (Jones, 1988). The ultramafic parent materials observed were classified as till and colluvium.

Soil surveyors (Valentine et al. 1987) included the area below treeline in a map unit of the Borin association, and classified the soils as Orthic Dystric Brunisols.



Shulaps Soil Genesis

The climate of the area is strongly influenced by topography. Lloyd et al. (1990) presented climate data considered typical for the region which were presented in Table 3.1. The mid valley bench has dryer and warmer conditions than the higher elevation locations.

The vegetation zones of the region reflect the climatic characteristics (Lloyd et al., 1990), as illustrated in Figure 4.3, which shows an elevation cross section of the Shulaps Range and the Yalakom Valley, along with the topographic position of the soil profiles used for the study.

4.3 MATERIALS AND METHODS

Soils from high elevation sites near treeline and from mid elevation on a gently sloping bench of the Yalakom valley were described and sampled during the summers of 1989 and 1990. Six soil profiles, representing a fairly complete range of soil environments and parent material combinations were selected for detailed study. Morphological properties of the six profiles are presented in Table 4.1. More detailed information is available for these soils and other associated soils in Appendix 1. The soil profiles had variable thickness of tephra over ultramafic materials, leading to a polygenetic soil sequence.

Three profiles with little or no tephra were described. Site 1 was located on a barren area above treeline, and was free of tephra. Site 1101 was located on an eroding ridge at the edge of a sparsely vegetated glacial meltwater channel on the mid-valley bench and was also free of tephra. Site 1104 was located on the mid-



Table 4.1. Horizon depths (cm) and descriptions for ultramafic soils.

SAMPLE	DEPTH	DESCRIPTION
Blue Creek	ultramafic	till (Profile 1):
Ah	0 - 5	olive brown; 80 % coarse fragments; very few roots.
AC1	5 - 25	olive brown; 50 % coarse fragments; very few roots.
AC2	25 - 40	olive brown; 60 % coarse fragments; very few roots.
С	40 +	olive; 60 % coarse fragments; very few roots.
Burkholder	Lake ultrar	nafic till (Profile 1101):
Ah	0 - 8	dark grayish brown; 40 % coarse fragments; few roots
AC	8 - 33	olive gray; 75 % coarse fragments; abundant roots
С	33 +	olive gray; 75 % coarse fragments: no roots
Burkholder	Lake Inlet	ultramafic till (Profile 1104):
LF	15 - 1	leaves and decomposing twigs
н	1 - 0	discontinuous layer of humic material
Ah	0 - 3	very dark brown; 70 % coarse frag; abundant roots
Bm	3 - 30	olive brown; 80 % coarse fragments; few roots
С	30 +	olive gray; 80 % coarse fragments; few roots
Blue Creek	tephra and	ultramafic till (Profile 3):
LF	2 - 0	mor humus form
Bm1	0 - 15	olive brown; abundant roots; tephra
Bm2	15 - 48	light yellowish brown; abundant roots; tephra
C1	48 - 55	olive; plentiful roots; tephra
C2	55 - 62	light gray; plentiful roots; tephra
IIBm1b	62 - 66	dark yellowish brown; 5 % coarse frag; very few roots
IIBm2b	66 - 85	dark yellowish brown; 50 % coarse frags; very few roots
IIBm3b	85 - 100	olive brown; 50 percent coarse frags; no roots
IIC	100 +	olive; 50 % coarse fragments; no roots
Burkholder	Creek teph	ra and ultramafic till (Profile 5) :
LFH	5 - 0	pine needle litter layer
Ae	0 - 3	light gray; plentiful roots; tephra
Bfj	3 - 4	pale brown; plentiful roots; tephra
С	4 - 20	light olive brown; plentiful roots; tephra
IIAhb	20 - 22	black; 10 % coarse fragments; few roots
IIBm1b	22 - 23	dark brown; 50 % coarse fragments; few roots
IIBm2b	23 - 32	olive brown; 50 % coarse fragments; plentiful roots
IIBC	32 - 40	olive; 60 % coarse fragments; no roots
IIC	40 +	olive; 60 % coarse fragments; few roots
Small pond	tephra and	ultramafic till (Profile 7):
LFH	8 - 0	mossy, mor humus form
Ae	0 - 8	olive gray; abundant roots; tephra
Bf	8 - 12	dark yellowish brown; abundant roots; tephra
С	12 - 27	light yellowish brown; abundant roots; tephra
IIAhb	27 - 28	discontinuous horizon enriched in organic matter
IIBm1b	27 - 31	dark brown; 30 % coarse fragments; plentiful roots
IIBm2b	31 - 36	dark brown; 50 % coarse fragments; plentiful roots
IIC	41 +	olive; 60 % coarse fragments: few roots

valley bench near a small inlet stream to Burkholder Lake, and the surface horizon contained a mixture of ultramafic materials with a small amount of tephra.

Three composite profiles were described with well developed tephra-derived soils overlying ultramafic paleosols. Site 3 was located in a gently sloping area at treeline and the profile included a weakly developed tephra-derived soil. Site 5 was located on a steep slope in a forested area of the mid valley bench and the profile included a tephra-derived soil with thin Ae and Bfj horizons. Site 7 was located in a small depressional area on the mid-valley bench, and included a well developed tephra-derived soil with distinct Ae and Bf horizons.

Samples were air dried and the fine earth fraction (< 2 mm) was separated with a stainless steel sieve. The methods used to analyze the fine earth fraction were the same as those described in Section 3.3.2. An additional method used in this investigation was NaOH extraction with flash heating for the determination of poorly crystalline aluminosilicates (Jackson et al., 1986).

4.4 RESULTS AND DISCUSSION

4.4.1 Particle size analysis.

Particle size distribution curves (Figures 4.4, 4.5, and 4.6) indicate that the ultramafic soil materials mostly had low clay content, but various texture classes including clay, silt loam, sandy loam, loamy sand, and sand were present.

The sandy ultramafic materials were formed by physical breakdown along planes of weakness within the rock. This is illustrated in Plate 1, a thin section micrograph of a peridotite coarse fragment from site 3 showing the network of cracks within the rock. Breakdown of this rock would yield many grains in the 0.05 to 0.2 mm size range. The presence of alteration products lining the fractures within the rock is also shown in the micrograph. Small amounts of smectite may form in these fractures.

The effects of wind erosion and surface deflation are illustrated in the particle size distribution curves for profile 1 (Figure 4.4). As indicated by the flat portion of the curve, the Ah horizon was depleted in particles between 0.20 and 0.01 mm in diameter at this exposed, barren, high elevation site. For profiles 1101 and 1104, the surface horizons had higher silt and clay contents than the underlying horizons, indicating that particle size reduction by physical and chemical weathering may be important processes in the soils, and/or that additions of eolian materials had been received.

Particle size distribution curves for profiles 3 (Figure 3.3), 5 (Figure 4.5) and 7 (Figure 4.6) show that there was marked stratification within the composite profiles. Texture classes for the tephra samples were sand or loamy sand. The predominance of coarse grains in the tephra materials likely reflects the expected settling of large particles in close proximity to the source at Meager Mountain (80 km west of the study area). Bridge River tephra was present at Banff, Alberta as a silty material (Westgate and Dreimanis, 1967; King, 1986).

Shulaps Soil Genesis



Plate 4.1 Photomicrograph of thin section (x-polarized) of coarse fragment from profile 5, showing fracture pattern of serpentinized peridotite. Minerals present include forsterite (FO) and serpentine (S). This material readily breaks along fractures to particles less than 2 mm in diameter. Scale bar is 0.5 mm.



Figure 4.4. Particle size distribution curves for soils with little or no tephra influence.



Figure 4.5. Particle size distribution curves for composite soil profile at site 5, located on a forested slope on the mid-valley bench, overlooking Burkholder Creek.



Figure 4.6. Particle size distribution curves for composite soil profile at site 7, located on a level forested area near a small pond on the mid-valley bench.

The particle size distribution curves for tephra samples from site 3 (Figure 3.3) show that the C1 horizon had a much higher proportion of silt and very fine sand than the horizons overlying and underlying it. The tephra horizons in profiles 5 and 7 also showed marked textural changes, with finer-textured Ae and Bf horizons overlying coarser C horizons. These data suggest that the tephra was ejected in discrete events that produced materials with varying particle size, and/or that differential settling rates of coarse and fine particles through the atmosphere may have acted to stratify the deposit. Sneddon (1973) observed a sharp contact separating fine-textured ash from underlying coarse ash and lapilli in a soil derived from Bridge River tephra near the eruption source. He believed that an initially more violent eruption of coarse materials was followed closely by a less violent eruption of finer material.

The high percentage of sand-sized tephra in these weakly developed soils indicates that pumice grains were stable over ca. 2350 years in the dry weathering environment. Weathering of the finer-textured tephra materials in Ae, Bfj, and Bf horizons of profiles 5 and 7 was indicated.

The ultramafic paleosols from sites 3 and 7 had parent materials with silt loam texture and a range of particle sizes that approximated a normal distribution. These parent materials were commonly observed on the slopes of the mid-valley bench, and are interpreted as the product of comminution of ultramafic rock by glacier ice ("rock flour"). Soil 5 had a buried Ah horizon with a very high clay content. This thin layer of fine-textured ultramafic material may have been formed by weathering in situ, and/or it may have been transported to its present location. The site was on sloping ground with no obvious depressional areas near it, favoring

the first explanation, but there was a dramatic texture change between it and the underlying IIBm1b, favoring the second explanation. The particle size data did not indicate accumulation of illuvial clays in the B horizons of the buried ultramafic soils, but evidence for illuviation may have been masked by the coarse texture of the parent materials.

4.4.2 Soil chemical properties.

Chemical properties of the soils are presented in Table 4.2. Since these soils lacked carbonates, the values obtained for Leco C represent organic C. Organic C of the soils was similar to, or lower than values reported for Brunisols on other dry sites in the interior of British Columbia (Valentine et al. 1987). Profile 1 had very low C levels resulting from a combination of high elevation, slope instability, droughtiness, and soil fertility factors which severely restricted the growth of plants. Profile 1101 had a surface horizon of organic matter accumulation, and profile 1104 had a well developed Ah horizon, along with considerable accumulation of organic matter in the Bm horizon.

The difference in organic matter content can be considered a crude measure of plant response to soil conditions. These three serpentinitic soils had similar parent materials, but elevation differences and moisture status had a tremendous effect on soil development. Soils 1 and 1101 lacked tree cover, occurred on steep slopes, and were eroded, but soil 1101 occurred at a lower elevation, with slightly better plant growth and more soil organic matter. Soil 1104 occurred at the same elevation as soil 1101, but in a wetter area with a north east aspect, and the effects

HORIZON	SAMPLE	EXCHA	NGEA	BLE CATIO	ONS (cma	ol kg ⁻¹)	pН	ORG
	NO.	Ca	Mg	H ⁺ + Al ³⁺	SUM	Ca:Mg	H ₂ O	C%
PROFILE	1:							
Ah	9	0.5	6.9	n.d	7.5	0.08	7.0	0.5
AC1	10	0.5	9.5	n.d	10.1	0.06	6.9	0.5
AC2	11	0.3	10.8	n.d	11.2	0.03	6.9	0.4
С	12	0.5	10.2	n.d	11.0	0.05	7.2	0.1
PROFILE	1101:							
Ah	60	3.5	10.3	0.0	14.0	0.35	7.0	1.9
AC	61	1.3	7.1	0.0	8.4	0.18	7.2	0.6
С	62	0.2	5.1	0.0	5.3	0.04	7.3	0.1
PROFILE	1104:							
Ah	67	2.7	12.7	0.0	15.5	0.21	5.2	3.9
Bm	68	4.5	13.8	0.0	18.4	0.32	6.0	1.8
С	69	3.8	10.0	0.0	13.9	0.38	6.9	0.8
PROFILE	3:							
LF	19	14.4	21.4	3.8	37.1	0.67	4.1	39.0
Bm1	20	0.3	1.7	0.1	2.1	0.20	5.9	0.5
Bm2	21	0.1	0.6	0.0	0.8	0.17	6.1	0.1
C1	22	0.1	0.4	0.0	0.6	0.29	6.1	0.1
C2	23	0.1	0.2	0.0	0.5	0.36	6.2	0.0
IIBm1b	24	0.7	6.4	0.0	7.3	0.11	6.2	0.6
IIBm2b	25	0.6	7.1	0.0	7.9	0.09	6.3	0.3
IIBm3b	26	0.6	8.1	0.0	8.8	0.07	6.6	0.2
IIC	27	0.5	6.7	0.0	7.4	0.07	6.8	0.1
PROFILE	5:							
LFH	183	15.6	4.9	8.5	24.7	3.16	4.1	n.d
Ae	31	0.7	2.4	0.9	3.3	0.29	5.4	0.7
Bfj	32	1.1	2.4	0.6	3.8	0.45	5.7	1.1
С	33	0.7	2.9	0.0	3.7	0.24	5.7	0.7
IIAhb	34	9.3	42.2	0.0	52.1	0.22	6.4	4.2
IIBm1b	35	1.7	10.8	0.0	12.6	0.16	6.2	0.9
IIBm2b	36	1.4	9.3	0.0	10.9	0.15	6.5	0.7
IIBC	37	1.0	7.3	0.0	8.4	0.14	6.6	0.5
IIC	38,41	1.1	6.4	0.0	7.5	0.17	0./	0.3
PROFILE	7:							
LFH	44	19.0	5.8	7.3	32.1	3.29	4.6	40.2
Ae	45	1.0	0.4	1.8	3.2	2.28	4.6	1.5
Bf	46	1.5	0.6	2.3	4.4	2.28	5.1	2.1
C	47	0.3	0.1	0.5	0.9	3.44	5.4	0.4
IIAhb	none	n.d	n.d	n.d	n.d	n.d	n.d	n.d
IIBm1b	48	1.4	2.4	1.8	5.6	0.57	5.1	1.0
IIBm2b	49	2.4	4.6	0.9	7.9	0.53	5.6	0.5
IIC	51	3.0	8.3	0.2	11.5	0.30	0.2	0.3

Table 4.2 Chemical properties of Shulaps ultramafic soils.

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of increased soil moisture on plant growth and organic matter accumulation were significant.

For the tephra-derived soils, profile 3 had a thin LF horizon, and the underlying Bm1 had low organic matter content. The tephra soils at the lower elevations (sites 3 and 5) had thicker LFH horizons and the surface Ae and Bfj or Bf horizons were enriched in organic matter. These differences likely resulted from the combined influence of elevation and texture of the surface mineral horizons. Profile 3 occurred near treeline, and had only scattered forest cover, while the lower elevation sites were occupied by continuous forest stands. In addition, tephra materials in the surface horizons of sites 5 and 7 contained much more fine sand and silt than those at site 3, providing greater available water storage capacity and likely better fertility. The finer-textured C1 horizon which occurred below 48 cm in soil 3 would not have aided plant establishment by providing moisture retaining fine pores near the surface, and release of nutrients from the unaltered tephra in this horizon likely occurred slowly.

Profiles 3, 5, and 7 had buried ultramafic horizons enriched in organic matter. The high organic C content of the IIAhb at site 5 indicates that a well developed organic layer was present at this mid-elevation site when the tephra was deposited. A similar, discontinuous organic rich horizon was also observed at site 7, but was not sampled. The IIBm1b at site 3 had much lower C levels, indicating a weakly developed organic layer was present in the ultramafic soil at elevations near the modern treeline.

Since well developed organic layers in the modern soils on sloping sites in the area were associated with forest vegetation, this evidence suggests that treeline was below site 3 prior to deposition of the tephra. A lower treeline is typical of ultramafic landscapes (Brooks, 1987). The location of the modern treeline very near to site 3 may reflect a buffering effect of the tephra on toxic weathering products present in the ultramafic soils, which may have encouraged the survival of trees at higher elevation.

The pH values of soils 1 and 1101 were nearly constant with depth, indicating that weathering of the ultramafic parent materials was limited. Soil 1104 had a moderately acid surface horizon due to leaching and the presence of organic acids generated during decomposition of organic matter at this wetter location. For the tephra-derived soils, the pH values at soil 3 were the highest, suggesting that this soil had experienced the least amount of weathering. Soil 5 had moderately acid Ae and Bfj horizons, while soil 7 had the lowest pH values of the three tephra-derived soils. The trends in soil pH for the tephra-derived soils were reflected in their corresponding serpentinitic paleosols, indicating that the microclimatic and topographic factors affecting pedogenesis of the modern tephra soils and ultramafic paleosols 2350 + years ago were similar.

A ratio of exchangeable Ca:Mg lower than 0.7 is considered diagnostic for ultramafic soils (Alexander et al. 1985), and this value is thought to represent the threshold where plant growth may be adversely affected by the weathering products of ultramafic minerals. In this study, forest floor samples had higher Ca:Mg ratios than tephra-derived samples, which were higher than ultramafic soil materials. Very low Ca:Mg ratios were observed in the ultramafic parent materials, while the IIB

horizons had lower Ca:Mg ratios due to the leaching of Mg from serpentine minerals, biocycling of Ca by the vegetation, and/or additions of Ca in eolian materials.

The low Ca:Mg ratios of some tephra samples likely resulted from addition of eolian or colluvial ultramafic materials in this active landscape. Total elemental analysis (by XRF) of Bridge River tephra from the Shulaps area and from Kwoiek Creek sediments (Souch, 1990) are presented in Table 4.3, showing that the tephra collected from the Shulaps had higher Mg, Ni, and Cr contents than the tephra collected from Kwoiek Creek. This indicates that ultramafic materials were likely present as contaminants in the tephra-derived soils at the Shulaps area. In addition, scanning electron microscope examination of very fine sand fractions from the tephra-derived Bm2 of site 3 revealed significant numbers of ultramafic grains. The low CEC (sum of cations) values for the tephra horizons indicates that these materials had very little CEC buffering. The tephra-derived soil at site 7 had the highest Ca:Mg ratios observed for mineral soils in this study, which suggests that tephra layers at this site were free from contamination with ultramafic grains.

The tephra-derived soils at sites 5 and 7 had higher total exchangeable acidity than the ultramafic paleosols. The values represent unbuffered acidity at the natural soil pH determined by KCl extraction and were lower than values determined by Graham et al (1990) with the BaCl₂-triethanolamine method (buffered at pH 8.2) for ultramafic soils in California. Exchangeable acidity was highest for the tephra-derived soil at site 7, which coincides with low pH values determined for these soil materials.

Element (%)	Shulaps	Kwoiek Creek
SiO ₂	65.4	67.6
Al ₂ O ₃	17.3	14.7
Fe ₂ O ₃	3.8	3.0
MgO	3.0	1.0
CaO	4.2	3.1
Na ₂ O	4.5	4.2
K ₂ O	1.9	2.5
TiO ₂	0.4	0.6
Element (mg kg ⁻¹)		
V	61	66
Cr	162	36
Mn	620	640
Со	30	9
Ni	118	7
Cu	19	30
Zn	44	82
Rb	29	43
Sr	666	349
Y	11	18
Zr	103	160
Nb	10	10
Ba	646	803
Pb	10	19

Table 4.3. Composition of Bridge River tephra from two locations.

Sources:

Shulaps: Kwoiek Creek: this study (XRF) Souch, 1990 (XRF) Mineral horizons had less than $0.1 \text{ cmol}(+) \text{ kg}^{-1}$ of exchangeable Na (data presented in Appendix 1), and low levels of exchangeable K. The Bridge River tephra contained more Na and K than the ultramafic parent materials, but the exchange complex of the paleosols appeared relatively unaffected by additions of these elements. Dahlgren and Ugolini (1989) found that additions of Mount St. Helens tephra to Spodosols in Washington State resulted in short lived pulses of cations entering the buried Spodosol, where Ca, K and Al were strongly retained, while Na and Mg were leached from the solum. They concluded that podzolization had been relatively unaffected by additions of tephra.

To summarize, chemical properties of the soils such as organic C showed a trend towards increasing soil development at the lower elevations compared to the high elevation sites. In addition, the effect of increasing site moisture status on properties such as Ca:Mg ratio, pH, and exchangeable acidity illustrates an important aspect of microtopographic control on soil development at the lower elevations.

Chemical analysis confirmed the landscape relations observed between ultramafic soil development and the distribution of tephra (Figure 4.2). The modern tephra-free soils at sites 1, 1101, and 1104 were at an earlier stage of development than the associated ultramafic paleosols present in composite profiles under tephra. The tephra-free soils occupied the more active portions of the landscape, where soil development was inhibited by erosion.

4.4.3 Extractable Fe, Al, and Si.

Table 4.4 presents data for DCB, AOD, and PYRO extractions of tephra and ultramafic samples from the Shulaps soils. A rough increase in Fe_d , Al_d , Fe_p , and Al_p was observed for surface horizons from soil 1 to 1101 to 1104, following the trends of organic matter accumulation and pH described in section 4.4.2. The Fe_d content of soil 1 was nearly constant with depth, indicating that very little release of Fe from the parent material had occurred. The levels of Fe_o were similar to, and often exceeded Fe_d levels for these soils.

The tephra-derived soils had much lower Fe_d than the underlying paleosols due to compositional differences between the materials (the ultramafic rocks contained more Fe than the tephra), and perhaps also reflecting a shorter timespan for pedogenesis on the tephra (ca. 2350 years versus ca. 11500 years total for the serpentine). The maximum Fe_d content for the tephra-derived soil at site 3 occurred in the Bm1 horizon, indicating that redistribution of Fe was not an important process at this high elevation site. In contrast, tephra-derived soils on forested slopes at sites 5 and 7 had maximum Fe_d levels in the Bfj and Bf horizons, indicating that Fe was mobile in these soils.

