COMPARISON OF SILICEOUS VOLCANICS FROM THE CLARNO AND JOHN DAY FORMATIONS, OREGON

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CHAPTER 1 INTRODUCTION

1.1 Introduction

Several major lithologic units of metamorphic, igneous, and sedimentary origin underlie the Blue Mountains Region of central Oregon (Fig 1.1). This report focuses on silicic volcanics from two major units within the Blue Mountains Region, the Clarno and John Day Formations (Fig 1.2).

Distinguishing between rhyolites from the Clarno and John Day Formations is necessary in order to unravel the petrologic and tectonic history of the Blue Mountains Region. Earlier attempts at distinguishing these rhyolites have proven unsuccessful (e.g. Walker and Robinson 1990a, Robinson et al. 1990). In this report, rhyolites of the Clarno and John Day Formations are compared petrographically, mineralogically, and geochemically to find distinguishing characteristics and to determine their origins.

The Clarno Formation consists largely of andesitic to dacitic lava flows, breccias, and tuffs of primarily Eocene age. The John Day Formation consists primarily of silicic pyroclastic rocks of probable Oligocene to early Miocene age. In gross aspect, these two formations are easily distinguishable. Locally, however, considerable overlap exists in lithology and possibly in age. Both units contain flows and domes of rhyolite that are indistinguishable in the field. Stratigraphic

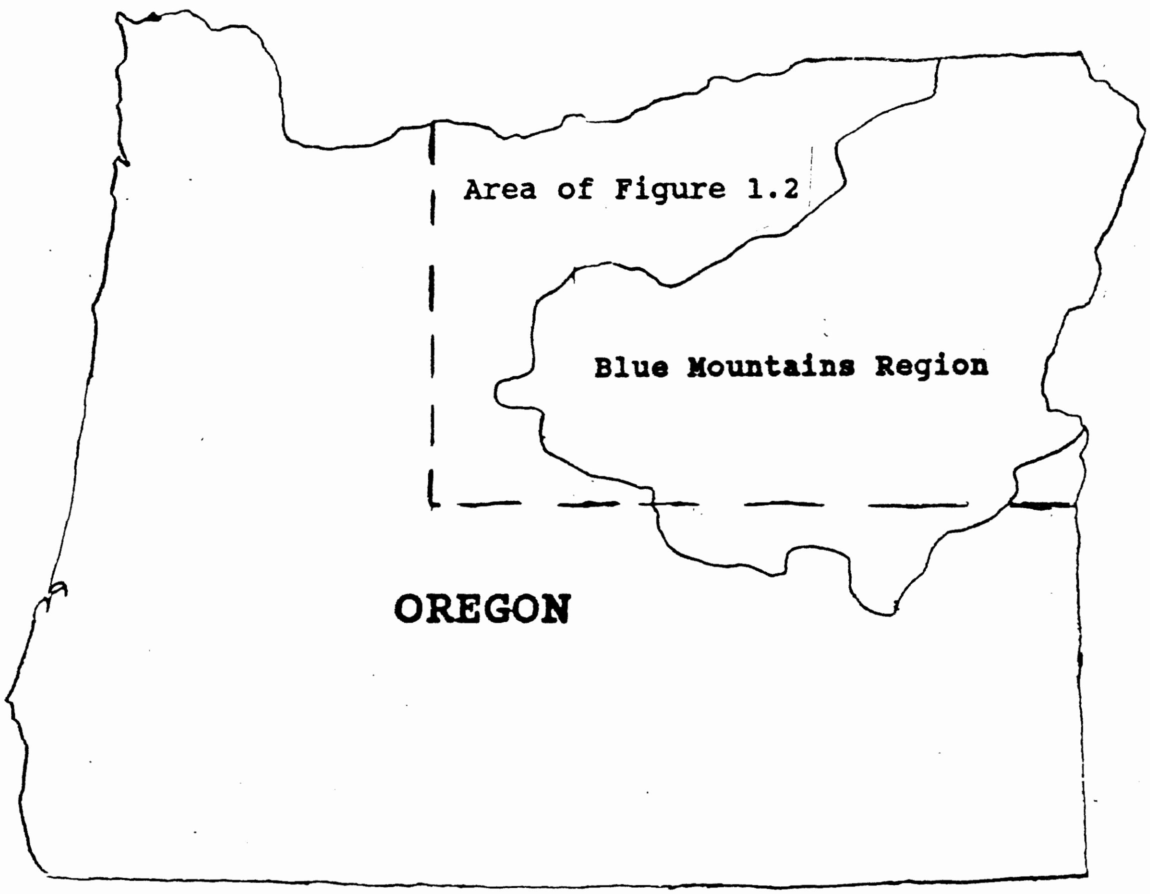


Figure 1.1. Location of the Blue Mountains Region in Oregon (after Baldwin, 1964).