Ultramafic paleosols had higher levels of Fe_d than the tephra-free ultramafic soils. The highest levels of Fe_d were extracted from the horizons immediately below the contact with the tephra. Although the Fe_d levels in the parent materials were similar, soil 3 had higher levels of Fe_d in the paleosol IIBm1b horizon than did soils 5 and 7. This result was unexpected because soil 3 occurred at high elevation and had weak profile development in the tephra materials. The parent materials for soil

	Fed	Ald	Sid	Feo	Alo	Sio	Fep	Alp	Sip
				p	ercent			-	
PROFIL	E 1:								
Ah	0.68	0.04	0.11	0.88	0.15	0.22	0.02	0.01	0.07
AC1	0.78	0.05	0.12	0.67	0.17	0.18	0.02	0.02	0.07
AC2	0.81	0.06	0.13	0.62	0.17	0.16	0.02	0.02	0.07
С	0.70	0.03	0.17	0.88	0.14	0.22	0.04	0.03	0.22
PROFIL	E 1101:								
Ah	0.86	0.03	0.13	0.54	0.07	0.08	0.05	0.01	0.13
AC	0.00	0.01	0.11	0.42	0.05	0.09	0.03	0.00	0.11
С	0.41	0.01	0.08	0.34	0.05	0.09	0.02	0.00	0.09
PROFIL	E 1104:								
Ah	0.98	0.29	0.16	0.96	0.39	0.16	0.26	0.22	0.08
Bm	0.79	0.11	0.09	0.83	0.19	0.10	0.10	0.06	0.05
С	0.73	0.06	0.07	0.62	0.14	0.10	0.06	0.03	0.05
PROFIL	Æ 3:								
Bm1	0.48	0.07	0.06	0.65	0.11	0.09	0.05	0.06	0.04
Bm2	0.11	0.03	0.02	0.22	0.09	0.04	0.02	0.05	0.03
C1	0.15	0.05	0.04	0.30	0.12	0.05	0.02	0.07	0.02
C2	0.05	0.02	0.01	0.19	0.05	0.02	0.00	0.03	0.04
IIBm1b	2.63	0.26	0.09	0.80	0.12	0.07	0.12	0.07	0.08
IIBm2b	1.92	0.18	0.10	0.78	0.20	0.13	0.12	0.11	0.15
IIBm3b	1.16	0.09	0.12	1.06	0.22	0.21	0.08	0.00	0.12
	0.90	0.05	0.11	0.97	0.10	0.25	0.04	0.05	0.11
PROFIL	E 5:							0.05	0.00
Ae	0.13	0.04	0.05	0.16	0.07	0.02	0.04	0.05	0.08
Bfj	0.39	0.11	0.06	0.32	0.17	0.04	0.09	0.11	0.12
С	0.16	0.04	0.05	0.22	0.06	0.02	0.03	0.04	0.07
llAhb	1.65	0.23	0.10	1.08	0.42	0.15	0.20	0.23	0.41
IIBm 1D	1.03	0.12	0.10	0.87	0.23	0.11	0.10	0.09	0.14
	1.15	0.10	0.09	0.74	0.14	0.00	0.05	0.04	0.10
	0.93	0.00	0.09	0.55	0.08	0.08	0.05	0.03	0.10
PROFIL	E 7.	0.05	0.02	0.51	0.00	0.000			
		0.04	0.06	0.09	0.05	0.01	0.04	0.05	0.05
Ae Bf	0.08	0.04	0.00	0.02	0.05	0.10	0.41	0.43	0.07
C	0.10	0.05	0.01	0.28	0.10	0.03	0.04	0.07	0.05
IIAhb	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
IIBm1b	1.02	0.16	0.06	0.49	0.20	0.04	0.10	0.15	0.07
IIBm2b	1.43	0.15	0.06	0.80	0.16	0.06	0.09	0.06	0.06
IIC	1.13	0.10	0.10	0.57	0.13	0.08	0.07	0.05	0.09

Table 4.4. Extractable Fe, Al, and Si from Shulaps soils.

3 contained 50 percent heavy minerals such as olivine, enstatite, amphibole and biotite (Section 3.4.4, and Figure 4.8) in the very fine sand fraction. Density separations were not performed on samples from sites 5 and 7, but nearby soils from Barren Valley had much lower heavy mineral content (about 10 percent). Biotite weathers rapidly in soils (Kodama et al., 1983), and Luce et al. (1972) observed that dissolution rates of Mg silicates decreased in the order forsterite > serpentine > enstatite. Therefore, the rate of release of Fe from soil parent materials depends on the extent of serpentinization and the presence of biotite. This provides a possible explanation for higher levels of free Fe in a soil which had less morphological profile development than soils from the low elevation sites. The levels of Fe_o for the ultramafic paleosols were highest in the lower solum.

Levels of Fe_d for ultramafic B horizons in the Shulaps soils were lower than values reported in the literature for ultramafic soils in other areas. For example, Miura et al. (1988) reported 15.7 percent Fe_d for a serpentinitic Eutrochrept in Japan, and Rabenhorst et al. (1982) reported 5.5 percent Fe_d for a serpentinitic Hapludalf in Maryland. These data indicate that the ultramafic soils from the Shulaps Range were less weathered than soils in unglaciated regions.

Levels of Fe_o were slightly higher than Fe_d for the tephra-derived samples, and Al_o was generally higher than Al_d for tephra and ultramafic materials. AOD has been shown to extract more Fe than DCB from finely divided magnetite (McKeague et al. 1971) and chlorite (Arshad et al. 1972). Sneddon (1973) observed that surface additions of Bridge River tephra may enhance the levels of Fe_o and Al_o extracted from underlying soils, but that levels of DCB and PYRO extractable elements were largely unaffected.

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Levels of Fe_p and Al_p were similar in the tephra and ultramafic samples, and tended to reflect the organic C content within each profile. While Fe_p constituted only a small fraction of Fe_d for a particular sample, Al_p values were similar to Al_d . The IIAhb at site 5 had a high organic matter content, was highly weathered, and had high levels of Fe_p and Al_p , suggesting that it acted as a trap for Fe, Al, and Si released from the tephra above. The ultramafic paleosol at site 3 had lower levels of Fe_p and Al_p immediately below the contact with tephra.

Levels of Fe_p and Al_p in the Bf horizon at site 7 were sufficient to meet the requirement for the Podzolic B (Agriculture Canada, 1987), but the horizon did not meet the morphological requirements (i.e. 10 cm thickness). The presence of large amounts of Fe_p and Al_p in the Bf horizon indicates that Fe and Al were translocated as organic complexes in this soil. The Bfj horizon from profile 5 had lower levels of Fe_p and Al_p .

The development of Ae and Bf horizons in tephra soils was closely related to microtopography and site moisture status. On wetter sites and in small depressions, bleached Ae horizons underlain by Bfj or Bf horizons were frequently observed. On drier sites and more convex slopes, less development of Ae and Bf horizons was observed. The development of these eluviated soils may also depend on the particle size characteristics of the tephra. In general, materials composed of fine sand and silt have higher specific surface, and faster weathering rates than coarse sands.

The tephra-derived samples did not have enough Al_0 and Si_0 to qualify as Andic materials. Shoji and Fujiwara (1984) estimated the allophane content of soils based on (Si₀ - Si_d). The low (Si₀ - Si_d) levels for tephra samples from this study

indicated that allophane was not an important constituent of the Shulaps soils, and that these coarse-textured materials had weathered slowly in the cool, dry climate of the area.

Table 4.5 presents results of NaOH extraction of some tephra and ultramafic samples (< 2 mm). These results show that amorphous materials may be present in small amounts in the C horizons of the tephra-derived soil at site 5. Ratios of Al/Si less than one reflect dissolution of a component with more Si than imogolite, allophane or kaolinite (Wada, 1989), and having a composition closer to a 2:1 phyllosilicate. These data suggest that amorphous materials present in the tephra layers near the surface of soil 5 may be translocated and accumulate in the underlying C and IIAhb horizons.

In summary, Fe_p most closely matched the differences in organic matter content, Ca:Mg ratio, pH, and morphology associated with pedogenesis of the modern tephra and ultramafic soils, but selective dissolution analysis did not provide satisfactory indications of pedogenesis for ultramafic paleosols. Fe_d was a good indicator of pedogenic development for tephra-derived B horizons, but not for ultramafic B horizons. These observations are similar to results obtained in Section 3.4.5.2 for other ultramafic soils in British Columbia.

	Al	Si	Al:Si
	perc	ent	
Profile 1101: Ah AC C	0.03 0.01 0.01	0.14 0.05 0.04	0.21 0.20 0.25
Profile 5: Ae Bfj C IIAhb IIBm1b IIBm2b	0.17 0.29 1.34 0.74 0.28 0.23	0.70 0.87 4.35 2.26 0.71 0.48	0.24 0.33 0.31 0.33 0.39 0.48
Profile 7: Ae Bf	0.11 0.25 0.07	0.62 0.97 0.19	0.18 0.26 0.37

Table 4.5 Results of NaOH extraction of Shulaps samples.

4.4.4 Mineralogy.

Samples from site 1 contained mostly serpentine in the fine sand fraction, while the fine silt and clay fractions contained serpentine and chlorite. The mineral assemblage did not vary with depth in this profile.

XRD results for clays from profile 1101 indicated that the fine clay fraction contained smectite > serpentine > chlorite. The coarse clays consisted of serpentine >> chlorite = smectite > talc. In this profile, the clays from Ah and C horizons also had the same proportions of each mineral.

The fine and coarse clays from soil 1104 also had the same mineral assemblage throughout the solum (Figure 4.7), even though soil pH values varied by more than 2 units in the Ah, Bm, and C horizons. The coarse clays contained chlorite = talc = serpentine > HI vermiculite. The fine clays contained smectite > serpentine > expanding chlorite.

These results show that modern ultramafic soils from the Shulaps area were at an early stage of weathering, with clay mineral assemblages in the solum which were largely derived from the parent materials.

XRD patterns for fine silt fractions of tephra-derived samples from the C1 horizon at site 3, and the Ae horizon at site 5 are presented in Figure 4.8. These samples were dominated by volcanic glass, giving high background and low peak heights on the XRD patterns. The most abundant minerals in both samples were plagioclase feldspar and quartz. A small amount of chlorite and talc was present in



Figure 4.7. X-ray diffractograms of fine and coarse clays: profile 1104.





the Ae horizon at site 5, likely reflecting colluvial or eolian ultramafic material that was mixed with the tephra at this steeply sloping site.

XRD patterns for the ultramafic-derived very fine sand fractions from the IIBm3b at site 3 and the IIAhb and IIC horizons at site 5 are also shown in Figure 4.8. The minerals indicated in these patterns were plagioclase, quartz, serpentine, talc, chlorite, forsterite, and amphibole. Small quartz porphyries occur throughout the ultramafic massif, and comminution of porphyritic rock during glacial transport likely resulted in the presence of quartz and feldspar in the very fine sands. Site 3 had lower amounts of serpentine, lacked chlorite and talc, and had significant amounts of forsterite in the very fine sand, indicating that the ultramafic parent materials were not as heavily serpentinized as those at site 5.

XRD patterns for silt and Mg-saturated clay fractions of the IIBm3b at site 3 are presented in Figure 4.9. The quantity of quartz, plagioclase and amphibole was much lower in the fine versus the coarse fractions, reflecting the instability of these minerals in clay size fractions. Small amounts of biotite and talc were present in all of these particle size fractions. Biotite was a constituent of porphyritic rocks in the area.

Chlorite and serpentine were the dominant minerals in the coarse clay fraction from the IIBm3b at site 3, along with a small amount of expanding chlorite. In the fine clay, smectite was present along with serpentine, and chlorite was less abundant. The content of biotite in the clay fractions declined in the upper solum of this ultramafic paleosol, indicating that pedogenic weathering of biotite had occurred.




XRD results for fine and coarse clays from profile 5 are presented in Figure 4.10. The fine clay fraction of the IIAhb contained smectite = HI vermiculite > serpentine = talc > chlorite. The IIC fine clays contained serpentine = expanding chlorite = talc = smectite. The smectite present in the IIC did not expand to 1.8 nm upon glycerol solvation. The coarse clay fraction of the IIAhb contained serpentine = talc = chlorite >> smectite. The coarse clay from the IIC contained serpentine = talc = chlorite >> smectite. The coarse clay from the IIC contained serpentine

Chlorite was greatly depleted in the IIAhb relative to the IIC, indicating that formation of smectite may have occurred at the expense of chlorite, possibly through expanding chlorite and HI vermiculite intermediates. For both horizons, the fine clay had more smectite and less serpentine, chlorite and talc than the coarse clay.

XRD patterns for the fine and coarse clays from the IIBm1b and IIC horizons of soil 7 (Figure 4.11) show that the clay mineralogy did not vary with depth in this soil. The minerals present in the fine clays were HI vermiculite > talc = serpentine. The coarse clays contained chlorite = serpentine = talc >> HI vermiculite. These clays from a profile with lower pH and higher Ca:Mg ratio were very similar to those described in the lower solum at site 5.

In summary, where biotite was present in the parent materials, it was depleted in the upper solum, indicating that dissolution had occurred during pedogenesis. The results also indicate that smectite was a product of ultramafic weathering in the soils of the Shulaps ultramafic complex. The environmental conditions of smectite formation in these soils are elusive, however. Most of the ultramafic paleosols of the area showed less Ah horizon development than profile 5,



Figure 4.11. X-ray diffractograms for fine and coarse clays from IIBm1b and IIC horizons of serpentinitic paleosol at site 7.

and evidence for different mineralogical compositions of IIB and IIC horizons was not present in most other profiles which were examined.

Smectite formation in serpentinitic soils in the Klamath Mountains, Oregon occurred mostly in poorly drained soils (Istok and Harward, 1982). The medium and coarse-textured soils of the Shulaps area were mostly freely drained, with little chance for reacting fluids to attain equilibrium in the solum. Bales and Morgan (1985) studied the dissolution kinetics of chrysotile and found it did not dissolve faster than rates reported for forsterite and enstatite, suggesting that physical breakdown of serpentinized peridotite may account for the presence of serpentine minerals in the clay size fractions of the Shulaps soils after ca. 11,500 years of soil formation since deglaciation.

4.5 SUMMARY

These investigations have confirmed the classification of the soils below treeline as Dystric Brunisols. Minor areas of soils classified as Regosols occurred on eroded ridge tops and recent landslides.

The environmental conditions of the Shulaps area are controlled by strong topographic gradients which were reflected in the morphological and chemical properties of the soils. Organic matter accumulated to a greater extent, and the exchangeable Ca:Mg ratio and pH were lower in soils developed in the wetter portions of the landscape at lower elevations compared to drier sites or high elevation sites. In general, the forested slopes at the lower elevations were covered by 10 to 30 cm accumulations of tephra. In wetter areas and local sites of runoff accumulation, the tephra layers developed a Podzol-like profile. The development of Podzol-like profiles occurred rapidly (ca. 2350 years) in the tephra, and was more pronounced in finer materials than in coarse-textured deposits.

Ultramafic materials were added to tephra-derived soils through colluvial and eolian processes, affecting the exchangeable Ca:Mg ratio. In contrast, tephra additions had little impact on morphological and chemical properties of the ultramafic paleosols.

There was no evidence for the presence of allophane in the tephra-derived soils. Large tephra particles had weathered slowly in the cool, dry climate.

The best morphological development (presence of a IIAhb), lower pH, higher Ca:Mg ratios, and higher organic C levels of the ultramafic paleosols coincided with the presence of the Podzol-like profiles in the modern tephra-derived soil. These observations were not substantiated by selective dissolution analysis for Fe, Al and Si, however.

The ultramafic soils at the Shulaps area exhibited an early stage of weathering compared to ultramafic soils from unglaciated regions, and a combination of climatic, topographic and parent material factors controlled pedogenesis. The dry climate of the study area restricted soil development because of low leaching intensity, low water activity, and restricted plant growth caused by water deficits. These effects were particularly evident on south facing slopes at mid

to lower elevations. The inhibitory effect of the ultramafic parent material on soil development was particularly obvious on eroded ridge tops where no continuous plant cover existed, and minimal soil development was partially attributed to a lack of biological activity. Low winter temperatures, a short growing season and summer moisture deficits likely inhibit plant growth and weathering reactions at higher elevations.

Mineralogy of the ultramafic paleosols from different areas within the ultramafic massif were similar, and the paleosols generally had uniform mineralogy throughout the solum. Biotite weathering was observed in one profile at high elevation, but biotite was not present in the low elevation parent materials. Alteration of ultramafic minerals was indicated by depletion of chlorite, serpentine, and talc from fine clays relative to coarse clays. In addition, smectite which appeared to be the product of chlorite alteration was observed in a buried IIAhb horizon.

The presence of buried IIAhb horizons at mid elevation sites, and the absence of such horizons at sites near the existing treeline was interpreted as evidence that treeline was at a lower elevation prior to deposition of the tephra.

The expression of pedogenesis in the ultramafic paleosols may have been restricted by low productivity of the original forest, climatic factors such as a lack of available moisture and short growing season, and the relatively short duration of pedogenesis since deglaciation.

5. WEATHERING PROCESSES OF ULTRAMAFIC AND TEPHRA-DERIVED PARENT MATERIALS

5.1 INTRODUCTION

Several studies of serpentine mineral dissolution were described in the literature review (Section 2.2.1), but few investigations have presented data on the simultaneous release of major elements and minor elements present in the serpentine crystal structure. Schreier et al. (1987a) showed that .017 M citric acid and .025 M oxalic acid leached significant amounts of Mg, Cr, Mn, Fe, Co and Ni from serpentinitic sediments in Washington State. A comparison of the weathering processes of serpentinitic and tephra materials will improve our understanding of the factors of soil formation affecting the polygenetic soils of the Shulaps Range and other serpentinitic soils in British Columbia.

This portion of the thesis describes the dissolution of three soil parent materials during a laboratory weathering experiment. The samples included (i) a typical massive serpentinite from the Shulaps area, (ii) a soft, powdery serpentinite from the Shulaps area, and (iii) Bridge River tephra. The objectives were (i) to determine the amount of major elements, Cr, Mn, Fe, Co and Ni released from the soil materials during leaching with dilute acids under controlled conditions, and (ii) to analyze the residues and original materials in order to elucidate the sources of elements that appeared in the solutions, and the processes affecting their release.

5.1.1 Chemistry of Cr, Mn, Fe, Co, and Ni

Transition elements assume a variety of oxidation states (Earnshaw and Harrington, 1973). Table 5.1 gives the oxidation states and ionic radii for some important ions in ultramafic soils.

Chromium occurs in Cr(III) and Cr(VI) oxidation states in natural environments, but Cr(III) is more common. Chromium(VI) is a powerful oxidant and will oxidize soil organic matter, reverting to Cr(III) in the process. Oxidation of Cr(III) to Cr(VI) may occur in the presence of Mn(IV). The balance of these redox processes depends on the amount of organic matter, the mineralogy of Mn oxides, and the sorption of Cr(III) by oxide surfaces. Manganese has several oxidation states, but Mn(II) and Mn(IV) are the most stable in aqueous systems at common values of electrode potential (Eh) and pH. Both Mn(II) and Mn(IV) are important in soils. Iron(II) and Fe(III) occur in natural systems, and both oxidation states are important in soils. Cobalt(II) and Ni(II) are the most common forms of these elements in soils. Oxidation states having electronic configurations with empty, half filled or completely filled d orbitals (e.g. FeIII, MnII) are stabilized as a result of the symmetrical distribution and minimum mutual repulsion of electrons in these configurations.

The data in Table 5.1 show that the ionic radius of transition metal cations is dependent on the oxidation state, electronic configuration (spin state), and coordination environment. Differences in ionic radii provide a partial explanation for the variable behavior of these cations during substitution, hydrolysis, ion exchange, and complexation reactions.

	Radius (Ar	Radius (Angstroms)				
	tetrahedral coordination	octahedral coordinatio				
Mg(II)	0.57	0.72				
Si(IV)	0.26	0.40				
	0.39	0.54				
		0.61				
$C_{\tau}(M)$	0.26	0.44				
Mn(II) low spin state	0.66	0.67				
Mn(II) high spin state		0.83				
Mn(IV)	0.39	0.53				
$\mathbf{F}_{\mathbf{A}}(\mathbf{I})$	0.63	0.78				
$E_{e}(III)$ low spin state		0.55				
Fe(III) high spin state	0.49	0.65				
re(III) high spin state	0.58	0.75				
Ni(II)	0.55	0.69				

Table 5.1. Ionic radii and oxidation states of important ions in ultramafic soils.

Source: Henderson (1979; p. 128-130).

Goldschmidt's rules (Goldschmidt, 1937 cited by Brownlow, 1979; p. 231) describe the expected range of substitution reactions for ions in crystal structures based on the ionic charge and ionic radius. Brownlow gave the following statement of Goldschmidt's rules:

"1. If two ions have the same radius and charge, they will enter into a crystallizing mineral with equal ease."

"2. If two ions have similar but not equal radii and the same charge, the smaller ion will be preferentially concentrated in early formed samples of a crystallizing mineral."

"3. If two ions have similar radii but different charges, the ion with the higher charge will be preferentially concentrated in early formed samples of a crystallizing mineral."

These rules help to explain observations that Al(III) and Fe(III) are the only ions capable of substituting for Si in tetrahedral coordination, while Al(III), Cr(III), Mn(II), Mn(IV), Fe(II), Fe(III), Co(II), and Ni(II) all form octahedral complexes with O donors.

Crystal field theory has been used to more accurately describe the substitution of transition metals in silicate structures. For example, considering the similar ionic radii of Ni(II) and Mg(II) and the higher electronegativity of Ni, early forming minerals such as olivine should not be enriched in Ni. The high Ni content of olivine is well known, however. Burns (1970) suggested this enrichment reflected a higher crystal field stabilization energy (CFSE) of Ni in the olivine structure relative to the magma. The CFSE for a particular transition metal cation is the energy difference between two possible electronic configurations, and depends on the field strength and orientation of coordinating ligands. Burns also discussed the implications of crystal field theory to weathering reactions, and stated that the behavior of transition metals during mineral weathering depends on the relative stabilities of hydrated and complexed ions in solution and in crystal structures. Transition metal ions generally occur in octahedral coordination in minerals, and as $M(H_2O)_6^{n+}$ ions in solution. Measurements indicate that the CFSE of transition metal ions in aqueous solutions and oxide structures are similar. For this reason, the properties of transition states (activated complexes) in mineral dissolution reactions may determine the extent of leaching.

Burns proposed that the CFSE of a seven coordinate (pentagonal bipyramid) activated complex may provide a measure of the ease with which ions could be removed from silicate structures. Large differences between the CFSE of the pentagonal bipyramid and the octahedral configuration were determined for Cr^{3+} and Ni²⁺, and these differences suggest that a high activation energy may inhibit release of these metals from ultramafic rocks undergoing lateritic weathering. Large differences in CFSE were also determined for Co^{2+} .

Upon release from a mineral structure, the mobility of a metal ion may be limited by the formation of insoluble hydroxides according to the following generic reaction:

$M^{2+}_{aq} + 20H^{-} ---> M(OH)_2.$

Figure 5.1 (compiled from several diagrams in Baes and Messmer, 1976) shows the total concentration of metal ions and their hydrolysis products as a function of pH in water. The solubility of most transition metals declines rapidly as pH values rise in the range of 6 to 8.



Figure 5.1. Total concentration of dissolved metals as a function of pH. (compiled from Baes and Messmer, 1976). The concentration of Fe³⁺ is for solutions saturated with goethite; Fe²⁺ for solutions saturated with Fe(OH)₂; Cr³⁺ for solutions saturated with Cr(OH)₃; Mn²⁺ for solutions saturated with Mn(OH)₂; Co²⁺ for solutions saturated with Co(OH)₂; and Ni²⁺ for solutions saturated with Ni(OH)₂.

According to Baes and Messmer, mononuclear Cr(III) species such as $CrOH^{2+}$, $Cr(OH)_2^+$, $Cr(OH)_4^-$, and probably $Cr(OH)_{3(aq)}$ form rapidly, but polynuclear species such as $Cr_2(OH)_2^{4+}$ form very slowly at 25 °C.

Figure 5.1 shows that Mn^{2+} is highly soluble below pH 8. The Mn^{2+} ion is resistant to hydrolysis, and $Mn(OH)^+$ occurs over a very small range near pH 8. The presence of Mn^{4+} in solution is unlikely because MnO_2 is extremely insoluble, and Mn^{3+} in solution rapidly dissociates to MnO_2 and Mn^{2+} .

The hydrolysis behavior of Fe^{2+} and Fe^{3+} are quite different. The Fe^{2+} ion is soluble over a wide pH range, while concentrations of Fe^{3+} are significant only in very acid solutions. The Co²⁺ ion is similar to Fe^{2+} , while Ni²⁺ is slightly less soluble in neutral to moderately basic waters.

Figure 5.2 (compiled from various diagrams in Brookins, 1988) shows the dominant soluble species for transition metals in relation to the Eh and pH limits of water. The positioning of the stability regions depends on all of the components of the solution, but this diagram is useful as a first approximation of metal behavior. In this diagram, phases whose solubility is independent of Eh have vertical lines separating the solid from solution. Insoluble redox species not shown on the diagram include Cr_2O_3 , MnO_2 , Mn_3O_4 , FeOOH, and Co_3O_4 . The field of Co^{2+} solubility would be reduced if CoCO₃ were considered.

Complexation alters the behavior of metal ions described in Figures 5.1 and 5.2, because the concentration of the free metal cation may be much smaller than the total dissolved metal concentration in the presence of complex forming ligands.



Figure 5.2. Stability fields for soluble species at Eh-pH conditions in water, and the superimposed range of Eh - pH measurements from citric acid (light shading) and water (dark shading) columns. (compiled from Brookins, 1988). The activity of all metal ions is fixed at 10⁻⁶ M.

In general, the stability of metal-ligand complexes with monodentate O donors depends on the basicity of the ligand. Therefore, complexes with the acetate (CH_3COO^-) ligand should have higher stability than for the nitrate (NO_3^-) ligand, because of its higher basicity $(CH_3COOH$ is a weaker acid than HNO_3).

The metal ions Al³⁺, Mg²⁺, Fe³⁺, Co³⁺, Cr³⁺, and Mn²⁺ are considered as hard Lewis acids (Sposito, 1981; p 76) and form their strongest complexes with electron donors of the second row of the periodic table (Morgan, 1987). In general, the ligand preference for hard Lewis acids is:

F > O > N = Cl > Br > I > S.

The bivalent transition metal cations with the exception of Mn^{2+} (it has a half filled d shell) are classified as borderline transition metals; they have weaker hydration shells and form moderately stable complexes with organic N, P, and S donors, Cl⁻, and S²⁻. The stability of the complexes with these ligands increases from Mn > Co > Ni.

Table 5.2 gives stability constants for metal complexes with citrate and acetate ligands. The stability constants reflect the equilibrium for the following type of reaction:

$M^+ + L^- ---> ML$ log K = log ([ML]/[M⁺][L⁻])

The data in Table 5.2 show that Mg^{2+} , Mn^{2+} , Fe^{2+} , Fe^{3+} , Co^{2+} , and Ni^{2+} all form stable complexes with the citrate ligand and less stable complexes with the acetate ligand. Generally, stability constants for Mg^{2+} and Mn^{2+} complexes are lower than for Co^{2+} and Ni^{2+} , which is expected from consideration of the Irving-Williams

	log K					
	citric acid: $M^x + cit^{3-} -> Mcit^{x-3}$	acetic acid: M ^x + ac ⁻ > Mac ^{x-1}				
<u>σ</u> 2+	3.4	0.51				
13+	9.6					
_3+		4.63				
r ³ +	3.7	1.40				
.n ² +	4.4	1.40				
-3+	11.5	3.40				
e ³	5.0	1.46				
0 ² ' i2+	5.4	1.43				

Table 5.2. Stability constants for metal-ligand complexes.

Sources:

Smith and Martell (1976) for all K except Norvell (1972) for Al³⁺.

series of metal-ligand stability (Sposito, 1989; p. 155). Higher stability constants are observed for the trivalent cations such as Fe^{3+} , Al^{3+} and presumably Cr^{3+} with citrate and acetate.

5.2 MATERIALS AND METHODS

The soil materials were collected from the Shulaps ultramafic complex. The Bridge River tephra (BR) and Barren Valley serpentine (BV) were the common parent materials forming the composite soils described in Chapters 3 and 4 of the thesis. The ID serpentine was a highly altered material often observed in outcrops in the Yalakom fault zone.

The BV serpentinite was a firm, compact material and was dark green to blue. Upon crushing the coarse fragments with a hammer or mortar, they shattered into angular and subangular particles of various sizes. This material was collected from the edge of a glacial meltwater channel at a depth of one meter.

The ID serpentinite was a soft material with a smooth greasy feel, and was easily crushed by light hand pressure to form a smooth powder. This material was light blue with small white flecks, and it was collected from a deep roadcut (about 13 m) in the Yalakom valley.

The BR tephra consisted of pea-sized pumice fragments. Individual particles of this hard material often had a porous appearance, but this was the most resistant of the three parent materials, requiring considerable effort to crush it to pass a .250 mm sieve. The BR tephra was light brown and was collected from a roadcut near Blue Creek.

Dilute acids were used to simulate the ionic strength of a soil solution. Two experimental designs were used. One experiment evaluated the stability of the soil materials in the presence of different ligands through the use of a batch technique where samples of the soil materials were reacted with various acids. Another experiment used a column apparatus to minimize the effects of particle abrasion which may be a problem with batch techniques. Column experiments more closely simulate surface chemical reactions because the continuous exposure of fresh surfaces is minimized. The column experiment also employed a lower soil:solution ratio (1:20 vs 1:10 for the batch experiment), and operated for a longer time period (52 days vs 9 days) than the batch experiment. In addition, the column solutions were periodically renewed.

For the weathering experiments, the samples were air dried, sieved through a 2 mm stainless steel sieve, then ground gently with a mortar and pestle to pass a 0.250 mm stainless steel sieve. The complete < 0.250 mm fraction of ground material was used for the batch experiment. For the column experiment, the sample was wet sieved through a 0.053 mm sieve because the presence of fine particles clogged the columns.

5.2.1 Batch experiment

The batch experiment involved adding 3.5 grams of soil material to 35 grams of extractant in a 50 ml screw cap centrifuge tube. Triplicate samples of the three

soil materials in .0166 M citric acid (pH 2.4), .0172 M acetic acid (pH 3.2), and demineralized water (pH 5.4) were reacted at 25°C for one, four, and nine days (two times two hour shaking periods per day) on a reciprocating shaker with temperature control. The shaker was only operated for four hours per day to minimize the effects of particle abrasion. At the end of the reaction period, the suspensions were centrifuged at 3600 g for 20 minutes (effectively removing particles smaller than 0.1 micron equivalent spherical diameter).

As a non-complexing and oxidizing acid, HNO_3 was also included. Triplicate samples in .016 M nitric acid (pH 1.9) were reacted at 25°C for nine days.

The pH, Eh, and electrical conductivity (EC) of the solutions were measured immediately after the reaction period had elapsed. The pH was determined with a combination electrode after calibration with commercially prepared buffer solutions. Eh was measured using a Pt electrode calibrated at 219 mv against a pH 4 suspension of quinhydrone in 0.1 M potassium acid phthalate (Bartlett, 1986). EC was measured using a conductivity meter and cell. The concentration of major and minor elements except Na and K were determined with ICP-AES, using multielement matrix matched standards. The instrument settings were optimized for each matrix. A Perkin-Elmer model 306 atomic absorption spectrophotometer was used to determine Na and K in the solutions.

The amount of an element released to solution was directly proportional to the solution concentration, because the soil:solution ratio was constant throughout the batch experiment. The original materials and residues were analyzed for total elemental content using XRF, and the non-toxic liquid Na-polytungstate was used to separate low and high density minerals for mineralogical analysis using XRD. Details of the heavy liquid separation, XRF and XRD procedures were described in Section 3.3.2.

Grain morphology of very fine sand fractions from the light and heavy mineral fractions were observed using a SEMCO Nanolab-7 scanning electron microscope equipped with an energy dispersive X-ray spectrometer (SEM-EDS) in the Geology Dept. at UBC. Samples for SEM were mounted on aluminum stubs using clear nail polish, and the samples were carbon coated with a DC arc coating system operating under vacuum. The SEM was run at 30 kV, and detail at a scale of about one micron were clearly observed.

5.2.2 Column experiment

In the column experiment, 50 gram samples of the soil materials were placed over 5 grams of plastic beads in plastic columns with neoprene stoppers at each end. Nylon mesh was used to hold the soil materials in the column while allowing the free flow of solution. Demineralized water and .0166 M citric acid solutions were circulated in a closed system upwards through the columns and into one liter solution reservoirs. The columns were air-free, but the solution reservoirs were open to the lab atmosphere. The temperature was $22 \,^{\circ}C \, +/- \, 3^{\circ}C$. The flow of solution was controlled at about 0.5 liter per hour by a Technicon peristaltic pump using 21 separate lines of tubing ((3 materials times 2 solutions times 3 replicates) + 4 blanks), all operating at the same speed. Small samples (4 ml) were withdrawn daily for measurement of pH, EC, and Eh. Every three days, larger samples (30 ml) were withdrawn for ICP-AES analysis of the solution composition. For the first 25 days, the reservoirs were not refilled as the sampling took place and occasional leaks occurred. After 25 days the reservoirs were refilled to one liter and maintained at that level immediately after sampling. The level of the solutions in the reservoirs was measured daily.

For the water columns, the solutions were renewed whenever the pH of the reacting solution reached 7.5. All solutions were renewed after 15 and 34 days by draining the reservoirs to the 0.201 level, and refilling with fresh solution.

Because the soil:solution ratio varied as leakage occurred and the columns were disturbed by sampling and renewal, the results of the column experiment are presented as cumulative amount released to solution over time. Cumulative release was based on the mass of an element present in solution on a particular day md:

$\mathbf{m_d} = (\mathbf{c_d}) \ (\mathbf{v_d}),$

where c_d is the solution concentration on day d, and v_d is the solution volume on day d. Values of v_d varied for the first 25 days of the experiment, and then remained at one liter for the rest of the experiment. The amount released to solution on a particular day, a_d was calculated as:

$a_d = m_d - (m_{d-1}) (p_d),$

where pd is the proportion of the solution volume that was carried over from the previous day. If no leaks occurred and no sampling were undertaken, p_d would equal 1. Removal of a .030 liter sample with renewal would give p_d of 0.97. When solutions were renewed, p_d equalled 0.2 (200 ml were carried over). Cumulative release was calculated as the sum of a_d for d = 1,...n.

The original materials and the residues were also analyzed using XRF, XRD, and SEM-EDS as described for the batch experiment.

5.3 RESULTS AND DISCUSSION

The effect of grinding the soil materials was to produce fresh surfaces and fine particles, with many high energy surface sites. For these reasons, the initial reaction occurred much faster than a surface reaction or transport controlled steady state characterized by the formation of a reaction border. For both experiments, the reaction slowed after an initial period of rapid dissolution.

The batch experiment used freshly ground materials, while materials for the column experiment were wet sieved to remove fine particles. For these reasons, the initial rate of release of elements to water observed in the batch experiment was slightly higher than in the column experiment. For citric acid, similar amounts were released in the early stages of batch and column experiments.

5.3.1 Batch experiment

5.3.1.1 total elemental analysis

Results of total elemental analysis and loss on ignition (LOI) of the samples are presented in Table 5.3. The two serpentine samples had higher LOI, MgO and Fe_2O_3 , and lower SiO₂, Al₂O₃, CaO, K₂O, and Na₂O content than the BR tephra. For the BR tephra, CaO and Na₂O were higher than K₂O, which is typical for plagioclase rich dacitic materials.

	SiO ₂ A	l ₂ O ₃ F	e ₂ O ₃ N	MgO C	aO N	Na ₂ O	к ₂ о	TiO ₂	LOI	SUM	
percent											
BV SERPENTINE	41.4	1.5	8.4	35.8	0.2	0.0	0.0	0.1	15.8	103.2	
ID SERPENTINE	38.8	0.9	7.1	38.4	0.8	0.1	0.0	0.0	17.0	103.0	
BR TEPHRA	65.4	17.3	3.8	3.0	4.2	4.5	1.9	0.4	5.1	105.5	
	v	Cr	Mn	Со	N , -1	i	Zn	Rb	Sr	Zr	
$=========mg kg^{-1} ====================================$											
BV SERPENTINE	28.5	1609	1012	96.0	20)75	35.7	0.2	4	17	
ID SERPENTINE	18.8	1732	899	96.3	20)84	29.1	0.2	4	14	
BR TEPHRA	61.5	162	620	30.0	1	18	44.5	28.6	666	103	

Table 5.3. Total elemental analysis (XRF) and LOI of parent materials.

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The ideal composition of serpentine minerals is 43.5 percent SiO₂, 43.5 percent MgO, and 13 percent H₂O, but the BV and ID serpentines had lower MgO and SiO₂, and higher H₂O than this ideal formula. The serpentines also had higher Fe₂O₃ content than reported values for chrysotile (Gronow, 1987; Bales and Morgan, 1985). According to Moody (1976), lizardite has higher Al₂O₃ and Fe₂O₃ than chrysotile, so the serpentine mineral in these parent materials may be lizardite. Leco C accounted for less than 0.2 percent of the BV and ID samples, indicating that LOI represents mostly H₂O.

The ID serpentine had more MgO, and less SiO_2 , Al_2O_3 , and Fe_2O_3 than the BV material. Both samples contained excess octahedral cations for the amount of serpentine that could be formed from the SiO_2 present. The compositional variations of these two serpentines likely reflect different conditions during serpentinization of the original ultramafic rocks, as well as different surficial environments.

The trace element composition of the serpentines was also different from the tephra. Chromium, Mn, Co and Ni were higher in the serpentine materials, while the BR tephra had higher levels of V, Rb, Sr and Zr.

5.3.1.2 pH EC, Eh

Figure 5.3 shows that the pH values of solutions in contact with the serpentine samples increased rapidly at the beginning of the experiment. For all treatments, the ID serpentine had the highest proton consumption and the BR tephra the lowest. The very high pH values associated with the ID serpentine, along



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with the higher MgO and H_2O content (Table 5.3) suggest that this material contained a small amount of brucite.

The pH values of the solutions in contact with the serpentines remained roughly constant or increased slightly after the first day. This indicates that dissolution occurred slowly after an initial stage of rapid proton consumption, probably enhanced by the presence of fresh surfaces and fine particles due to grinding. As an exception, citric acid continued to react with the BV serpentine throughout the experiment, suggesting that complex formation with citrate ligands enhanced dissolution at near-neutral pH values.

In general, the EC values (Figure 5.3) for water and acetic acid solutions increased as soluble ions were released to solution. EC values declined for citric acid solutions in contact with the BV and BR materials due to complex formation between citrate and metal ions released from the soil materials. Complex formation reduces the population of charged species in solution as illustrated in the following example where citric acid reacts with serpentine to form a soluble Mg-citrate complex and a Mg-depleted serpentine:

> $3H^+ + cit^{3-} + Mg_3Si_2O_5(OH)_4 --->$ Mg(cit)⁻ + H⁺ + Mg_2Si_2O_5(OH)_2.2H_2O.

The EC of citric acid solutions in contact with ID serpentine increased slightly during the experimental period, indicating that dissolution of this material continued after uncomplexed citrate was no longer present in the solution.

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The Eh values ranged from a low value of 290 mv to a high value of 380 mv, and generally declined slightly during the course of the experiment. Solutions in contact with ID serpentine had Eh values at the low end of the range, while solutions with BR tephra had the higher values. These data illustrate the interdependence of Eh and pH. At lower pH values, Eh values were slightly higher.

If proton consumption is considered a measure of the extent of weathering, these results show that the ID serpentine was most susceptible to acid weathering in the presence or absence of complex forming ligands, the BV serpentine was intermediate, and the BR tephra was most resistant.

5.3.1.3 major elements

The concentrations of Si and Mg in the solutions are shown in Figure 5.4. The amount released to these solutions generally increased in the order citric acid > acetic acid > water. Levels of major elements in nitric acid solutions were similar to the levels in acetic acid. These results reflect the pH of the solutions and the presence of the complex forming citrate ligand compared to non-complexing acetate.

In general, Si was released rapidly at the beginning of the experiment, and then a period of slower release occurred. For the acid solutions, BR tephra released more Si with each measurement. The BV sample also released Si to the acid solutions throughout the experiment, but the Si concentration of the citric acid solution declined after the fourth day, perhaps reflecting a solubility limit near 100



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to 120 mg l⁻¹ for Si in this solution. ID serpentine released much lower amounts of Si than BV serpentine or BR tephra.

Large amounts of Mg were released from the two serpentine samples under acid conditions, while much lower Mg concentrations were observed for the solutions in contact with the BR tephra. The ID serpentine reacted quickly with all solutions, then the concentration of Mg remained roughly constant. The BV sample reacted more slowly than the ID sample, but after nine days equal amounts of Mg had been released from the two serpentines. The limit on total Mg concentration in the citric acid solutions appeared to be near 600 mg l^{-1} .

The molar ratios of total Mg:Si (by XRF) for the serpentine samples, and the molar ratios of Mg:Si released to water, acetic acid, and citric acid are shown in Table 5.4. These results show that both samples dissolved incongruently. The ID sample released large excesses of Mg relative to Si for all treatments. For the BV serpentine, Mg was preferentially released under acid conditions, while higher pH values (in water) favoured release of Si relative to Mg.

Incongruent dissolution as observed for the BV sample was also observed by Wildman et al. (1968a). These authors found that solutions with higher CO_2 partial pressure (lower pH) extracted more Mg from California serpentines, but after long time periods, the solutions tended towards congruent dissolution. There was no consistent relation between the Mg:Si ratio of the California serpentines and the composition of the weathering solutions at higher pH values.

Table 5.4. Molar ratios of Si:Mg in original samples and in solutions.

	Total Si:Mg	Demin water		Acetic acid		Nitric acid	Citric acid	
		1 day	9 days	1 day	9 days	9 days	1 day	9 days
BV SERPENTINE :	0.78	2.0	2.2	0.27	0.33	0.29	0.19	0.15
ID SERPENTINE:	0.68	.002	.002	.004	.001	.001	0.07	0.06

The composition of solutions contacting the serpentine materials after nine days is shown in Figure 5.5 relative to the stability fields for serpentine and brucite determined by Wildman et al. (1971). Using the stability constants in Table 5.2, and assuming that all Fe in solution was complexed with citrate, calculations showed that the concentration of uncomplexed Mg²⁺ was near 300 mg l⁻¹ for the citric acid solutions contacting BV and ID serpentine.

Figure 5.5 shows that solutions contacting BV serpentine are undersaturated with respect to serpentine while the ID solutions were oversaturated relative to serpentine, but undersaturated relative to brucite. These results are consistent with the presence of brucite in the ID sample.

The concentration of Fe, Al, and Ca in solutions from the batch experiment are shown in Figure 5.6. Very small amounts of Fe were released from all materials in water and acetic acid solutions. Examination of Figure 5.2 shows that Fe^{2+} is not stable in solution (relative to FeOOH) at neutral to alkaline pH values and Eh near 350 mv. Much higher levels of Fe were present in the citric acid solutions in contact with BV serpentine and BR tephra, reflecting the lower pH values and the presence of the complex forming citrate ligand. Very low amounts of Fe were released from the ID serpentine, which maintained pH values over 7.5 for all solutions.

Water released more Fe from the BV sample than acetic acid, even though the pH was over two units higher. This observation may reflect tetrahedral substitution of Fe for Si in the serpentine structure, and incongruent dissolution favouring Si at near-neutral pH values may result in release of Fe associated with Si. The Fe was likely present as colloidal material in the solutions.



Figure 5.5. Composition of solutions contacting serpentine materials after nine days, and the stability fields for serpentine and brucite determined by Wildman et al. (1971).



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More Al was released from the BR tephra than from the serpentines, reflecting the higher total Al content of the tephra parent materials. Release of Al from the BR tephra sample was most rapid in the first day of the experiment, and was highly dependent on pH and the presence of the citrate ligand.

The dependence of Al release on complex formation may be illustrated by comparison of acetic, nitric, and citric acid solutions. Acetate (Table 5.2) and nitrate form much weaker complexes with polyvalent metal cations than does citrate. After nine days a nitric acid solution in contact with BR tephra was slightly more acidic (pH 3.0 vs pH 4.0) and contained ten times more Al (57.6 mg l⁻¹ vs. 6.3 mg l⁻¹) than the acetic acid solution as a result of the lower pH. In the presence of citric acid at pH 3.4, complexation enhanced dissolution of the tephra and the total Al concentration in solution was 128 mg l⁻¹. A similar result was obtained for Fe in acetic, nitric, and citric acid solutions in contact with the BR tephra. These results indicate that complex formation enhanced the dissolution of Fe and Al.

Very low concentrations of Ca (Figure 5.6), Na and K were present in the solutions in contact with the serpentines. The BR tephra released large amounts of Ca to the citric acid solution at the beginning of the experiment. Detailed solution analysis revealed that large amounts of P were released in conjunction with Ca, suggesting that apatite dissolution may have occurred. The release of Ca, Na and K from the BR tephra was dependent on the solution pH, but was insensitive to the presence of citrate. For example, after nine days the average concentration of Ca in nitric acid solutions was 78 mg l⁻¹ while the citric acid solutions had 75 mg l⁻¹. The concentrations of Na (10.4 vs. 11.8 mg l⁻¹) and K (6.8 vs 6.4 mg l⁻¹) in the nitric and

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citric acid solutions were also very similar, indicating that dissolution of these monovalent ions was not enhanced in the presence of the complex forming ligand.

In summary, the serpentine materials experienced incongruent dissolution. Magnesium was preferentially released from the BV sample under acidic conditions, while at higher pH values Si release was favoured, along with small amounts of Fe. The presence of brucite was indicated for the ID sample by a very rapid release of Mg and the high pH values in all solutions.

The dissolution of Mg, Al, Ca, Na, and K strongly reflected the different total elemental composition of serpentine and tephra materials. In general, release of these elements was enhanced at lower pH values. Dissolution of Fe, Al, and Mg was enhanced in the presence of the citrate ligand, while Ca, K, and Na were not affected.

As a measure of the rate of weathering, the largest pH changes occurred for the serpentines, especially the ID sample. A different measure would be the total amount of dissolved cations released to solution. Total dissolved cations (Al, Ca, Co, Cr, Fe, K, Mg, Mn, Na, Ni, Si) from the 3.5 gram samples of BV, ID, and BR were 30.2, 23.6, and 20.7 mg after nine days in citric acid, and 8.9, 11.4, and 9.2 mg after nine days in nitric acid. For water solutions, the total dissolved cations were 1.74, 2.40, and 0.55 mg for the BV serpentine, ID serpentine, and Br tephra respectively. These data show that under acid conditions in a closed system, the three materials dissolved at similar rates, while the serpentines dissolved faster than the tephra at neutral and slightly alkaline pH values.

5.3.1.4 Cr, Mn, Co, and Ni

Very low levels of Cr, Mn, and Co were released from all samples in the presence of water (Figure 5.7), reflecting the low concentrations of these elements in the BR tephra and the alkalinity (pH 9.3) of water in contact with the serpentines. Examination of Figure 5.1 shows that the solubility of Cr^{3+} and Ni^{2+} is very low at pH values near nine, and Figure 5.2 shows that Co^{2+} and Mn^{2+} may be subject to oxidation at high pH and Eh values near 350 mv. Schreier et al. (1987a) also showed that very low amounts of Cr, Mn, Co and Ni were released from serpentinitic sediments to water.

More Cr was released to water from the BV serpentine than to acetic acid. This result coincides with the preferential release of Si and Fe at near-neutral pH values, and may reflect tetrahedral substitution of Cr in a manner analogous to the behavior of Fe (discussed in previous section).

The release of Ni to water exceeded the release of other trace elements, and BV serpentine released more Ni than ID serpentine or BR tephra. Figure 5.1 indicates that the solubility of Ni²⁺ is highly dependent on pH in mildly alkaline solutions. The significance of soluble Ni levels near 0.2 mg l⁻¹ to plant growth is not known, although Proctor and Woodell (1975) cited evidence that levels of a few mg Ni l⁻¹ in solution cultures may elicit acute toxicity in plants. The Ni levels in water contacting BV serpentine are lower than these values, but may still be significant if present for long time periods.



Figure 5.7. Concentrations of Cr, Mn, Co, and Ni in solutions in contact with serpentine and tephra materials during the nine day batch experiment.
For the citric acid solutions, the largest amount of Cr was released from the ID sample, and release occurred mostly in the first day of the experiment. Slightly more Cr was released from this sample than Fe, even though the total concentration of Fe in the ID serpentine was 30 times higher than Cr. The BV serpentine released Cr throughout the experiment, and the Cr levels in solution were about one percent of the Fe levels. The BR tephra released very low, but detectable levels of Cr to citric acid solutions.

The BV serpentine released large amounts of Mn to citric acid at the beginning of the experiment, and the solution concentration achieved the highest levels of the three samples. The BR tephra released more Mn to acetic acid than the serpentines. The amount of Mn present in solutions of nitric acid ($3.0 \text{ mg } l^{-1}$) and citric acid ($3.9 \text{ mg } l^{-1}$) in contact with BR tephra were very similar, indicating that pH was a more important factor than complexation in Mn release. For the citric acid solutions, BV serpentine released large amounts of Mn at the beginning of the experiment, and the solution concentration achieved the highest levels of the three samples.

The behavior of Co in citric acid solutions was similar to that described for Mn, with BV serpentine releasing the largest amounts, and much smaller levels being released from ID serpentine and BR tephra. The BR tephra also released slightly more Co than the serpentines to acetic acid solutions.

Both serpentines released large amounts of Ni to citric acid solutions early in the experiment. The amount of Ni released from the ID sample was ten times higher than the amount of Fe released. For the BV serpentine, Ni release continued for the first four days of the experiment, following a trend similar to Mg and Fe, and coinciding with increasing pH values.

In summary, the release of trace elements generally followed patterns established for the major elements. The coincidence of incongruent dissolution favouring Si and the release of small amounts of Cr from the BV sample to water suggests that small amounts of Cr may be associated with Si in the serpentine structure.

The levels of Ni in water solutions contacting the BV serpentine were below values which elicit acute toxicity in plants, but the chronic effects of such Ni levels may be significant. The amounts of Cr and Co released to water were much lower than Ni, and support the conclusions of Proctor and Woodell (1975) and Brooks (1988) that toxic effects of Ni to plants and soil microorganisms are more likely to occur than Cr or Co toxicity.

Although very low levels of Fe were released from the ID sample, the highest Cr and Ni levels of any sample were released from this material to citric acid,

indicating either that Cr and Ni do not occupy the same sites in the crystal structure as Fe, or that Cr and Ni have lower stability in the sites.

5.3.2 Column experiment

5.3.2.1 mineralogy

Figure 5.8 presents XRD results for the soil materials used in the column experiment. Serpentine was the only mineral detected in the BV and ID samples. The serpentine mineral present in the BV sample was likely lizardite, since it has a high Fe content (Section 5.3.1.1) and there were relatively strong diffraction peaks at 0.460, 0.249, and 0.215 nm (Bailey, 1980; p 18). The ID serpentine has weaker or absent peaks at these locations, suggesting that this mineral may be antigorite, although identification of serpentine polymorphs using XRD alone is difficult.

The presence of small quantities of brucite in ID serpentine was suggested by the results from the batch experiment, but this mineral was not detected using XRD. This may reflect (i) it was present at concentrations below the XRD detection limit, or (ii) it was removed during wet sieving of the material for use in the column experiment.

Small amounts of heavy minerals were separated from the serpentine samples using heavy liquid. Magnetite was the major component present in the heavy mineral separate for both of the serpentine samples. The heavy fraction comprised four percent of the BV material, and six percent of the ID material.



Figure 5.8. X-ray diffractograms for the 0.053-0.250 fraction of BV serpentine, ID serpentine, and BR tephra. Minerals present include serpentine (S), serpentine lizardite (SL), plagioclase feldspar (F), and quartz (Q)

The BR sample contained mostly plagioclase and quartz, with heavy minerals such as magnetite, biotite and hornblende making up approximately 10 percent of the material.

No change was observed in the diffractograms obtained for residues removed from the citric acid columns after 54 days compared to the diffractograms of the original materials.

5.3.2.2 demineralized water columns

Results of solution analyses for the water columns (averages of three replicates) are presented in Figure 5.9. The patterns of pH change were broadly similar to the results observed in the batch experiment. For example, ID serpentine maintained the water at pH values over 8.5 throughout the 54 day experiment, the solutions in contact with BV serpentine had near-neutral pH values, and the pH of water percolating through BR tephra had slightly acid pH values. A gradual decline in the solution pH for the ID columns reflects the daily renewal of these solutions.

Figure 5.9 also presents the cumulative release of major elements to water, showing that BV serpentine released more Si than Mg, while large amounts of Mg were released from ID serpentine in the early stages of the experiment. After six days, the rate of Mg release from ID serpentine slowed and the rate of Si release increased shortly after, perhaps indicating that an initial period dominated by brucite dissolution was followed by a period where serpentine dissolution predominated.



Figure 5.9. Solution pH values, and cumulative release of Si, Mg, and Na from serpentine and tephra materials to demineralized water during a 54 day column experiment.

In the later stages of the experiment, release of Si and Mg more closely reflected congruent dissolution for BV serpentine. For example, the molar ratio of Si:Mg released from BV serpentine on day 54 was 0.87 compared to a total Si:Mg ratio of 0.73, indicating a slight excess of Si. Luce et al. (1972) also observed that initial incongruent dissolution of Mg silicates gave way to congruent dissolution after longer time periods. For ID serpentine, the molar ratio of Si:Mg released to water on day 54 was 0.33, which represents a considerable degree of incongruency compared to the total Si:Mg ratio of 0.66.

Release of Fe, Al, Ca, Na, and K to water solutions from the serpentine samples were near detection limits for the ICP-AES, and no Cr, Mn, Co or Ni was detected in the solutions. The absence of fine particles, and the possible loss of soluble constituents during wet sieving likely account for the low release of these elements in the column experiment compared to the batch experiment. In addition, examination of Figure 5.2 shows that Fe, Co, and Mn may be oxidized and precipitate from solution as insoluble oxides in the range of Eh and pH characterizing the solutions, while Cr^{3+} (and Al^{3+}), and Ni^{2+} are subject to the formation of insoluble hydroxides.

The BR tephra dissolved more slowly than the serpentine samples at the near-neutral pH values present in the water columns. The amount of Si and Na released from the tephra exceeded Mg release. About one mg of K was also released from the tephra during the 54 day experiment.

5.3.2.3 citric acid columns

pH, EC, and Eh:

Figure 5.10 shows the changes in pH, EC, and Eh for the citric acid columns (averages of 3 replicates) during the 54 day experiment. For all samples, the pH values were lower than those occurring during the citric acid batch experiment. The pH values declined sharply after the solutions were renewed on days 15 and 34. The decrease in pH after 25 days occurred when the solutions were topped up to one liter, where they were maintained for the remainder of the experiment. The dramatic variation of pH in response to disturbance was characteristic of a dynamic system with a fast tendency to equilibrium. In the later stages of the experiment, the response was less dramatic, which may be related to a modification of surfaces as dissolution occurred.

In the early stages of the experiment, the pattern of changing pH for solutions in contact with the soil materials was similar to the results from the batch experiment, with the ID serpentine showing the greatest pH change and the tephra the least. After about 20 days, the BV serpentine solutions had slightly higher pH values than the solutions in contact with ID serpentine.

Electrical conductivity of the solutions in contact with serpentine varied in opposition to the pH. In the presence of uncomplexed citrate, dissolution may lower the EC (please see discussion in Section 5.3.1.2). The EC values of solutions percolating through the BR tephra were lower than those of solutions in contact with the serpentines.



Figure 5.10. pH, EC, and Eh values of citric acid solutions percolating through BV serpentine, ID serpentine, and BR tephra during a 54 day column experiment.

The Eh values for the solutions declined shortly after the experiment began, and remained in the sub-oxic range for the duration of the experiment. Figure 5.2 includes a plot of the Eh-pH range for the citric acid columns, indicating that Mn^{2+} , Co^{2+} , and Ni²⁺ would be the most stable oxidation states of the free metal ions in these solutions. Hydrolysis of uncomplexed Cr^{3+} would be expected at pH values greater than 4, and uncomplexed Fe^{2+} may be subject to oxidation and precipitation as FeOOH.

In summary, the pH changes reflect disruptions which occurred during renewal and refilling of the solution reservoirs. The serpentines had a much greater impact on solution pH than the tephra throughout the experiment. In addition, the serpentine columns represent dynamic chemical systems, where pH, EC, and Eh respond to disturbance, and then tend rapidly to attain a new equilibrium.

Major elements

The cumulative release of Si, Mg, Fe, and Al from the soil materials to citric acid is presented in Figure 5.11. The relative amounts of these elements released from the BV serpentine, ID serpentine, and BR tephra during the early stages of the experiment followed the same trends as were described for the batch experiment. For example, the serpentines released more Mg than the tephra, and the tephra released higher amounts of Al, Ca, Na, and K. Similar amounts of Si were released from the three soil materials in the citric acid columns although the pattern of release varied, emphasizing another trend that was partially observed in the batch experiment. The serpentines dissolved rapidly, and the dissolution process quickly responded to addition of fresh acid by a rapid adjustment of the system. Dissolution





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of the BR tephra was less sensitive to these short term fluctuations, and element release was generally steady.

The concentration of Si in solutions contacting the serpentines rapidly stabilized near 100 mg l^{-1} after the systems were disturbed, suggesting that solubility factors controlled dissolution of Si. For the BR tephra, dissolution was more likely controlled by reaction kinetics, because Si was released consistently throughout the experiment.

The behavior of Mg also suggests that Mg^{2+} rapidly achieved equilibrium in the solutions contacting the serpentines. For most of the experiment, the total Mg^{2+} in both of the solutions was about 600 mg l⁻¹. As was discussed in Section 5.3.1.3, about 300 mg l⁻¹ was likely present as the free Mg^{2+} ion. After three disturbances, the release of Mg slowed slightly, but both serpentine samples continued to dissolve incongruently for the duration of the experiment. During the last 15 days, the molar ratio of Si:Mg present in the solutions was near 0.1, indicating that a large excess of Mg was released under acid conditions.

The release of Fe in the early stages of the citric acid column experiment was also very similar to the results observed in the batch experiment. The BV sample released more Fe to the citric acid solution than the BR tephra and the ID serpentine released the least amount of Fe. The two serpentines contained similar amounts of Fe, but the BV material released Fe much more readily than the ID sample. In the later stages of the experiment, the release of Fe from ID serpentine increased slightly, probably in response to lower solution pH.

The release of Ca (Figure 5.12) from the BR tephra was very rapid in the early stages of the column experiment, then slowed dramatically. This behavior represents an exception to the pattern of steady release generally associated with the tephra, and probably indicated the presence of apatite, because P was also released during this stage (please see discussion in Section 5.3.1.3).

In summary, the column experiment showed that the rapid release of Mg, Si, and other elements from the serpentines was a reflection of a dynamic system with a fast tendency to equilibrium, but after three cycles of disturbance and 54 days of leaching, the release of Mg from BV and ID serpentines slowed slightly.

With the exception of Ca, cumulative release of elements from the BR tephra followed a steady trend that was not sensitive to additions of fresh acid. This likely occurred because dissolution of the tephra was kinetically controlled and far from equilibrium.

The total amount of Si, Mg, Fe, Al, Ca, Na, and K dissolved from BV serpentine, ID serpentine, and BR tephra was 1908, 1860, and 717 mg, indicating that in open systems, where leaching may take place, the serpentines dissolved at a faster rate than the tephra.

Cr, Mn, Co, and Ni

The release of Cr, Mn, Co, and Ni (Figure 5.13) generally coincided with the trends described for the batch experiment. In addition, the release of Co was strongly enhanced by the renewal of the solutions, and the levels of Co in the



Figure 5.12. Cumulative release of Ca, Na, and K to citric acid from serpentine and tephra materials in a 54 day column experiment.





and tephra materials during a 54 day column experiment.

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solution declined considerably once the pH started to rise. A similar, although less dramatic effect was observed for Mn, but examination of Figure 5.2 indicates that Co^{2+} and Mn^{2+} should not be subject to oxidation or precipitation in the Eh-pH range of the citric acid columns. The loss of these metals from solution appeared to coincide with the attainment of equilibrium for Mg²⁺.

As was discussed in Section 5.3.1.4, the ID serpentine released large amounts of Cr and Ni. In the early stages of the experiment, the amount of Ni released from ID serpentine exceeded the amount of Fe released, although Ni concentrations declined in the later stages of the experiment, while the release of Fe accelerated.

In summary, the behavior of the transition metals during dissolution was more clearly observed in the column experiment. The depletion of Co and Mn from solution under conditions where the bivalent cations should be stable points out the limitations of using generalized stability diagrams as a measure of element mobility.

Total elemental analysis and mass balance

Table 5.5 provides total elemental analysis data determined by XRF for the tephra and serpentine materials before and after the weathering experiment. The major element composition of the original materials used in the column and batch experiments (Table 5.3) were very similar despite the removal of silt and clay from the column experiment materials by wet sieving. For the trace elements, Cr levels were also very similar, but loss of Co and Ni from the ID serpentine occurred during

Total elemental analysis (XRF) and LOI of materials from column experiment. Table 5.5.

	si02	A1203	Fe203	обw	CaO	Na ₂ 0	K ₂ 0	Ti02	IOI	NUS	Сr	Мn	cc	Nİ
					perce	ent						6w===	kg ⁻¹ =	
BV original	39.7	1.1	8.4	36.4	0.2	0.1	0.0	0.0	15.9	101.7	1696	838	69	2114
BV citric	42.6	1.1	8.1	34.5	0.2	0.1	0.0	0.0	15.6	102.3	1512	575	34	1572
ID original	37.9	0.9	7.2	38.0	0.8	0.0	0.0	0.0	16.9	101.8	1753	864	85	1661
ID citric	40.0	0.9	7.5	35.8	0.8	0.1	0.0	0.0	16.2	101.3	1527	620	52	410
BR original	61.6	17.1	4.2	3.3	4.9	4.6	1.6	0.5	4.6	102.4	186	666	34	101
BR citric	63.1	17.5	3.9	2.2	4.8	4.8	1.7	0.5	4.3	102.7	167	621	39	20

wet sieving. Whether these elements were contained in the silt fraction or dissolved and lost in the water during sieving is not known.

The residues after citric acid leaching were slightly enriched in Si and depleted in Mg relative to the original material, which reflects the loss of Mg and a corresponding negative enrichment of Si during incongruent dissolution. The content of other major elements did not change much during the experiment. Depletion of Cr, Mn, Co, and Ni was observed for the two serpentine materials. For the BR tephra, Mg and Fe were depleted, with a slight negative enrichment of Si. Nickel was also depleted from the BR tephra.

A mass balance for the column experiment is presented in Table 5.6. Due to losses of materials caused by leaking columns and other problems, the weight loss of the materials during the experiment was not obtained. However, approximate weight loss values of 3300 mg for the serpentines, and 1200 mg for the BR tephra were based on the sum of the oxide equivalents of the elements that appeared in the solutions. These values were used along with XRF data to calculate the amount of an element present in the residue. With the exception of Si, the values obtained agreed well with values calculated from the XRF data.

	Sİ	Al	Fe	Mg	Са	Na	К	Cr	Mn	ဗိ	Nİ
BV SERPENTINE: mg in 50 g column (a)	9263	291	2940	10974	71	37		84.8	41.9	3.5	105.7
mq in 46.7 g residue (b)	9366	274	2665	7779	67	35		71.1	27.0	1.6	73.9
Lost from sample (a-b)	-102	17	275	1197	4	7		13.7	14.9	1.9	31.8
mq in SOLUTION (c)	219	25	227	1434	m	0	1.65	4.7	0.6	1.5	23.0
% RELEASED (100*c/a)	7	80	80	13	4	Ч		ß	21	43	22
ID SERPENTINE: mg in 50g column	8843	238	2520	11457	286	1 1 1		87.7	43.2	4.3	83.1
mg in 46.7 g residue	8773	224	2468	10146	269			71.8	29.1	2.4	19.3
Lost from sample	70	14	53	1311	17			15.9	14.1	1.8	63.8
mq in SoLUTION	248	19	51	1540	7			6.4	8.6	1.6	46.2
% RELEASED	m	8	7	13	1			7	20	38	56
BR TEPHRA: ma in 50 a column	14373	4526	1470	995	1750	1706	664	9.3	33.3	1.7	5.1
mg in 48.8 g residue	13840	4354	1283	623	1611	1674	663	7.8	29.2	1.8	0.9
Lost from sample	533	172	187	371	139	33	1	1.5	4.1	-0.1	4.1
mg in SOLUTION	187	58	102	314	46	9	4	0.7	1.9	0.1	3.2
& RELEASED	7	Ч	٢	32	m	0	Ч	٢	9	6	63

Table 5.6. Mass balance of citric acid column experiment.

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Weathering Processes of Parent Materials

The mass balance highlights some important features of the dissolution experiment. For example, the two serpentines released similar proportions of Mg, Al, and Si, but Fe was retained to a greater extent by the ID serpentine. Magnesium was also readily removed from the BR tephra, suggesting that small amounts of serpentine may have been mixed with the tephra as a result of eolian additions, colluviation or bioturbation.

Cobalt and Ni were the most easily mobilized trace elements, while Cr was retained strongly and release of Mn was intermediate. More than 50 percent of the Ni present in the ID serpentine was released during the course of the experiment, while only 13 percent of the Mg was released from this material. These results are similar to those of Schreier et al. (1987a) for serpentinitic sediments in Washington State. These authors also observed that Cr was leached more effectively from serpentine minerals by oxalic acid than citric acid. The high mobilities of Mn, Co, and Ni relative to Mg suggests that these elements substitute for Mg in the serpentine structure, and that they are less stable in the structural positions than Mg. The proportion of Cr released from the BV sample was similar to the proportion of Fe, indicating that these elements likely occupy similar structural positions and have approximately equal stability.

To summarize, the total elemental analysis and mass balance results support the observations made through analysis of solutions, and emphasize the high mobility of Ni and Co present in the serpentine structure.

Selective dissolution analysis

The results of selective dissolution analysis of original materials and residues from the column experiment are shown in Table 5.7. While dissolution of Mg was minimal, large proportions of the Co and Ni present in the serpentines were dissolved by DCB and AOD. Over 50 percent of the total Co present in BV and ID serpentines was extracted by DCB and AOD. The levels of Ni_d and Ni_o removed from the original ID serpentine materials represent about 50 percent of the total Ni content of this material, but smaller amounts of Ni were extracted from BV serpentine. About 20 percent of the total Mn was extracted from the BV serpentine, while smaller amounts of Cr were extracted.

Much smaller amounts of all elements were released by AOD and DCB from the BR tephra material and residues than from the serpentine materials.

These results confirm the observations that Ni and Co were easily leached from the serpentine minerals under acid conditions and/or in the presence of complexing ligands. The results also show that the release of Ni and Co from the serpentines does not depend on destruction of the serpentine structure, and indicate that the removal may be considered as a leaching process which penetrates deeply in to the structure.

Examination of grain morphology with SEM

Examination of original ID serpentine material with SEM-EDS (Plate 5.1) showed that the surface had a feather-like appearance, with tufts of material

	Mgd	Fed	Ald	Sid	Crd	Mnd	Cod	Nid
		· perc	ent			==== mg	kg-1 ===	
BV original	0.18	0.29	0.01	0.12	13	154	53	174
BV citric	0.31	0.30	0.00	0.17	15	32	26	128
ID original	0.96	0.23	0.04	0.13	38	170	60	812
ID citric	0.39	0.32	0.01	0.20	45	31	41	139
BR original	0.02	0.12	0.03	0.03	4	23	< 14	23
BR citric	0.02	0.06	< .01	0.10	4	6	< 14	30
	Mg ₀	Feo	Alo	Sio	Cro	Mn _o	Coo	Nio
		perc	ent			==== mg	kg-1 ===	
BV original	0.44	0.15	0.03	0.04	8	150	47	207
BV citric	0.95	0.89	0.05	0.06	< 6	65	18	187
ID original	0.55	0.57	0.09	0.14	42	41	35	900
ID citric	0.65	0.98	0.07	0.14	26	39	27	150
BR original	0.04	0.30	0.06	0.04	< 6	35	< 6	12
BR citric	0.02	0.30	0.01	0.04	< 6	18	< 6	< 6

Table 5.7. Selective dissolution analysis of original materials and residues from column experiment.





Plate 5.1. SEM-EDS image of very fine sand grain from ID serpentine, showing feather-like tufts on grain surfaces.

intimately interwoven with the interior of the particle. The grains present in the weathered residue generally had smoother surfaces, and occasionally pitted grains were observed as shown in Plate 5.2. The feather-like tufts may have been intergrowths of magnesite or brucite, which may have dissolved during the experiment. Another interpretation is that the presence of intense Si peaks for the material indicates that it is a form of serpentine.

The morphology of several grains from the original BV serpentine material is shown in Plate 5.3. These various grains all had similar EDS spectra. The grain surfaces for the BV serpentine did not have the fibrous morphology so often observed for the ID material. Due to the great variation in original grain morphologies, it was not possible to determine distinctive morphological features associated with the weathering experiment, although structurally deteriorated and Mg depleted grains were observed in the residues as shown in Plate 5.4.

5.4 SUMMARY

XRD and chemical analysis confirmed that the two serpentines were distinct, as was inferred from their different physical properties and morphology. The BV serpentine had properties characteristic of lizardite, while the ID sample may have been antigorite. The ID serpentine was characterized by the presence of feather-like tufts on grain surfaces. These tufts were less common in weathered residues, and likely dissolved partially during the experiment. Analysis of the solutions also revealed that brucite was likely present in the ID serpentine. The distinct properties of these two serpentines affected their dissolution behavior, indicating that





Plate 5.2. SEM-EDS image of pitted grain of ID serpentine.





Plate 5.3. SEM-EDS image showing the varied grain morphologies of BV serpentine very fine sand fraction.



Plate 5.4 SEM-EDS image of structurally deteriorated grain from BV serpentine sample after 54 day column experiment.

pedogenic processes may be affected by subtle differences in serpentinitic parent materials.

The results of these weathering experiments show that serpentine materials dissolve more quickly than tephra, especially under acid conditions and in open systems where the weathering products can be removed. The dissolution of serpentine by citric acid was limited by solubility factors throughout the batch and column experiments, and disturbance of the reaction systems by addition of acid to the columns resulted in a rapid release of Mg and a return to equilibrium.

While not directly comparable because the soil materials were prepared differently, the batch and column experiments illustrated several common themes of serpentine dissolution. First, these minerals dissolved incongruently, with Mg release favoured under acidic conditions while Si was preferentially released from the BV serpentine to water at neutral to slightly alkaline pH values.

Incongruent dissolution also applied to the trace metals present in the serpentine structures. Nickel and Co were more easily leached from the structure than either Mg or Fe, while lesser amounts of Cr were released.

The mass balance and selective dissolution analysis emphasized the extent of dissolution of the serpentines and the tephra, and the amount of trace metal release associated with serpentine weathering.

For the BV serpentine, significant quantities of Mg (13 percent of the total Mg), Co (43 percent), Mn (22 percent) and Ni (22 percent), were released to citric

acid columns, while smaller amounts of Al (8.1 percent), Fe (7.8 percent), Si (2.4 percent), and Cr (5.6 percent) were released.

Seven percent of the Fe, 3 percent of the Ca, and 1 percent of the Si and the Al were released from the BR tephra to the citric acid columns.

These results provide insight into the use of trace elements such as Cr, Mn, Co and Ni as pedogenic indicators (Chapter 3). For example, the ease with which Ni was released from the parent materials clarifies the role this element plays as an indicator of the early stages of pedogenesis and in weakly developed soils.

This experiment also places the results of Chapter 4 in context, emphasizing the paradox between rapid dissolution of serpentine minerals under acidic conditions and their apparent stability in weathering environments in southwestern British Columbia. The dissolution of serpentine minerals under near-neutral conditions occurs at a much slower rate than under acidic conditions.

6. DISCUSSION AND OVERALL SUMMARY

Pedogenesis of ultramafic materials in southwestern British Columbia has given rise to soils that reflect the climatic, topographic and geologic diversity of the region. In areas influenced by maritime climates, Podzolic soils developed on ultramafic parent materials, while in drier areas, Brunisolic soils developed on gentle slopes and Regosols were found on steep, eroding slopes.

Topographic position, as it affected soil environment and slope stability was an important control on soil development in the Shulaps Range and in the other areas. The effects of parent material variation on soil morphology were more difficult to interpret. While the soils investigated represent only a partial range of climate and parent material combinations, the degree of serpentinization did not appear to exert a major control on soil development in these unconsolidated materials, although compositional differences among the parent materials were reflected in the soils.

The major pedogenic processes in these soils were (1) dissolution of serpentine and other minerals characteristic of ultramafic rocks, (2) translocation of soluble elements such as Mg, Ni, and Co, and (3) transfer of metals such as Fe and Cr from silicate to oxide phases.

Pedogenic development in the moderately well developed soils was indicated by alteration of clay minerals such as chlorite and biotite to vermiculite and smectite. Pedogenic processes included the release of Mg from primary minerals, and leaching of Mg from the surface horizons was followed by release of Fe and the

formation of soluble complexes of Fe with soil organic matter. In addition, transition metals such as Cr, Mn, Co, and Ni were released and redistributed within the profiles to varying degrees. Chromium was highly immobile in the wet environment, while Mn, Co, and Ni were readily translocated to the BC and C horizons.

For the weakly developed soils in the drier areas, the mineralogy of the soil materials varied only slightly with depth in the profiles. Although biotite was not a common constituent of the parent materials from the Shulaps area, the weathering intensity was sufficient that biotite was depleted from the surface horizons of these Brunisolic soils. Pedogenic development was typically expressed as a loss of Mg relative to Ca from the exchange complex, acidification of surface horizons and accumulation of organic matter.

The amount of free Fe (Fe_d) in the Brunisolic soils did not correlate well with climatic variation, but the distribution of total and extractable Cr, Mn, Co, and Ni within the profiles provided information about pedogenesis. The mobilization of Ni and Co occurred in soils from all but the driest of sites, while Mn redistribution occurred only in the wetter environments. The behavior of these transition metals during pedogenesis was broadly explained on the basis of their hydrolysis and oxidation behavior.

Accumulation of Cr, and coincident depletion of Mg and Ni in B horizons compared to the parent materials provided strong evidence that the soils had developed in relatively uniform parent materials. The distinct distribution trends for these elements also suggested that dissolution of serpentine minerals was an important pedogenic process, particularly in the soils from the wetter environments.

Serpentine minerals are expected to be unstable in surficial environments, and Cr provides a useful indicator of the amount of weathering because of its immobility.

Although the data in the thesis do not allow a detailed evaluation of the extent of land surface reduction due to dissolution, Cr was typically concentrated in the B horizons by a factor of two or three compared to the parent materials. These results suggest that a 10 to 15 cm layer (approximately the depth of the B horizons) of material had dissolved since deglaciation.

The influence of Bridge River tephra additions on ultramafic paleosols at the Shulaps area was found to be relatively insignificant, except for the possible accumulation of weathering products in a buried IIAh horizon. In contrast, the mixing of eolian and colluvial ultramafic materials gave rise to modern tephraderived soils with properties transitional to ultramafic soils. It is more difficult to generalize about the effects of tephra beyond the Shulaps Range. The coarse textured Bridge River tephra weathered slowly in the dry environment, but finertextured tephra materials have been shown to weather rapidly in moist environments. Finer-textured tephra or eolian additions at Olivine Mountain may have had an important effect on the mineralogy of the Bm horizon.

Modern-day tephra soils in the Shulaps range appeared to be more productive than the ultramafic paleosols were prior to deposition of the tephra. The gentle, tephra-veneered slopes of the Shulaps Range were covered by continuous forests, but the contact between tephra layers and serpentinitic paleosols generally showed little evidence of a buried forest floor. The role of tephra additions in ameliorating the "serpentine factor" on these sites is enigmatic, but the Shulaps

ultramafic complex would provide an ideal venue for research on this topic, since the elevation range encompassed by the ultramafic massif likely includes the former treeline. Palynological analysis of ultramafic samples taken from just below the contact with the tephra may provide information about this intriguing subject.

The weathering experiment showed that serpentine parent materials dissolve more rapidly than tephra under acidic conditions with free drainage. Large amounts of Mg were released from the dissolving serpentine, and the dissolution reaction buffered solution pH values in the alkaline range.

The trace metals present in serpentine minerals were preferentially released compared to major elements such as Mg, Si, and Fe. This suggests that isomorphic substitution of elements such as Cr, Mn, Co, and Ni within the serpentine structure occurs at sites where these metals are less stable than the Fe or Mg which they replace. The results also suggest that these potentially toxic trace elements may be released early in pedogenesis, reaching high levels in soil solutions containing complex-forming ligands, with possible biological significance for soil fauna and flora.

For the composite soils of the Shulaps Range, the results of the weathering experiment provide insight into the stratification observed within the profiles. The BR tephra was more resistant to weathering than the serpentines, suggesting that the tephra affected the properties of ultramafic paleosols gradually. Dissolution of serpentine minerals in the paleosols may have proceeded faster than the tephra materials altered at the surface, preserving the differences between the modern tephra-derived soils and the serpentinitic paleosols.

While this investigation did not attempt to determine the causes of poor plant growth on serpentine soils, many observations of soils and tree growth were made during the field work, and may provide impetus for further research. For example, the presence of whitebark pine on exposed sites at mid-elevation sites (1400 m.a.s.l.) in the Shulaps and Tulameen areas represents an example of a species which occurs outside its normal geographic range on ultramafic sites. Whitebark pine is expected to occur at higher elevations in these areas. The biogeoclimatic ecosystem classification system employed by the B.C. Ministry of Forests (Pojar et al., 1987) may provide a method to investigate the ecological effects of ultramafic rocks in British Columbia.

Field observations of barren areas and of tree growth on ultramafic soils from the Shulaps, Tulameen and Coquihalla areas suggested that more intensive soil development on ultramafic soils was correlated with better tree growth. In the Shulaps area (and perhaps at Grasshopper Mountain), the least productive sites generally appeared on exposed, eroding slopes with minimal soil profile development. Better soil development at the Coquihalla site was associated with better tree growth (i.e. a decrease in the so-called "serpentine factor). These cursory observations are consistent with suggestions that (1) the causes of the "serpentine factor" may be found within a suite of chemical, physical and biological processes, as suggested by Kruckeberg (1984) and (2) intensive leaching of Mg and Ni from soil profiles may detoxify the rooting environment and encourage plant growth.

This research has contributed information of interest to environmental scientists concerned about the hazards associated with ultramafic rocks. The amount of asbestos in the soil materials was not determined, but serpentine minerals were

present in the surface horizons, indicating that natural weathering of chrysotile is unlikely to proceed fast enough to significantly reduce the hazards associated with exposed deposits such as tailings piles. Considering the barren condition and instability of many serpentine materials, the potential for exposure to hazardous dusts should be communicated to people living or working near such materials.

The trace element distribution patterns observed within these ultramafic showed that relatively mobile elements (Mg, Co, Ni) are leached from ultramafic parent materials in moist environments, while Cr was relatively immobile. These results will be of interest to geochemists and environmental scientists concerned with the mobility of trace metals.

In conclusion, ultramafic parent materials in southwestern British Columbia have been significantly affected by pedogenic processes since deglaciation. Various techniques were used to detect serpentine dissolution and redistribution of weathering products. The results provide a basis for comparison of pedogenesis on ultramafic parent materials in other environments in British Columbia.

This research has documented the major pedogenenic processes affecting ultramafic parent materials in southwestern British Columbia. The results show that the hazards associated with freshly exposed ultramafic rocks (including asbestos rich mining and milling residues) are reduced through the action of natural processes. Over time frames relevant to humans, however, the rate of such hazard reduction is minimal. For this reason, the hazards associated with asbestos-rich materials are best reduced by minimizing soil disturbance and keeping these materials under a protective vegetative cover.

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APPENDIX 1A

SHULAPS SOILS

PROFILES 1,2,3,4,5,7,8,9,10,11,12, 25,26,27,28,29,30,31,32,33,1101,1103,1104)

Appendix 1A. Shulaps Soils

Profile 1:

2280 m.a.s.l.; grid reference EM318541; high elevation site above treeline; N.E. aspect; ten percent vegetation cover, surface lag deposit of coarse fragments; alpine tundra species present include moss campion (<u>Silene acaulis</u>), willow (<u>Salix</u> <u>ED.</u>), and occasional grasses.

HORIZON	DEPTH	
(ILAB NO.)	(cm)	DESCRIPTION
Ah (CB 9)	0 - 5	Olive brown (2.5Y 4/4 m); sandy loam; 80 percent coarse fragments; single grain; loose; very few, fine, oblique roots; clear, smooth boundary.
AC1 (CB 10)	5 - 25	Olive brown (2.5Y 4/4 m); sandy loam; 50 percent coarse fragments; weak, medium subangular blocky; very friable; very few, fine, horizontal roots; diffuse boundary.
AC2 (CB 11)	25 - 40	Olive brown (2.5Y 4/4 m); sandy loam; 60 percent coarse fragments; weak, medium subangular blocky; very friable; very few, fine, horizontal roots; clear, wavy boundary.
с (СВ 12)	4 0 +	Olive (5Y 4/3 m); sandy loam; 60 percent coarse fragments; weak, medium subangular blocky; very friable; very few, fine, horizontal roots.

Profile 1 (cont.):

Selected properties:

		PERCE	1			HC		XCHN	101	10174	SN	UBU
	BAND	BILT	CLAY	0	H 20	CaCl2	6M	Ca	×	AN	WD 8	TOTAL
Ah	71.8	13.0	15.2	0.5	7.0	7.0	6.9	0.5	0.1	0.0	7.5	8.6
ACI	58.6	33.7	7.7	0.5	6.9	6.9	9.5	0.5	0.0	0.0	10.1	11.3
AC2	55.9	32.1	6.9	0.4	6.9	6.9	10.8	0.3	0.1	0.0	11.2	13.6
υ	53.3	41.5	5.2	0.1	7.2	7.1	10.2	0.5	0.3	0.0	11.0	12.5

Extractable elements:

		DITHI	ONITE			OXAL	ATE 1		λđ	ROPHO	S PHAT	يد 32
	94	IK	81	Mn	94	N	8i	Mn	Po	IN	ßİ	Wu
Ah	0.7	0.0	0.1	0.0	6.0	0.2	0.2	0.0	0.0	0.0	0.1	0.0
ACI	0.8	0.0	0.1	0.0	0.7	0.2	0.2	0.0	0.0	0.0	0.1	0.0
AC2	0.8	0.1	0.0	0.0	0.6	0.2	0.2	0.0	0.0	0.0	0.1	0.0
U	0.7	0.0	0.2	0.0	0.9	0.1	0.2	0.0	0.0	0.0	0.2	0.0

Profile 2:

2150 m.a.s.l.; grid reference EM123539; gently sloping site near treeline, at the edge of a small drainage channel; S.E aspect; parent material is a mixture of tephra and ultramafic till; Krumholtz vegetation of subalpine fir (Abies lasiocarpa), whitebark pine (Pinus albicaulis), willow, arctic lupin (Lupinus arcticus), mountain heather (Cassiope mertensiana).

250	HORIZON LF (CB 13) Bm1 (CB 14) (CB 14) (CB 15) (CB 15) (CB 16) (CB 17) (CB 17)	DEFTH (cm) (cm) 20 - 20 20 - 30 20 - 53 30 - 53 53 - 73	DESCRIPTION mor type humus layer consisting mostly of pine needles over a thin root mat. Olive brown (2.5Y 4/4 m); sandy loam; 40 percent subrounded coarse fragments; single grain; very friable; abundant, medium, oblique roots and plentiful, fine random roots; diffuse boundary. Dark yellowish brown (10YR 4/4 m); sandy fragments; single grain; very friable; plentiful medium, and few, coarse oblique roots; clear wavy boundary. Olive (5Y 4/3 m); loam; 50 percent subrounded coarse fragments; single grain; very friable; horizontal roots; yeadual smooth. Olive (5Y 4/3 m); sandy loam; 50 percent subrounded coarse fragments; single grain; very friable; no roots; diffuse boundary.
	C3 (CB 18)	73 +	Olive (5Y 4/3 m); sandy loam; 50 percent subrounded coarse fragments; single grain; very friable; no roots; 85 cm total depth.

Profile 2 (cont.):

Selected properties:

SAND SILT CLAY C H ₂ O Cacl ₂ LF - - 44.0 5.3 4.9 4 Bm1 68.7 22.2 9.1 1.4 6.5 6.5 Bm2 61.3 26.0 12.7 1.0 6.7 6.6 C1 - - 0.3 6.9 6.6 C2 69.3 25.1 5.6 0.2 6.9 C3 - - 0.0 6.9 6.5				THOP TO		
LF 44.05.3 4.9 4 Bm1 68.7 22.2 9.1 1.4 6.5 6.5 Bm2 61.3 26.0 12.7 1.0 6.7 6.6 C1 0.3 6.9 6.6 C2 69.3 25.1 5.6 0.2 6.9 6.7 C3 0.0 6.9 6.5	CLAY C H20	CaCl ₂ Mg	Ca	Na N	F WOR	LOTAL
Bm1 68.7 22.2 9.1 1.4 6.5 6.5 Bm2 61.3 26.0 12.7 1.0 6.7 6.6 C1 - - 0.3 6.9 6.6 C2 69.3 25.1 5.6 0.2 6.9 6.7 C3 - - 0.0 6.9 6.5	- 44.05.3	4.9 46.7	20.21.0	0.1 6	1 6.7	33.6
Bm2 61.3 26.0 12.7 1.0 6.7 6.6 C1 0.3 6.9 6.6 C2 69.3 25.1 5.6 0.2 6.9 6.7 C3 0.0 6.9 6.5	9.1 1.4 6.5	6.5 9.3	1.40.1	0.01	0.8	14.9
C1 0.36.96.6 C2 69.325.15.60.26.96.7 C3 0.06.96.5	12.7 1.0 6.7	6.6 9.5	0.80.1	0.01	0.3	15.0
C2 69.3 25.1 5.6 0.2 6.9 6.7 C3 0.0 6.9 6.5	- 0.36.9	6.6 8.5	0.50.1	0.0	9.1	10.6
C3 0.06.96.5	5.6 0.2 6.9	6.7 7.8	0.50.5	0.0	8.8	9.8
	- 0.0 6.9	6.5 5.1	0.30.1	0.0	5.6	5.7

Extractable elements:

	-	DITEI	ATINO	*		OXAL	ATE 4	5	PY	ROPHO	FRHAT	يد 19
	94	I	ßi	Mn	Fe	IK	Bi	Mn	Fe	T	ßi	Ä
LF			•	۱	•	I	ı	I	I	ı	ł	ŝ
Bml	1.1	0.1	0.1	0.0	1.2	0.2	0.2	0.0	0.1	0.0	0.1	0.0
Bm2	1.6	0.1	0.1	0.0	6.0	0.2	0.2	0.0	0.1	0.0	0.1	0.0
ប	0.9	0.0	0.1	0.0	0.8	0.1	0.2	0.0	0.0	0.0	0.1	0.0
3	0.7	0.0	0.1	0.0	0.8	0.1	0.2	0.0	0.0	0.0	0.1	0.0
ប	0.6	0.0	0.1	0.0	0.8	0.1	0.2	0.0	0.0	0.0	0.1	<u>.</u>

Appendix 1A: Shulaps Soils

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Profile 3:

2150 m.a.s.l.; grid reference EM323539; gently sloping site near treeline; S.E aspect; 62 cm of tephra over ultramafic till; Krumholtz vegetation of subalpine fir, whitebark pine, willow, arctic lupin, mountain heather.

HORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
LF (CB 19)	2 - 0	Black (10YR 2/1 m); fibrous leaf litter of Whitebark pine needles; plentiful, fine, obligue roots; abrupt, smooth boundary.
Bm1 (CB 20)	0 - 15	Olive brown (2.5Y 4/4 m); sand; single grain; loose; abundant, medium, horizontal and oblique roots, and plentiful, fine, oblique roots; gradual, smooth boundary.
Bm2 (CB 21)	15 - 48	<pre>Light yellowish brown (2.5Y 6/4 m); sand; single grain; loose; abundant, medium, oblique roots; clear, smooth boundary.</pre>
C1 (CB 22)	48 - 55	Olive (5Y 5/3 m); loamy sand; single grain; very friable; plentiful, medium, vertical, and very few, fine, vertical roots; clear, smooth boundary.
C2 (CB 23)	55 - 62	Light gray (2.5Y 7/2 m); sand; single grain; loose; plentiful, medium, vertical, and very few, fine, vertical roots; abrupt, smooth boundary.
IIBmlb (CB 24)	62 - 66	Dark yellowish brown (10YR 4/4 m); silt loam; five percent subrounded coarse fragments; moderate, medium subangular blocky; friable; very few, fine, vertical roots; gradual, smooth boundary.
IIBm2b (CB 25)	66 - 85	Dark yellowish brown (10YR 4/4 m); silt loam; 50 percent subrounded coarse fragments; moderate, medium subangular blocky; friable; very few, vertical, fine roots; gradual, smooth boundary.
IIBm3b (CB 26)	85 - 100	Olive brown (2.5Y 4/4 m); silt loam; 50 percent subrounded coarse fragments; friable; no roots; gradual, smooth boundary.
IIC (CB 27)	100 +	Olive (5Y 4/3 m); loam; 50 percent subrounded coarse fragments; firm; no roots.

Profile 3 (cont.):

Selected properties:

	A 1	ERCEN	E		<u></u>	pH C=C1	12	CHANG	5	UII)	18 Alth	CEC
	BAND	1719		J	5 C C	21000		}				
L.	•	ı	+	39.0	4.8	4.5	21.4	14.41	~	0.1	37.1	117.4
Bml	97.4	2.6	١	0.5	5.5	5.1	1.7	0.30	г.	0.0	2.1	6.9
Bm2	97.5	2.5	ı	0.1	6.1	15.1	0.6	0.10	.1	0.0	0.8	5.0
1	71.2	17.3	1.5	0.1	6.1	15.2	0.4	0.10	г.	0.0	0.6	2.
5	96.7	3.3	I	0.0	6.5	2 5.3	0.2	0.10	~	0.0	0.5	ۍ.
IIBml	lb28.5	61.3	10.2	0.6	9	2 5.4	6.4	0.70	г.	0.0	7.3	11.
I I Bm2	2b 28.6	59.2	12.2	0.3	6.5	3 5.7	7.1	0.60		0.0	7.9	12.
IIBm3	3b 28.7	63.0	8.3	0.2	6.(5 6.1	8.1	0.60	г.	0.0	8.8	11.
IIC	43.8	49.8	6.4	0.1	6.1	8 6.4	6.7	0.50	Ξ.	0.0	7.4	7.

Extractable elements:

		DTTRY	ONTTR			OXN	ATE	-	ЪХ	ROPHO	SPHAT	a
	Pe	N	Bi	M.	Fe	-	ßi	H	Pe	7	81	W
E					i							
Bml	0.4	0.1	0.1	0.0	0.7	0.1	0.1	0.0	0.0	0.1	0.0	0.0
Bm2	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0 0
C1	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.1	0.0	0.0
C	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IIBml	lb2.6	0.3	0.1	0.0	0.8	0.1	0.1	0.0	0.1	0.1	0.1	0.0
IIBm	2b1.9	0.2	0.1	0.0	0.8	0.2	0.1	0.0	0.1	0.1	0.2	0.0
IIBm	3 b1.2	0.1	0.1	0.0	1.1	0.2	0.2	0.0	0.1	0.1	0.1	0.0
IIC	6.0	0.0	0.1	0.0	1.0	0.2	0.2	0.0	0.0	0.0	0.1	0.0
						1 1						•

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44	
0	
- 64	
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1525 m.a.s.l.; grid reference EM435460; small barren ridge top at edge of glacial meltwater channel occupied by Burkholder Creek; S. aspect; ultramafic till; occasional, stunted lodgepole pine (Pinus contorta var latifolia) and Douglas fir; steep, eroding slope to the south is barren of ash and most vegetation, more gentle north facing slope has thicker ash cover and apparently hashithy stand of lodgepole pine and Douglas fir; understory has approximately 45 percent cover of juniper (Juniperus gp), five percent bearberry (Arctostaphylos uva-urgi), and yellow flowered plant also present.

DESCRIPTION	Olive brown (2.5Y 4/4 m); 30 percent coarse fragments: single grain; loose; plentiful, fine, oblique roots; clear, smooth boundary.	Dark grayish brown (2.5Y 4/2 m); 75 percent coarse fragments; single grain; loose; abundant, fine and plentiful, medium, vertical roots; clear, wavy boundary.	Dark grayish brown (2.5Y 4/2 m); 95 percent coarse fragments; single grain;loose; plentiful, fine, vertical roots.
DBPTH (cm)	9 - 6	6 - 21	21 +
HORIZON (LAB NO.)	Ah (CB 28)	AC (CB 29	C (CB 30)

Belected properties:

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		PERCE	NT.	46		pH	64	XCHN	NGE	DITE	NS	CEC
	BAND	BILT	CLAY	υ	H 20	CaC12	Бw	e S	M	Ma	BUM	TOTAL
Ah	73.9	15.9	10.2	6.0	6.8	6.4	8.4	2.6	4.0	0.0	11.4	15.5
AC	1	ı	1	1.0	7.0	6.6	10.9	1.6	0.2	0.0	12.7	15.5
J	ī	1	ı	1.0	•		•			1		

Profile 5:

1550 m.a.s.l.; grid refence EM43459; steeply sloping site on mid valley bench; N.E. aspect; young stand of lodgepole pine, with occasional whitebark pine and regenerating Douglas fir; understory dominated by White flowered rhododendron (Rhododendron albiflorum) and low blueberry (<u>Vaccinium</u> myrtillug).

HORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
нат	5 - 0 S	<pre>Black (loYR 2/1 m); fibrous leaf litter of pine needles; plentiful, fine, oblique roots; abrupt, smooth boundary; (NOT SAMPLED).</pre>
Ae (CB 31)	е I О	Light gray; (10YR 7/1m); loamy sand;single grain; loose; plentiful fine, and abundant medium and coarse, oblique roots; clear, wavy boundary.
Bfj (CB 32)	н 1	Pale brown (10YR 6/3 m); sand; single grain;loose; plentiful fine, and abundant medium and coarse roots; discontinuous horizon.
с (СВ 33)	4 - 20	Light olive brown (2.5Y 5/4 m); sand; single grain; loose; plentiful, fine roots, and abundant, medium and coarse roots; abrupt, smooth boundary.
IIAhb (CB 34)	20 - 22	Black (10YR 2/1 m); clay; ten percent coarse fragments; moderate, medium granular; very friable; few fine, and plentiful medium and coarse, oblique roots; clear, smooth boundary.
IIBmlb (CB 35	22 - 23	Dark brown (10YR 3/3 m); 50 percent subrounded coarse fragments; strong, medium subangular blocky; friable; few, fine, oblique roots; discontinuous horizon.
IIBm2b (CB 36)	23 - 32	Olive brown (2.5 Y 4/4 m); loam; 50 percent subrounded coarse fragments; moderate, medium subangular blocky; friable; plentiful, medium oblique roots; gradual, smooth boundary.
IIBC (CB 37)	32 - 40	Olive (5Y 4/3 m); loam; 60 percent subrounded coarse fragments; moderate, medium subangular blocky; friable; no roots; diffuse boundary.
IIC CB 38,41	40+	Olive (5Y 4/3 m); loam; 60 percent subrounded coarse fragments; weak, medium subangular blocky; friable; few, medium horizontal roots; 73 cm total depth.

Profile 5 (cont.):

Selected properties:

	H	ERCEN	Ę	*	Â	H	1	CEANGI	ບ 	NTIOI	9K	CEC
	BAND	BILT	CLAY	U	H20	cac1.2	БW	5		R'A	NDS	TOTAL
LEFH	•	•	•	1	4.1	3.5	4.9	15.64	•	0.1	24.7	118.5
Ae	75.6	22.0	2.4	0.7	5.4	4.9	2.4	0.70		0.0	3.3	4.4
Bfj	87.5	10.2	2.3	1.1	5.7	4.8	2.4	1.10	2	0.1	3.8	9.8
е С	100	0.0	0.0	0.7	ł	1	2.9	0.70		0.0	3.7	10.8
dhAll	13.7	24.1	62.2	4.2	6.4	5.9	42.2	9.30	ŝ	0.1	52.1	62.9
IIBmlb	1	1	ı	0.9	6.2	5.7	10.8	1.70		0.0	12.6	16.3
IIBm2b	51.2	36.6	12.2	0.7	6.5	6.0	9.3	1.40	τ.	0.0	10.9	13.1
IIBC	52.4	35.4	12.2	0.5	6.6	6.1	7.3	1.00		0.0	8.4	10.1
IICI	46.4	40.1	13.5	0.3	6.7	6.2	6.4	1.10	τ.	0.0	7.5	8.2
IIC2	ł	1	1	0.3	6.6	6.1	7.0	1.10		0.0	8.1	8.1
11C3	ł	I	ł	0.3	6.7	6.2	8.6	1.30		0.0	6.6	10.9
IIC4		I	ł	0.2	6.7	6.3	9.9	1.10	г.	0.0	11.1	10.9

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Extra	ctab]	e ele	ments									
		DITHI	ONITE	*		OXAL	ATE &		IXd	ROPHO	S PHAT	*
	Pe	N1	81	Mn	Pe	M	81	ų	Pe	I	8 1	Ч Ж
LFH	1	1	ı	ı	ı	I	1	•	ı	1	ı	ı
Åe	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.1	0.0
Bfj	0.4	0.1	0.1	0.1	0.3	0.2	0.0	0.1	0.1	0.1	0.1	0.0
υ	0.2	0.0	0.1	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.1	0.0
IIAhb	1.6	0.2	0.2	0.3	1.1	0.4	0.2	0.5	0.3	0.2	0.4	0.0
IIBMII	b1.0	0.1	0.1	0.1	0.9	0.2	0.2	0.1	0.1	0.1	0.1	0.0
IIBm2]	61.1	0.1	0.1	0.0	0.7	0.1	0.1	0.0	0.1	0.1	0.1	0.0
IIBC	0.9	0.1	0.1	0.0	1.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0
IICI	0.8	0.0	0.1	0.0	0.5	0.1	0.1	0.0	0.0	0.0	0.1	0.0
11C2	0.9	0.1	0.1	0.0	0.4	0.1	0.1	0.0	0.0	0.0	0.1	0.0
IIC3	0.9	0.0	0.1	0.0	0.4	0.1	0.1	0.0	0.0	0.0	0.1	0.0
IIC4	1.0	0.1	0.1	0.0	0.3	0.1	01	0.0	0.0	0.0	0.1	0.0

Profile 7

1500 m.a.s.l.; grid reference EM447452; level site near a small pond on mid valley bench; edge of an old fire road; stable site of tephra accumulation; edge of old growth forest of Engelmann spruce (<u>Picea engelmannii</u>) and subalpine fir with some young indogepole pine; understory dominated by white flowered

HORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
LFH (CR 44)	0 8	Black (10YR 2/1 m); thick, mossy mor humus, abrupt, smooth boundary.
Ae	8 - 0	Olive grav: (5Y 5/2 m): loamv cand: cincle
(CB 45)		reference and the second secon
Bf	8 - 12	Dark yellowish brown (10YR 3/6 m): loamv
(CB 46)		<pre>sand; weak, medium granular; very friable; abundant, medium and coarse, random roots, and very few, fine roots; clear, smooth boundary.</pre>
U	12 - 27	Light yellowish brown (2.5Y 6/4 m); sand;
(CB 47)		single grain; loose; abundant, medium and Coarse, random roots, and very few, fine roots; abrupt, wavy boundary
IIAhb	27 - 27	<pre>Black; very thin, discontinuous horizon; (NOT SAMPLED).</pre>
IIBmlb	27 - 31	Dark brown (10YR 4/3 m); silt loam; 30
(CB 48)		percent subrounded coarse fragments; weak, fine to medium subangular blocky; very friable; plentiful, medium and coarse, random roots; clear broken boundary.
IIBm2b	31 - 36	Dark brown (10YR 4/3 m); silt loam; 50
(CB 49)		percent subrounded coarse fragments; weak, fine to medium subangular blocky; very friable; plentiful, medium and coarse, random roots; clear broken boundary.
IIBC	36 - 40	Olive brown (2.5Y 4/4 m); silt loam; 60
(CB 50)		percent subrounded coarse fragments; friable; few, medium and coarse, random roots; gradual, wavy boundary
IIC	40+	Olive (5Y 5/3 m); silt loam; 60 percent
(CB 51)		<pre>subrounded coarse fragments; very friable; few, medium and coarse, random roots; 45 cm total depth.</pre>

Profile 7 (cont.):

Selected properties:

	BAND	PERCEI	CLAY	<u>ب</u> ن م	120 F	cac12	5W	Ca R	CATIO Na	NS BUM	TOTAL
LFH	•	•	•	40.2	4.6	4.0	5.8	19.01.7	0.1	26.6	123.2
le	87.2	11.7	1.1	1.5	4.6	3.7	0.4	1.00.1	0.0	1.6	8.8
Зf	82.3	15.1	2.6	2.1	5.1	4.3	0.6	1.50.1	0.0	2.2	23.5
	98.2	1.8	0	0.4	5.4	4.5	0.1	0.30.0	0.0	0.5	7.8
IIAhb											
IIBml	b31.0	58.5	10.5	1.0	5.1	4.2	2.4	1.40.1	0.1	4.0	13.5
[IBm2]	b32.8	54.2	13.0	0.5	5.6	4.6	4.6	2.40.2	0.1	7.3	12.3
LIBC	ł	ł	,	I	5.4	4.6	5.1	2.20.6	0.1	7.9	12.9
CI C	25.0	60.2	14.8	0.3	6.2	5.5	8.3	3.00.1	0.1	11.4	13.2

Extractable elements:

		DITHI	JTINO	*		OXAL	ATE		λđ	ROPHO	SPHAT	يد 10
	Pe	N	81		8	R	81	ų	94	7	Bi	ЦЦ И
LFH	1	•	1	1	•	4	•	1	1		•	
Ae	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bf	0.8	0.6	0.1	0.0	0.9	0.7	0.1	0.0	0.4	0.4	0.1	0.0
o	0.1	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.1	0.0	0.0
IIAhb												
IIBml	b1.0	0.2	0.1	0.0	0.5	0.2	0.0	0.0	0.1	0.2	0.1	0.0
IIBm2	b1.4	0.2	0.1	0.0	0.8	0.2	0.1	0.0	0.1	0.1	0.1	0.0
IIBC	I	I	I	ł	ı	ł	ł	ł	1	ŧ	ı	ı
IIC	1.1	0.1	0.1	0.0	0.6	0.1	0.1	0.0	0.1	0.0	0.1	0.0

Profile 8:

1560 m.a.s.l.; grid reference EM431464; wet, level site near a small creek; edge of old growth forest of Engelmann spruce with some whitebark pine, and fir regeneration; understory dominated by white flowered rhododendron, with mountain bilberry (Vaccinium vitis-idaea).

HORIZON	DEPTH	
(ILAB NO.)	(cm)	DESCRIPTION
LEH	0 - 6	mossy mor humus, mostly leaf material, with 1 cm of H; abundant fine, medium and coarse roots; abrupt, smooth boundary; NOT SAMPLED.
ye	0 - 2	<pre>single grain; loose; abundant, medium and coarse, horizontal roots, and plentiful, fine, random roots; abrupt wavy boundary; NOT SAMPLED.</pre>
Bfj	2 - 10	<pre>single grain; loose; abundant, medium and coarse, horizontal roots, and plentiful, fine, random roots; clear wavy boundary; NOT SAMPLED.</pre>
с (СВ 52)	10 - 17	Brownish yellow (10YR 6/6 m); single grain; loose; abundant, medium and coarse, horizontal roots, and plentiful, fine, vertical roots; clear, smooth boundary.
IIBmb (CB 53)	17 - 23	Dark brown (7.5YR 4/4 m); loam; 60 percent coarse fragments; weak, fine granular; plentiful, fine, vertical roots; clear, smooth boundary.
IIBCb (CB 54)	23 - 34	Olive brown (2.5Y 4/4 m); loamy sand; 75 percent coarse fragments; single grain; diffuse boundary.
IIC (CB 55)	34 +	Olive (5Y 4/3 m); loamy sand; 75 percent coarse fragments; single grain; 45 cm total depth.

Profile 8 (cont.):

Selected properties:

	Ā	ADC A	E			DH H		EXCHANG	ပ မ	NTIO	88	CEC
	GNNS	BILT	CLAY	. 0	E 20	CaCl	b w	C	M	MA	8UM	TOTAL
LFH												
Ae												
Bſj												
υ	ı	T	ı	0.4	ີ ທ	2 4.4	ı	ı	1	ł	ŀ	ı
d m B I I	45.7	43.4	10.9	1.4	ີ ທ	2 4.3	I	I	1	I	I	ı
IIBCb	I	I	н Х	0.6	ີ. ທ	6.4.9	ı	ī	ı.	I	ı	ı
IIC	79.3	12.3	8.4	0.4	9	4 6.0	1	•		'	•	,

Ĭ

		DTRUT	ONT WP			OXAL	ATE &		FYR	ROPHOE	PHAT	*
	Pe	NI	Bi	ц щ	Pe.	14	81 1	ų,	Pe.	-	81	Mn
LFH												
Åe												
Bfj												
υ	0.2	0.2	0.1	0.0	0.2	0.2	0.0	0.0	0.0	0.1	0.1	0.0
TIBmb	1.9	0.4	0.1	0.0	1.6	0.5	0.1	0.0	0.2	0.4	0.1	0.0

0.0 0.0

0.0

0.1

0.1 0.2

0.1

0.1

0.0 0.0

0.2 0.2

0.3 0.2

2.0 2.0

0.0 0.0

0.1 0.1

0.2 0.4

0.0

0.1

0.1

1.1 IIBCb 1.4 IIBmb 1.9

IIC

Profile 9:

1560 m.a.s.l.; grid reference EM482445; edge of landing in clearcut; N.E. aspect; five year old Douglas fir regeneration with bearberry and grass ground cover.

DESCRIPTION	mostly leaf material; abundant fine, medium and coarse roots; abrupt, smooth boundary.	humis lavar		granular structure		single grain; loose; abundant, medium and	coarse, horizontal roots, and plentitul, fine, random roots; clear wavy boundary.	Light gray (2.5Y 7/2 m); sand; single grain;	loose; abundant, tine, vertical roots; abrupt, wavy boundary.	Dark brown (10YR 4/3 m); clay loam; five	percent coarse tragments; mouerate, meutum granular; friable; plentiful, medium, vertical roots; clear, wavy boundary.	Yellowish brown (10YR 5/4 m); clay loam;	five percent coarse iragments; moderate, medium subangular blocky; very friable; few coarse, vertical roots; diffuse boundary.	Yellowish brown (10YR 5/4 m); clay; fifteen	percent coarse Iragments; modelate, medium subangular blocky; very friable; few, coarse, vertical roots.
DEPTH (cm)	2 - 0.5	0 2 C		0 - 1		1 - 2		2 - 16		16 - 33		33 - 63		63 +	
HORIZON (LAB NO.)	411	(CB 162) u	 (CB 163)	Ą	(CB 164)	Bm	(CB 165)	υ	(CB 56)	dm811	(CB 57)	IICI	(CB 58)	11C2	(CB 29)

Profile 9 (cont.):

Selected properties:

	6	ERCEI	Ę	*	ä	Ш	23	CHANG	์ เว	VIION	8	CEC
	GNND	BILT	CLAY	U U	50	cac12	бw	e S	M	NA NA	RUR	TOTAL
E	•	•	.	1	5.7	5.0	•	•	.	•	•	•
H	I	I	ı	15.2	6.0	5.3	6.6	26.11	6.1	0.0	34.7	46.7
Ą	ı	ŀ	ł	I	6.4	5.7	2.6	8.9]	0.1	0.0	12.6	23.7
Bm	ı	ł	Ľ	ł	ŧ	ı	ŀ	I	÷	ı	ı	ŀ
U	91.9	6.8	1.3	0.5	5.5	4.6	0.6	1.00	0.2	0.0	1.8	9.3
daa II	35.6	35.5	28.9	0.7	6.1	5.4	6.5	11.02	2.2	0.0	19.7	25.2
IJCI	41.9	22.6	35.5	0.9	6.5	5.9	17.7	21.2(0.7	0.0	39.7	44.5
IIC2	32.2	25.2	42.6	0.6	6.4	5.8	15.9	21.2(6.0	0.0	38.0	44.0

Extractable elements:

		DITHIC	DNITE			OXAL	ATE I	مد	IXd	ROPHOI	PHAT	بد ده
	70	T	8i	Ä	Pe	IN	ßi	H	Pe	2	8i	÷.
LF	.	•	1	1	ł	ı	ı	ı	ı	ŀ	i	ı
н	ł	I	ı	ı	ı	ŀ	ł	ł	ŀ	ı	ı.	I
A h	0.5	0.1	0.1	0.1	0.2	0.2	0.0	0.2	ı	ī	ı	ı
Bm	0.6	0.2	0.1	0.0	0.6	0.3	0.0	0.1	0.1	0.2	0.0	0.0
J	0.2	0.1	0.0	0.0	0.3	0.1	0.0	0.0	0.1	0.1	0.1	0.0
II Bmb	1.7	0.2	0.1	0.1	0.8	0.2	0.0	0.1	0.1	0.2	0.2	0.0
IICI	2.0	0.2	0.1	0.1	0.3	0.2	0.0	0.1	0.1	0.4	0.5	0.0
11C2	2.2	0.2	0.1	0.1	0.2	0.2	0.0	0.1	0.1	0.6	0.7	0.0

Profile 10:

2210 m.a.s.l.; grid reference EM310446; alpine site on a small bench: S.W. aspect; 24 cm accumulation of tephra over sepentinitic colluvium; barren.

DESCRIPTION	unvegetated tephra; some weathering indicated by slight reddish color near surface; (NOT SAMPLED).	Very dark grayish brown (10YR 3/2 m); sandy loam; 70 percent coarse fragments; moderate, medium subangular blocky; friable.	Dark brown (10YR 3/3 m); 70 percent coarse fragments; single grain.	
DEPTH (cm)	0 - 24	24 - 27	27 +	2
HORIZON (LAB NO.)	υ	II A hb (CB 80)	IIBmb (CB 81)	24

Belected properties:

PERCENT	-		P.H.	M	ECHANGE	CATIO	NS	CEC
BAND BILT CLAY	0	120	cac1 ₂	вw	Ca M	Na	MUS	TOTAL
υ								

Profile 11:

2120 m.a.s.l.; grid reference EM302441; alpine site on top of a small knoll; S.S.W. aspect; 15 cm of serpentinitic colluvium over serpentinitic till; occasional whitebark pine, with lupin, lance leaved stonecrop (Sedum lanceolatum) and common yarrow.

HORIZON (LAB NO.)	(cm)	DESCRIPTION
Ah (CB 83)	0 - 2.5	Olive gray (5Y 5/2 d); sand; single grain; loose; plentiful, fine, random roots; clear smooth boundary.
BC (CB 84)	2.5 - 15	Yellowish brown (10YR 5/4 m): Discontinuous lenses of B horizon mixed in with C horizon, probably by colluviation.
U	2.5 - 15	Discontinuous horizon; single grain; loose; plentiful, fine, medium and coarse roots; claear wavy boundary; (NOT SAMPLED).
IIBm (CB 85)	15 - 18	Olive brown (2.5Y 4/4 m); loam; 60 percent coarse fragments; single grain; very friable; plentiful, coarse roots; gradual smooth boundary.
IIBC (CB 86)	18 - 40	Olive (5Y 4/3 m); sandy loam; 60 percent coarse fragments; single grain; friable; very few roots; 40 cm total depth.

Selected properties:

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	[PERCEI	t	*		H		XCHM	NGE C	ATIO!	NS	CEC
	GININ	2112	CLAY	U	H ₂ 0	CaC12	Mg	a U	×	M	MUS	TOTAL
Ah	ł	1	ŧ	3.2	•	1	1.7	2.1	0.2	0.0	4.1	19.9
BC	ł	ł	ı	1.2	ł	ı	6.5	0.8	0.1	0.0	7.5	21.9
υ	•	1	I	F	ı	ı	ł	ł	I	ı	ı	ı
JIBmb	47.8	43.2	9.0	0.7	ł	ł	5.6	0.5	0.0	0.0	6.1	17.2
IIBC	58.3	33.6	8.2	0.3	7.1	6.6	5.9	0.5	0.1	0.0	6.4	9.3
Extra	ctabl	e ele	aen te									

.

		DITEL	ONITE	*		OXAL	ATE &		ľλđ	SOPHO	SPHAT	مبر دد
	9	R	8i		P.e	TR	ßi	Mn	Pe	7	ßi	£
Ah	0.2	0.1	0.1	0.0	0.3	0.1	0.0	0.0	0.0	0.1	0.1	0.0
ည္ရပ	1.3	0.3	0.1	0.0	1.2	0.4	0.1	0.0	0.1	0.2	0.1	0.0
IIBmb	0.8	0.2	0.1	0.0	0.5	0.2	0.1	0.0	0.1	0.1	0.0	0.0
IIBC	0.5	0.0	0.1	0.0	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0

Appendix 1A: Shulaps Soils

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ding II IIAhb

Profile 12:

1970 m.a.s.l.; grid reference EM302437; roadcut on steep slope; S.S.W. aspect; mixed stand of lodgepole pine and whitebark pine.

HORIZON	DEPTH (cm)	DESCRIPTION
Ľ	1 - 0	pine leaf litter; (NOT SAMPLED).
Ae	6 - 3	bleached volcanic ash; (NOT SAMPLED).
Bfj (CB 88)	6 E	Light olive brown (2.5Y 5/4 m); weak, fine and medium granular; very friable; plentiful, fine roots; clear, broken boundary.
IIC	9 - 14	<pre>thin layer of ultramafic colluvium; gravel and pebbles; plentiful, fine roots; clear, broken boundary; (NOT SAMPLED).</pre>
IIIBmb (CB 89)	14 - 20	Olive (5Y 4/3 m); sand; moderate, medium granular; very friable; plentiful, fine roots; clear, wavy boundary.
IIIC1 (CB 90)	20 - 50	Olive gray (5Y 4/2 m); sand; 80 percent coarse fragments; single grain; loose; few roots; clear, wavy boundary.
IIIC2 (CB 91)	50 - 90	Olive gray (5Y 4/2 m);sandy loam; very friable; moderate, medium subangular blocky; few, fine and medium roots.

Selected properties:

	PER	CER	E			DR		XCHANGE	0	NOL	20	CEC
	BAND BI	5	CLAY	U U	H 20	cac12	БW	R CB		4	MUB	TOTAL
LF												
Ae												
Bfj					5.5	9 5.3						
IIC												
IIIBm					6.(6.5.9						
IJICI	92.2 3	5.	4.3	I	6.9	9 6.7	ŀ	i I		1	ı	ı
IIIC2	68.9 2	1.9	9.2	ı	7.(0 6.8	ı	1			1	ı

.

Profile 25:

1880 m.a.s.1.; grid reference EM402455; stable mid elevation site on mid valley bench; N.W. aspect; mixture of juvenile whitebark pine and lodgepole pine with occasional Engelmann spruce and subalpine fir; understory includes grouseberry (<u>Vaccinium scopatium</u>). red heather (<u>Phyllodoce empetriformis</u>), and white moss heather (<u>Cassiope mertensian</u>).

Profile 26:

1670 m.a.s.l.; grid reference EM408480; steeply sloping site on mid valley bench; N.E. aspect; mature lodgepole pine with regenerating Douglas fir and subalpine fir; understory includes white flowered rhododendron, <u>Peltigera 5p.</u>

HORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
LFH	1 - 0	forest floor; abrupt, smooth boundary.
(CB 148)		
Ae	0 - 4	Light brownish gray (10YR 6/2 d); sandy
(CB 149)		<pre>loam; 20 percent coarse fragments; single grain; loose; plentiful, fine, random roots; abrupt, smooth boundary.</pre>
Bf	4 - 10	Very pale brown (10YR 7/3 d); sand; 20
(CB 150)		percent coarse fragments; single grain; loose; plentiful, fine, oblique roots, and abundant, medium, horizontal roots; clear, broken boundary; discontinuous horizon.
U	10 - 19	White (10YR 8/2 d); sand; 20 percent coarse
(CB 151)		<pre>fragments; single grain; loose; plentiful, fine, oblique roots; abrupt, smooth boundary.</pre>
d m8 I I	19 - 35	Very pale brown (10YR 7/3 d); sandy loam; 80
(CB 152)		percent coarse fragments; single grain; very friable; plentiful, fine, and few, medium and coarse, oblique roots; clear, smooth boundary.
IIC	35 +	Light gray (2.5Y 7/2 d); sandy loam; 80
(CB 154)		percent coarse fragments; single grain; very friable; very few, fine, and few, medium and coarse, oblique roots; 55 cm total depth.

Profile 27:

1455 m.a.s.l.; grid reference EM418483; gently sloping site on mid valley bench; N.E. aspect; dense lodgepole pine stand with white flowered rhododendron, alder (<u>Alnus sp.</u>), red mountain heather, and rose (<u>Rosa sp.</u>).

HORISON	DEPTH	DERCETOR
LFH	2 - 0	forest floor.
(CB 155)		
Aej	<u>е</u> – О	Light brownish gray (l0YR 6/2 d); sand; 40
(CB 156)		percent coarse fragments; single grain; loose; plentiful, medium, horizontal roots, and plentiful, fine random roots; clear, smooth boundary.
Bfj (CB 157)	9 1 5	Pale brown (10YR 6/3 d); sand; 40 percent coarse fragments; single grain; loose; plentiful, medium, horizontal roots, and plentiful, fine, random roots; gradual, smooth boundary.
C (CB 158)	6 - 12	Light gray (10YR 7/2 d); sand; 40 percent coarse fragments; single grain; loose; few, medium, oblique roots; abrupt, smooth boundary.
IIBmlb (CB 159)	12 - 22	Very pale brown (10YR 7/3 d); loamy sand; 80 percent coarse fragments; single grain; very friable; few, fine, oblique roots; gradual, smooth boundary.
IIBm2b (CB 160)	22 - 32	Light gray (2.5Y 7/2 d); loamy sand; 80 percent coarse fragments; single grain; very friable; few, fine, oblique roots; gradual, smooth boundary.
IIC (CB 161)	32 +	Light brownish gray (2.5Y 6/2 d); loamy sand; 80 percent coarse fragments; single grain; very friable; few, fine, oblique roots; includes some black "shaly fragments similar to those found in profile 9.

Profile 28:

1575 m.a.s.l.; grid reference EM358541; sloping site on Blue Creek road; S.E. aspect; ultramafic and other lithology in till; Engelmann spruce, lodgepole pine, juniper, and bearberry.

RIZON DEPTH B MO.) (cm) DESCRIPTION
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Profile 28 (cont).:

Belected properties:

	8	ERCEL	Ľ	J.		0		-	KCHA	NGE C	NTIO	88	CEC
	BAND	BILT	CLAY	υ	Ē	0	cac12	БW	C B	M	Na	MUB	TOTA
1	1	1		38.	-	5.2	4.4	10.4	18.	7.0.7	0.0	29.8	64.3
FH	ł	ł	I	40.	5	5.5	4.8	18.4	25.	60.9	0.0	45.0	78.9
Bml	86.4	I	•	1.	N	5.8	4.8	2.2	Ϊ.	20.2	0.0	3.6	8.7
Bm2	86.5	١		•	-	5.8	4.7	1.2	·.	30.1	0.0	1.6	5.4
IIBml	b79.1	14.3	6.6	•	ŝ	6.6	6.1	11.1	•	90.1	0.0	12.1	15.6
IIBm2	b79.1	11.8	9.1		ŝ	7.0	6.3	1.11	0.	80.1	0.0	12.1	15.2
IIC	90.0	4.8	5.2		~	6.7	6.2	7.9	1.	10.1	0.0	9.1	5.0

Extractable elements:

		DITHI	ONITE			OXNI	ATE		ЪХI	ROPHO	SPHAT	8 3
	Pe	T	8i	Ma	Pe	IL	ßi	Mn	Pe	T	Bi	H
	ł	1	ı	•	•	ı	S 1	ł	I	•	ı	ı
FH	ł	I	ł	•	ı	•	I	ı	ı	I	ł	I
Bml	0.3	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.1	0.1	0.1	0.0
Bm2	0.2	0.1	0.0	0.0	0.4	0.1	0.0	0.0	0.0	0.1	0.0	0.0
IIBml	b1.3	0.1	0.1	0.0	0.5	0.2	0.0	0.0	0.1	0.0	0.1	0.0
IIBm2	b1.0	0.0	0.1	0.0	0.4	0.1	0.0	0.0	0.1	0.0	0.1	0.0
IIC	0.6	0.0	0.1	0.0	0.4	0.1	0.0	0.0	0.0	0.0	0.1	0.0

Profile 29:

725 m.a.s.l.; grid reference EM525415; gently sloping site on large fan. above ultramaric roadcut; N.E. aspect; ash and silt accumulation over ultramafic; open stand of ponderosa pine (Pinus ponderosa), with soopolallie, juniper, pinegrass (Calamagrostis rubescene), bunchgrass (Agropyron spicatum), rose, common yarrow, fleabane (Erigeron spi), and hawksbeard (Crepis atrabarba).

HORIZON	HLARD	DEADTBOTON
FEH	1 - 0	forest floor
(CB 176)		
Ae	0 - 1	Grayish brown (10YR 5/2 d): very weak
(CB 177)		coarse granular; friable; plentiful, medium and coarse, horizontal roots.
Bſj	1 - 7	Light gravish brown (10YR 6/2 d); single
(CB 178)		grain; loose; plentiful, medium and coarse, horizontal roots.
υ	7 - 10	Light gray (loYR 7/2 d): single grain:
(CB 179)		loose; plentiful, medium, horizontal roots.
IIBml	10 - 25	Grayish brown (2.5Y 5/2 d); verv weak
(CB 180)		subangular blocky; very friable; plentiful, medium, obligue roots.
IIBm2	25 - 50	Grayish brown (2.5Y 5/2 d); verv weak
(CB 181)		subangular blocky; very friable; few roots.
IIC	50 +	Blue (5BG 5/1); 30 percent coarse fragments:
(CB 182)		very friable; very few roots; 70 cm total denth

Profile 29 (cont.):

Belected properties:

-		PERCE	CLAY	#U	¹ 20	Cacl2	N M	KCHANGE Ca K	CATIO Na	NB BUM	CEC
ггн	.		.	26.1	5.9	5.5	22.6	10.52.	0.0	35.9	74.7
Ae	ı	I	ł	2.7	6.6	6.3	9.7	5.70.3	0.0	16.1	28.2
Bm 1	ı	ł	,	1.0	6.8	6.5	7.1	2.80.4	0.0	10.3	14.5
n	ī	•	1	0.7	6.6	6.2	6.0	1.50.3	0	7-1	
[[Bmlb	ı	ł	ı	0.7	7.0	6.7	14.2	2.20.1		16.5	
[IBm2b	I	ı	,	0.4	7.1	6.6	0.6				
IIC	ı	•	ı	0.2	7.2	6.9	3.1	0.50.0	0.0	3.6	5.8

Extractable elements:

	94	DITEI	Si Si	*	Pe	OXAL	ATE :	r r	λd	ROPHO	SPHAT	به د
H.J.1										2	1	
:			I	•	ı	I	ı	ı	I	ı	I	ı
Ae	0.5	0.1	0.1	0.1	0.3	0.2	0.1	0.1	0.1	0.0	0.2	0.0
Bml	0.4	0.1	0.1	0.0	0.3	0.2	0.0	0.1	0.0	0.0	0.1	0.0
υ	0.2	0.1	0.1	0.0	0.4	0.1	0.0	0.0	0.0	0.0	1.0	0
IIBm]	(b0.7	0.1	0.2	0.4	0.2	0.2	0.1	0.0	0.1	0.0	0.2	0.0
IIBm	300.6	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0
IIC	0.2	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix 1A: Shulaps Soils

Profile 30:

1515 m.a.s.l.; grid reference EM434459; young lodgepole pine stand with white flowered rhododendron, low blueberry, <u>Peltigera sp.</u>, alder.

HORIZON (LAB NO.)	DEPTH	
		DESCRIPTION
LFH : (CB 183	0 - 9	mostly a thick F layer; plentiful, fine, medium and coarse, random roots.
Ae ((CB 184)	- e	Light brownish gray (2.5% 6/2 d); 10 percent coarse fragments; single grain; loose; plentiful, fine, medium and coarse, horizontal roots; clear, wavy boundary.
Bfj 6 (CB 185)	- 14	Pale brown (10YR 6/3 d); 20 percent coarse fragments; single grain; loose; plentiful, fine and medium, and few, coarse, horizontal roots; clear, wavy boundary.
C 14 (CB 186)	1 - 26	White (10YR 8/2 d); 50 percent coarse fragments; single grain; loose; few, fine and medium, oblique roots; clear, broken boundary.
IIBmb 2((CB 187)	- 30	Light gray (10YR 7/2 d); 80 percent coarse fragments; single grain; friable; few, fine and medium, vertical roots; gradual, wavy boundary.
IIC (CB 188)	30 +	Light gray (2.5Y 7/2 d); 80 percent coarse fragments; massive; friable; very few roots; 65 cm total depth.

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Belected properties:

	-	PERCE	IN	*		pH	64	XCHANGE	CATIO	NB	CEC
	BAND	8117	CLAY	U	H20	CaCl ₂	БW	м 8	Na	MUS	TOTAL
LFH	1	ı	ł	ŧ	4.1	3.5	4.9	15.64.(0.1	24.7	118.5

Profile 31:

1410 m.a.s.l.; grid reference EM47445; gently sloping site 10 m N.E. of small ridge crest; N.E. aspect; 22 cm of tephra, 80 cm of till over incompetent serpentinitic bedrock; lodgepole pine, Douglas fir, with juniper, scopolallie, bearberry, and huckleberry (<u>Vaccinium sp.</u>).

BORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
LF	1 - 0.5	forest floor.
(CB 189)		
H	0.5 - 0	Dark gray (10YR 4/1 d); plentiful, fine,
(CB 190)		random roots.
Bm	9 - 0	Light brownish gray (lOYR 6/2 d); sand;
(CB 191)		<pre>single grain; plentiful, fine and medium, random roots, and plentiful, coarse,</pre>
		horizontal roots; gradual, smooth boundary.
υ	6 - 20	Light gray (loYR 7/2 d); loamy sand; single
(CB 192		grain; plentiful, coarse, horizontal roots; abrupt, smooth boundary.
IIBmlb	20 - 28	Yellowish brown (10YR 5/4 d); loam; 10
(CB 193)		<pre>percent coarse fragments; very weak subangular blocky; plentiful, medium, oblique roots; gradual, smooth boundary.</pre>
IIBm2b	28 - 40	Light olive brown (2.5Y 5/4 d); sandy loam;
(CB 194)		30 percent coarse fragments; massive; few, medium, vertical roots; diffuse, smooth
		boundary.
IIC	40 - 100	Olive (5Y 5/4 d); sandy loam; 70 percent
(CB 195)		coarse tragments; massive; very few, medium, vertical roots; clear, smooth boundary.
IIIC	100 +	Olive (5Y 5/3 d); sand; 95 percent coarse
(CB 196)		fragments; massive; very few roots.

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Profile 31 (cont.):

Selected properties:

	ρ.	ERCED	E	*	9	×	N	KCHAN	GEC	ATIO	ĮS	CEC
	GIND	8117	CLLAY	0	50	cac12	БW	Ca Ca	M	Ma	NU8	TOTA
LF	1	•		35.6	5.1	4.4	13.7	15.0	1	0.0	30.2	83.0
H	I	ł	ł	17.4	5.3	4.6	6.9	7.2	•	0.0	14.6	25.0
Bm	86.0	ł	ł	0.9	6.0	5.4	2.9	1.4	0.2	0.0	4.5	4.6
υ	82.2	ł	ł	0.4	5.9	5.3	0.8	0.7	0.1	0.0	1.6	2.5
IIBml	b54.0	27.8	18.2	0.7	6.7	5.9	16.3	1.2	0.1	0.0	17.7	14.5
IIBm2	:b 67.5	15.0	17.5	0.5	6.8	5.9	20.2	0.7	0.1	0.1	21.1	25.4
IIC	59.8	19.6	20.6	0.3	6.6	6.3	15.8	0.5	0.1	0.0	16.4	11.8
IIIC	90.7	74.1	5.2	0.2	7.3	6.7	6.1	0.2	0.0	0.0	6.3	5.6

Extractable elements:

		DITHI	ONITE	*		OXAL	ATE 1		Ŀλ	ROPHO	SPHAT	يد 12
	Pe	T	8; 8	ц и	a i	N	ßi	Мп	Fe	IN	Si	Mn
LF												
н												
Bm	0.4	0.1	0.1	0.0	0.7	0.1	0.0	0.0	0.1	0.1	0.1	0.0
υ	0.2	0.1	0.0	0.0	0.4	0.2	0.0	0.0	0.0	0.1	0.0	0.0
IIBml	b2.2	0.1	0.2	0.1	0.6	0.2	0.0	0.1	0.2	0.1	0.2	0.0
IIBm2	b1.2	0.1	0.2	0.1	0.4	0.1	0.0	0.1	0.3	0.1	0.5	0.0
IIC	0.7	0.0	0.2	0.0	0.3	0.1	0.0	0.0	0.2	0.1	0.4	0.0

Appendix 1A: Shulaps Soils

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IIIC

(CB 196)

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Profile 32:

1410 m.a.s.l.; grid reference EM47445; barren ridge crest, 7 m S.W. of profile 31; level; 15 cm of tephra, 60 cm of till over serpentinitic bedrock.

HORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
LF	0.5 - 0	(NOT SAMPLED).
Bu	0 - 7	<pre>loose; plentiful, fine and medium, and few, coarse, horizontal roots; clear, smooth boundary; (NOT SAMPLED)</pre>
υ	7 - 16	<pre>single grain; loose; few, fine and medium, horizontal roots; abrupt, smooth boundary; (NOT SAMPLED).</pre>
IIBml	16 - 26	20 percent coarse fragments; very weak, subangular blocky; friable; few, fine and medium, horizontal roots; gradual, smooth boundary; (NOT SAMPLED).
IIBm2	26 - 36	<pre>50 percent coarse fragments; massive; friable; very few, fine and medium, horizontal roots; diffuse, smooth boundary; (NOT SAMPLED).</pre>
IIC	36 - 75	70 percent coarse fragments; massive; friable; very few roots; abrupt, smooth boundary; (NOT SAMPLED).

Profile 33:

1410 m.a.s.l.; grid reference EM47445; exposed slope 6 m below barren ridge crest, and 7 m S.W. of profile 31; S.W. aspect; lag deposit of serpentinitic cobbles and colluvial material over 15 cm of fractured bedrock.

EORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
1A	е – 1 0	lag deposit of ultramafic cobbles; (NOT SAMPLED).
AC	3 - 4	<pre>clay in pores of coarse fragments; (NoT SAMPLED)</pre>
C	4 - 20	fractured bedrock; (NOT SAMPLED).
IIC	20 +	same as IIIC in profiles 31 and 32; (NOT SAMPLED).

95 percent coarse fragments; massive; no roots; (NOT SAMPLED).

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1425 m.a.s.l.; grid reference EM445462; small ridge top at edge of glacial meltwater channel similar to location of profile 4; S aspect: occasional, stunted whitebark pine and Douglas fir; understory has scattered juniper, scopolallie (<u>Shepherdia</u> <u>canadensis</u>), bearberry, stonecrop (<u>Sedum ED.</u>), common yarrow (<u>Achillea millefolium</u>) and low blueberry.

DEPTH (cm) DEBCRIPTION	0 - 8 Dark grayish brown (2. 40 percent coarse frag loose; few, fine, obli smooth boundary	<pre>8 - 33 Olive gray (5Y 4/2 m); coarse fragments; sing abundant, fine, vertic boundary.</pre>	<pre>33 + Olive gray (5Y 4/2 m); coarse fragments; sing</pre>
	Y 4/2 m); loamy sa ents; single grain ue roots; clear,	sand; 75 percent e grain; loose; l roots; diffuse	sand; 75 percent e grain; loose; no

Belected properties:

	ES UNS	RCENT	 U	H20	Cac12	a 5	CHAN	M C	ATIO! Na	ND BUM	CEC
Ah	78.6 1	1.2 0.2	1.9	7.0	6.9	10.3	3.5	0.2	0.0	14.0	18.8
AC	94.3 1	.8 3.9	0.6	7.2	7.0	7.1	1.3	0.0	0.0	8.4	9.8

Extractable elements (percent):

		DITHI	ONITE	*		OXAL	ATE 1		ЪХI	ROPHO	BPHAT	*
	Pe	IK	ßi	Mn	Pe	N	81 1	Mn	84	N1	8i	ų
Ah	0.9	0.0	0.1	0.0	0.5	0.1	0.1	0.0	0.0	0.0	0.1	0.0
AC	0.5	0.0	0.1	0.0	0.4	0.0	0.1	0.0	0.0	0.0	0.1	0.0
υ	0.4	0.0	0.1	0.0	0.3	0.0	0.1	0.0	0.0	0.0	0.1	0.0

Profile 1103:

1425 m.a.s.l.; grid reference EM41463; small barren ridge top at edge of glacial meltwater channel similar to location of profile 1101; S aspect; occasional, stunted whitebark pine and Douglas fir; understory has scattered juniper, bearberry, and yellow flowered plant.

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HORIZON	DEPTH	
(TAB NO.)	(CIN)	DEBCRIPTION
Ah (CB 63)	0 - 10	Dark grayish brown (2.5Y 4/2 m); 60 percent coarse fragments; single grain; loose; plentiful. fine. random roots: clear smooth
ACI	10 - 27	boundary. Dark olive gray (5Y 3/2 m); sand; 65 percent
(CB 64)		<pre>coarse fragments; single grain; loose; plentidu, fine vertical roots; gradual emoth houndary</pre>
AC2	27 - 40	Dark olive gray (5Y 3/2 m); sand; 65 percent
(CB 65)		coarse fragments; single grain; loose; plentiful, fine vertical roots; gradual smooth boundary.
U	40+	Black (5Y 2.5/2 m); sand; 70 percent coarse
(CB 66)		fragments; single grain; loose; few, fine, oblique roots: 70 cm total denth.

Selected properties:

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	BAND	BILT	CLAY	• •	H20 F	Cacl 2	j Šv	8	×	RN R	WNS	TOTA
4	1			0.8	7.1	6.8	11.0	1.1	0.1	0.0	12.3	16.6
ACI	94.2	1.0	4.8	0.4	7.3	7.0	8.3	0.8	0.1	0.0	9.2	12.2
AC2	96.1	1.3	2.6	0.1	7.3	7.1	4.9	0.3	0.0	0.0	5.3	8.2
0	97.4	•	2.6	0.1	7.4	7.3	5.1	0.4	0.0	0.0	5.5	7.9
Extra	lctable	e le	hents									
Extra	97.4 Ictable	0	2.6 Bents:	0.1	7.4	7.3	5.1	4.0	0.0	1	0.0	0.0 5.5

		IHIIO	ONITE	*		OXAL	ATE 1		PXI	ROPHO	SPHAT	جو انبا
	P.	TR.	81	W	Pe	N	8i		94	I	ŝi	Mn
Ah	0.9	0.0	0.1	0.0	0.4	0.1	0.1	0.0	0.0	0.0	0.1	0.0
ACI	0.6	0.0	0.1	0.0	0.4	0.1	0.1	0.0	0.0	0.0	0.1	0.0
AC2	0.5	0.0	0.1	0.0	0.3	0.0	0.1	0.0	0.0	0.0	0.1	0.0
υ	0.4	0.0	0.1	0.0	0.3	0.0	0.1	0.0	0.0	0.0	0.1	0.0

Appendix 1A: Shulaps Soils

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s.l.; grid reference EM413456; forested portion of mid ench near Burkholder Lake inlet stream; N aspect; mixed on with ash present and serpentinite; paralithic at 50 cm; thick stand of Engelmann spruce; understory itail (Equisetum Sp.) and other herbs.	DEPTH (cm) DESCRIPTION	<pre>15 - 1 thick layer of leaves and decomposing twigs; (NOT SAMPLED).</pre>	<pre>1 - 0 discontinuous layer of well humified organic material; (NOT SAMPLED).</pre>	0 - 3 Very dark brown (10YR 2/2 m); sandy loam; 70 percent coarse fragments; single grain; very friable; abundant, fine, random roots, and abundant, medium and coarse, oblique roots; clear, wavy boundary.	3 - 30 Olive brown (2.5Y 4/4 m); sandy loam; 80 percent coarse fragments; weak, medium subangular blocky; very friable; few, medium and coarse, oblique roots.	<pre>30 + Olive gray (5Y 4/2 m); sandy loam; 80 percent coarse fragments; very friable; few, fine, vertical roots; 50 cm total depth.</pre>	properties:	PERCENT % PH EXCHANGE CATIONS CEC ID BILT CLAY C H50 CAC1, MG CA K MA BUH TOTAL
1425 m.a.s.l. valley bench Ah horizon w. contact at 50 has horsetail	HORIZON (LAB NO.)	LF 1:	Н	Ah 0 (CB 67)	Bm 3 (CB 68)	c (CB 69)	selected pro	IA UND 8100

PH BICHANGE CATIONS CEC Cacl ₂ Mg Ca K Na BUM TOTAL
PH EXCHANGE CATIONS Cacl ₂ Mg Ca K Ma SUM
PH EICHANGE CATIO Cacl ₂ Ng Ca K Na
PH BICHANGE CaCl2 MG Ca K
PH EICHAN Cacl ₂ Mg Ca
PK E Cacl ₂ Mg
pH CaCl ₂
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RCENT &
PERCENT & ID BILT CLAY C

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13.8 4.5 0.1 0.0 18.4 23.5 13.9 16.6 12.7 2.7 0.2 0.0 15.5 34.1 0.0 0.1 10.0 3.8 5.2 4.8 6.0 5.9 6.8 6.9 35.4 44.3 20.3 3.9 68.6 22.7 8.7 1.8 0.8 7.7 70.2 22.1

Extractable elements:

		DITHI	ONTEE	*		OXAL	ATE		λđ	ROPHO	SPHAT	
	•	IK	81	M	70	R	ßi	ų	8	N	81	W
ц												
_												
ş	1.0	0.3	0.2	0.0	1.0	0.4	0.2	0.0	0.3	0.2	0.1	0.0
H	0.8	0.1	0.1	0.0	0.8	0.2	0.1	0.0	0.1	0.1	0.0	0.0
	0.7	0.1	0.1	0.0	0.6	0.1	0.1	0.0	0.1	0.0	0.0	0.0

APPENDIX 1B

TULAMEEN SOILS

PROFILES GMWET, GMDRY, 13, 14

B. Tul ameen Ultramafic Complex

Profile GMWET:

1225 m.a.s.l.; grid reference FK5289; small drainage 10 m from intermittent creek in depositional area on Grasshopper Mountain; S.E. aspect; ultramafic till; open forest of Douglas fir with thick grass understory.

DESCRIPTION	grass litter.	Black (10YR 2/1 m); loam; 20 percent subrounded coarse fragments; strong, mediu granular; very friable; abundant roots.	Very dark grayish brown (10YR 3/2 m); sand) loam; 20 percent subrounded coarse fragments; moderate, medium subangular blocky; very friable; plentiful roots.	Very dark gray (10YR 3/1 m); loam; 20 percent subrounded coarse fragments; moderate, medium granular; friable; abunda roots.	Dark grayish brown (2.5Y 4/2 m); sandy loal 20 percent subrounded coarse fragments; weak, medium subangular blocky; very friable.
DEPTH (cm)	9 - C	0 - 10	10 - 40	40 - 50	50 +
HORIZON (LAB NO.)	LF	_е Аћ (СВ 1)	Bm (CB 2)	IIAh (CB 3)	IIC (CB 4)

Selected properties:	PERCENT & Sand Silt Clay C	1 1 1
ute; piencliui roocs. 10YR 3/1 m); loam; 20 3d coarse fragments; granular; friable; abundant	<pre>vn (2.5Y 4/2 m); sandy loam; inded coarse fragments;</pre>	angular blocky; very

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Profile GMDRY:

1260 m.a.s.l.; grid reference FK5289; exposed, droughty site on barren knoll on Grasshopper Mountain; S. aspect; ultramafic till; barren.

HORIZON	DEPTH	
(IAB NO.)	(cn)	DESCRIPTION
LFH	1 - 0	thin forest floor.
Bm	0 - 17	Dark grayish brown (10YR 3/4 m); loamy sand;
(CB 5)		<pre>20 percent subrounded coarse tragments; moderate, medium to coarse granular; very friable; few roots.</pre>
BC	17 - 26	Dark grayish brown (2.5Y 4/2 m); loamy sand;
(CB 6)	1	20 percent subrounded coarse fragments; moderate, fine granular; very friable; no roots.
υ	26 +	Grayish brown (2.5Y 5/2 m); sandy loam;
(CB 7)		weak, medium subangualr blocky; friable; no roots.

	BAND	BILT	CLAY	U	H2O	CaCl 2	Б ж	C C	M	Na	WNS	TOTAL
LFH	1	•		•	1	ı	•	•		1	1	.
Bm	I	ı	ı	1.6	6.2	5.9	5.1	1.7	0.1	0.0	7.0	13.8
BC	I	ı	ı	0.5	6.7	6.2	7.3	0.5	0.1	0.0	7.9	11.4
υ	ł	ł	ı	0.4	6.8	6.4	14.5	0.7	0.1	0.0	15.3	19.7
Extra	ctab]	le ele	ments	••								
	8	DITHI	ONITE Bİ	* #	9	OXALA	TB 1 Bi	ų	PY Fe	ROPHO A1	SPHAT Si	Kn Mn
LFH	•	•	•		ı	1	ŧ	ł	ł	ł	1	I

Appendix 1B: Tulameen Soils

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Profile 13:

1730 m.a.s.l.; grid reference FK535867; shallow, residual soil on summit of Olivine Mountain; nearly level site; vegetation of subalpine fir with occasional whitebark pine, white flowered rhododendron, creeping juniper (<u>Juniperus horizontalis</u>), lupin, cow parsnip (<u>Heracleum sphondylium ssp. montanum</u>), and grouseberry (<u>Vaccinium scoparium</u>).

HORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
Bml (CB 92)	0 - 15	Dark reddish brown (5YR 3/3 m); sandy loam; weak, medium granular; friable; plentiful, very fine and fine, oblique roots, and plentiful, coarse, horizontal roots; abrupt, smooth boundary.
Bm2 (CB 93)	15- 20	Dark brown (7.5YR 4/4 m); sand; weak, medium granular; friable; few, fine, horizontal roots; clear, broken boundary.
BC (CB 94)	20 - 26	Dark yellowish brown (10YR 4/6 m); sand; weak, medium subangular blocky; firm; very few, fine, horizontal roots; clear, broken boundary.
C (CB 95)	26 +	Dark yellowish brown (lOYR 4/6 m); massive; firm weathered dunite.

Selected properties:

	4 BAND	BILT	NT CLAY	ن مړ	0	K Cacl,		XCHAN		ATION Na	KS BUM	CEC
)		9		8	5			
Ah	74.4	18.0	3 7.6	1.5	6.3	6.3	5.3	1.0	0.1	0.0	6.3	13.0
Bin	83.5	11.4	15.1	0.6	6.2	5.9	2.6	0.4	0.0	0.0	3.0	1.1
BC	89.7	7.6	3 2.5	0.1	6.6	6.3	1.3	0.1	0.0	0.0	1.4	2.0
J	ł	1	ł	0.3	7.1	6.8	1	1	•	+	,	ı

Extractable elements:

		DITHI	ONITE	*		OXNI	ATE		Хđ	ROPHO	BPEAT	*
	70	IX	8 1	Mh	Pe	T	81	Mn	Pe	M	81	W
Ah	1.6	0.2	0.1	0.0	1.2	0.1	0.3	0.1	0.1	0.1	0.0	0.0
Bm	1.5	0.2	0.1	0.0	1.2	0.2	0.2	0.0	0.1	0.1	0.1	0.0
BC	0.8	0.0	0.1	0.0	1.2	0.0	0.4	0.0	0.1	0.0	0.1	0.0
U	6.0	0.0	0.2	0.0	1.2	0.0	0.4	0.0	0.1	0.0	0.1	°.0

Profile 14:

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1370 m.a.s.l.; grid reference FK543879; sloping site at mid elevation from roadcut on Olivine Mountain; N aspect; soil pit includes shear zone; colluvium and till; mature forest of Engelmann spruce and Douglas fir.

	HORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
	LFH	8 - 0	Black (10YR 2/1 m); mossy mor humus.
	(CB 97)		
	Bfl	0 - 26	Dark reddish brown (5YR 3/4 m); sandv loam:
	(CB 98)		25 percent angular coarse fragments; moderate, medium granular; friable; abundant; fine and medium, random roots, and few coarse roots; clear, smooth boundary.
	Bf2 (CB 99)	26 - 86	Dark yellowish brown (10YR 4/4 m); 50 percent coarse fragments; strong, medium pseudo platy and weak, medium granular; very friable; few, fine, medium and coarse, vertical roots; abrupt, smooth boundary; this horizon occupies one-half of the soil pit.
270	BC (CB 100)	26 - 51	Olive gray (5Y 4/2 m) with reddish brown (7.5YR 6/8 m) coatings on cleavage planes; 90 percent coarse fragments; weak, medium granular; friable; very few, medium, horizontal roots; gradual, smooth boundary; this horizon occupies one-half of the soil pit.
)	C1 (CB 101)	51 +	Yellowish brown (l0YR 5/6 m); 90 percent coarse fragments; strong, medium, pseudo Platy; friable; no roots; underlies Bfl.
	C2 (CB 102)	86 +	Dark olive gray (5Y 3/2 m); 90 percent coarse fragments; strong, medium, pseudo Platy; firm, no roots; underlies Bf2.

Profile 14 (cont.):

Belected properties:

	-	PERCE	LN	*	1	H	PA -	XCHAN	JGP (CTTO!	87	Ugu Ugu
	BAND	81LT	CLAY	U	^н 20	CaC12	БW	с В	×	Na	MUS	TOTAL
LFH	•	•		•				'	1	1		
Bfl	•	ł	ı	1.0	5.3	4.4	0.9	1.6	0.4	0.0	3.0	15.2
Bf2	ı	•	•	0.6	5.3	4.4	0.9	2.3	0.2	0.0	3.4	10.6
BC	ı	•	ł	0.6	5.5	4.8	1.2	2.0	0.1	0.0	3.3	7.6
C1	•	۲	•	0.4	5.5	4.8	1.8	3.6	0.2	0.0	5.7	13.9
C2	•	ı	•	0.8	6.3	5.5	0.8	2.4	0.1	0.0	3.3	6.4

Extractable elements:

		DITHI	ONITE	*		OXAI	ATE		λđ	ROPHO	PEHO S	بد 2
	Fe	TK	8i	Mn	F 0	R	81	Mn	94	IN	8i	, F
LFH	ı	ł	•	•	1		1	·	'		•	'
Bfl	2.3	0.4	0.1	0.0	6.0	0.3	0.0	0.0	0.2	0.2	0.0	0.0
Bf2	2.7	0.2	0.1	0.0	0.8	0.1	0.0	0.0	0.2	0.1	0.0	0.0
BC	2 .6	0.0	0.1	0.0	0.9	0.0	0.0	0.0	0.1	0.0	0.0	0
1	3.0	0.1	0.1	0.0	1.3	0.1	0.1	0.0	0.1	0.0	0.0	0
C	2.2	0.0	0.1	0.0	1.2	0.0	0.1	0.0	0.0	0.0	0.1	0

APPENDIX 1C

COQUIHALLA SOIL

PROFILE 34

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C. Coquihalla Serpentine Belt

Profile 34:

950 m.a.s.l.; grid reference FK239850; steeply sloping site on small deposit of serpentinitic till on west arm of Ladner Creek; S.E. aspect; 1.5 to 2 m of serpentinitic till over serpentinitic bedrock.; subalpine fir, yellow cedar, western hemlock, low blueberry, sworfern (<u>Polystichium munitum</u>).

BORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
HJ	1 - 0	abundant fine roots; clear, smooth boundary.
(CB 201)		
Bfl	0 - 10	Brown (7.5 YR 5/4 d); loam; 20 percent coarse fragments; moderate, fine granular; very friable; abundant, fine, random roots, and abundant, medium, horizontal roots; clear, wavy boundary.
Bf2 (CB 203)	10 - 30	Light yellowish brown (10YR 6/4 d); sandy loam; 20 percent coarse fragments; weak, fine granular; friable; abundant, fine, random roots; gradual, wavy boundary.
Bf3 (CB 204)	30 - 45	Very pale brown (10YR 7/4 d); sandy loam; 25 percent coarse fragments; weak, medium, subangular blocky; firm; few, fine, random roots, and plentiful, medium, oblique roots; gradual, wavy boundary.
BCC (CB 205)	45 - 70	Light yellowish brown (2.5% 6/4 d); sandy loam; 30 percent coarse fragments; massive; firm;common, medium, distinct (10VR 5/6) mottles; very few, fine, vertical roots; diffuse, wavy boundary.
сс (СВ 206)	70 +	Light gray (2.5Y 7/2 d); sandy loam; 35 percent coarse fragments; massive; firm; few mottles; very few, fine, vertical roots; 90 cm total depth.

Profile 34 (cont.):

Selected properties:

	E SAND	ERCE BILT	NT CLAY	÷0	E20 F	H Cacl ₂	(a 5 W	CHAN	0 11 11 11 11 11 11	ATIOI Na	80M	CEC
H	1	'	1	27.1	5.4	4.5	11.2	12.5	0.1	0.0	24.4	41.5
3f1	46.8	37.7	15.5	2.1	5.7	4.6	4.8	0.6	0.1	0.0	5.5	12.2
3f2	58.5	27.9	13.6	1.3	5.9	5.1	4.8	0.4	0.0	0.0	5.3	14.7
3£3	69.6	21.4	9.0	0.7	6.0	5.1	4.2	0.4	0.0	0.0	4.7	9.3
gc	71.3	20.4	8.3	0.4	6.2	5.3	3.9	0.4	0.0	0.0	4.3	7.1
2	71.3	19.1	9.6	0.1	6.6	6.0	4.8	0.4	0.0	0.0	5.3	5.0

Extractable elements:

		DITHI	ONITE	ar 5		INXO	ATE	, ,	NA S	ROPHO	SPHAT.	ر مر د ده
		:	1			2	1		2	7	10	uu
FΗ	I	ı	ı	ł	ı	I	I	ı	ł	ł	ı	ı
Bfl	2.9	0.2	0.1	0.0	1.5	0.2	0.0	0.0	0.7	0.2	0.1	0.0
Bf2	1.8	0.3	0.1	0.0	0.3	0.3	0.0	0.0	0.6	0.2	0.1,	0.0
Bf3	1.0	0.2	0.1	0.0	0.8	0.2	0.0	0.0	0.3	0.1	0.0	0.0
BCc	0.9	0.1	0.1	0.0	0.7	0.2	0.0	0.0	0.2	0.1	0.0	0.0
ပ္ပ	0.8	0.1	0.1	0.0	0.5	0.1	0.0	0.0	0.1	0.0	0.1	0.0

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APPENDIX 1D

TWIN SISTERS SOILS

PROFILES 20, 21

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D. Twin Bisters Area

Profile 20:

970 m.a.s.l.; 400 m east of Daly Frairie; 122⁰ North lattitude, 48⁰ 43¹ East laongitude; S aspect; roadcut on mixed ultramafic till; edge of clearcut in yellow cedar (<u>Chamaecyparis</u> nootkatensis), amabilis fir (<u>Abies amabilis</u>) and western hemlock (<u>Tsuga heterophylla</u>) forest.

BORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
LFH (CB 110)	7 - 0	Black (10YR 2/1 d); moder forest floor with very thin L layer over thich F and H; abrupt boundary.
Ae (CB 111)	- 0 4	Light gray (10YR 7/1 d); loam; weak, coarse granular; friable.
Bfl (CB 112)	4 - 10	Light yellowish brown (10YR 6/4 d); sandy loam; weak, medium subangular blocky; friable.
Bf2 (CB 113)	10 - 25	Very pale brown (10YR 7/4 d); sandy loam; weak, fine subangular blocky; friable; common, medium, distinct (7.5YR 6/8) mottles.
BC (CB 114)	25 - 33	Light yellowish brown (2.5Y 6/4 d); sandy loam; 40 percent coarse fragments; weak, medium subangular blocky; very firm; common, medium, distinct (7.5YR 6/8) mottles.
с (СВ 115)	33 +	Pale olive (5Y 6/4 d); sandy loam; 40 percent coarse fragments; weak, medium subangular blocky; few, medium, prominent (7.5YR 6/8) mottles; 43 cm total depth.

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Profile 20 (cont.):

Selected properties:

		PERCE	LN.			H	E	CHANGE	5	TION	8	CEC	
	BAND	BILT	CLAY		120	cac12	БW	Ca		Na	MUS	TOTA	,
LFH	•	1	.	35.5	4.4	3.6	10.7	11.30.	2	0.1	22.6	114.0	8
Ae	51.0	39.4	9.6	1.4	4.2	3.4	0.6	0.30.	0	0.0	0.9	1.1	
Bfl	68.2	22.6	9.2	3.5	4.9	4.1	1.8	0.10.	0	0.0	1.9	28.3	tii
Bf2	4	4	ı	1.7	4.9	4.4	0.1	0.30.	0	0.0	0.5	15.9	-
BC	63.8	31.1	5.1	0.7	5.4	4.8	0.1	0.1.0	•	0.0	0.2	9	
υ	58.9	36.0	5.1	0.2	5.4	5.0	0.0	0.10		0.0	0.2	4.8	_
			æ										

Extractable elements:

	-	DITHI	ONITE	-		OXAL	ATE	مد	ĿΧd	ROPHOS	SPHAT	ж ы
	Fe	M	81	Ma	Pe	7	Bi	-	Pe.	7	8i	Ř
LFH	4	1	1	4	I	ł	ı	I	I	ı	ı	ı
Ae	0.2	0.1	0.0	0.0	0.1	0.2	0.0	0.0	0.1	0.2	0.0	0.0
Bfl	1.5	1.1	0.1	0.0	0.9	1.3	0.1	0.0	0.6	1.0	0.1	0.0
Bf2	1.3	0.8	0.1	0.0	1.1	1.0	0.1	0.0	0.5	0.7	0.1	0.0
BC	0.7	0.4	0.0	0.0	0.6	0.8	0.1	0.0	0.2	0.3	0.0	0.0
υ	0.5	0.2	0.0	0.0	0.4	0.4	0.1	0.0	0.0	0.2	0.0	0.0

Profile 21:

1030 m.a.s.l.; roadcut on logging road above profile 20; S aspect; mixed till.

HORIZON (LAB NO.)	DEPTH (cm)	DESCRIPTION
LFH	5 = 0	Black (10YR 2/1 d); forest floor.
(CB 116)		
Ae	0 - 0.5	discontinuous layer; (NOT SAMPLED).
Bfl	0.5 - 10	Brownish yellow (10YR 6/6 d); moderate,
(CB 117)		medium subangular blocky; friable.
Bf2	10 - 45	Brownish yellow (loyR 6/6 d); moderate,
(CB 118)		medium subangular blocky; friable.
U	45 +	Light yellowish brown (2.5Y 6/4 d);
(CB 119)		moderate, medium subangular blocky; very firm: contains yellowish red (5yR 5/8)
		veinlets and root mats (rootmat sample CB
		Tool / / J CH COLD TOOL TO CH

Prcfile 21 (cont.):

Belected properties:

		PERCE	7	P			J	CEC					
	BAND	SILT	CLAY	U	H2(0	CaC12	ы	Ca	M	PN	MUS	TOTM
H.J.	•	1	1	46.6	4		3.5	3.4	3.3	0.3	0.0	7.1	141.0
e													
3f1	I	ı	ı	2.4	5	•	4.3	1.4	0.9	0.1	0.0	2.4	24.5
3f2	ł	I	ł	2.1	5	۳.	4.5	1.2	0.9	0.1	0.0	2.2	13.7
	ı	I	i	i	9	۰.	5.1	2.5	0.2	0.1	0.0	2.8	14.9

		DITHIC	ATINO			OXAL	ATE 1		ΪĀđ	SOPHO	SPHAT	مر دع
	9	IN	8i	Nu.	Pe	N	Bi	aw	Pe	R	si	Mn
LFH	1	1	1		1	ı	ı	t	ı	ı	ł	ı
Ae												
Bfl	2.4	0.8	0.1	0.0	1.2	1.0	0.1	0.0	6.0	0.7	0.1	0.0
Bf2	2.5	0.9	0.1	0.0	1.8	1.1	0.1	0.0	1.4	0.9	0.2	0.0
ر	6.1	0.6	0.1	0.0	1.4	1.1	0.3	0.0	0.6	0.6	0.1	0.0

0.0

0.3

1.1

0.0 1.4

0.6 0.1

1.3

υ

APPENDIX 2: RATIONALE FOR SITE SELECTION

The primary aim of the field research was to study sites that reflected the potential development of soils on ultramafic materials under various climatic regimes. The major criteria employed during site selection were to select soil profiles that (1) occupied stable portions of the landscape, (2) were free of lithologic discontinuities, and (3) were developed in ultramafic parent materials unaffected by additions or mixing of materials with non-ultramafic lithologies.

The profiles selected for study did not necessarily represent the dominant soils in the landscape. No attempt was made to determine the areal extent of ultramafic soils with particular properties, or to quantify the natural variation of soil properties across the landscape.

This approach was used because, at the outset of the study, little information was available concerning the range of soil properties expected in ultramafic terrain in southwestern British Columbia. This study has provided information on what may be the endmembers of some climatic, lithologic, and topographic sequences, and forms the basis for more detailed investigations of soil variability within ultramafic landscapes.

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