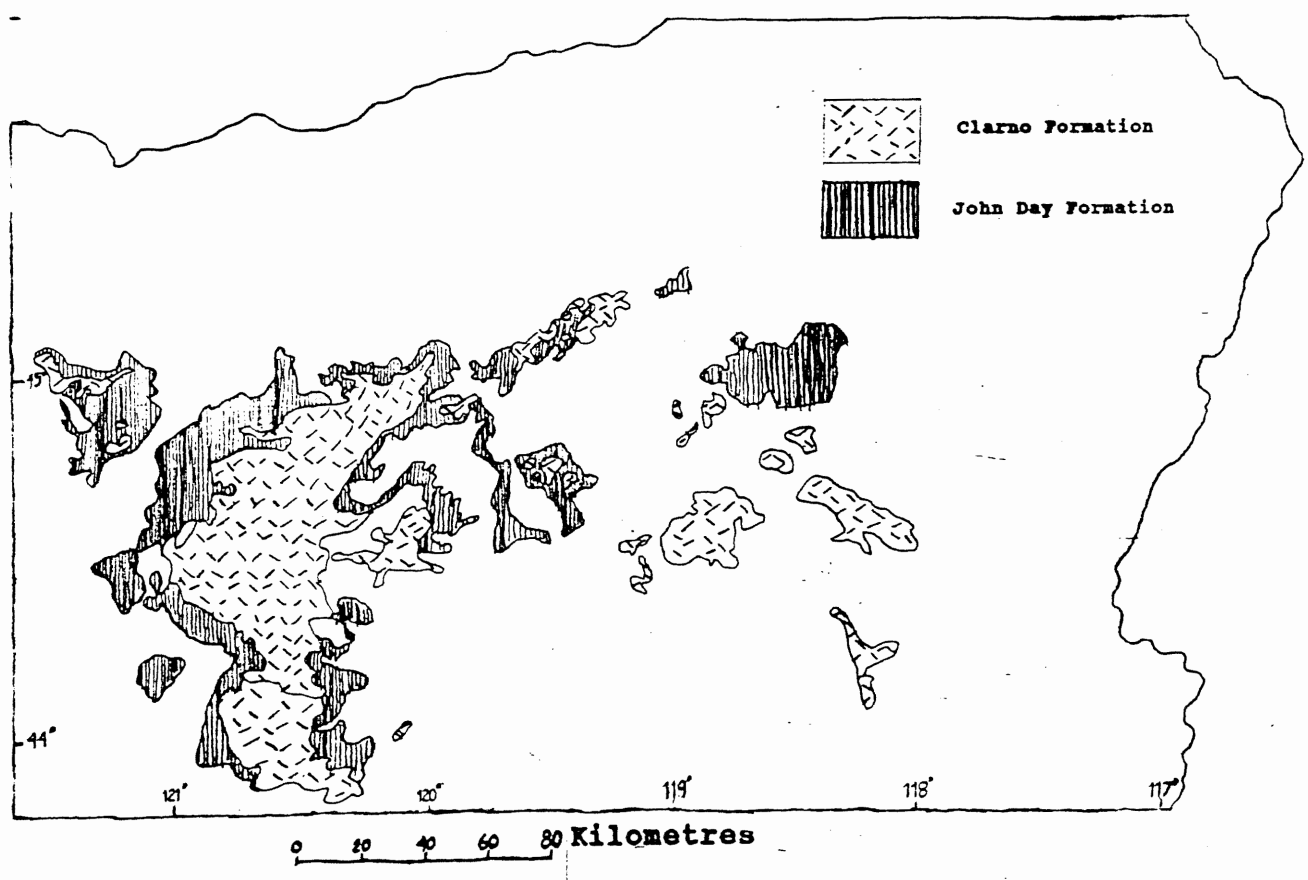


Figure 1.2 Outcrop area of the Clarno and John Day Formations in the Blue Mountains Region (Walker 1990).

relationships are unclear because many of the domes display an intrusive relationship with Clarno lavas, but are not overlain by younger rocks. Thus, these domes could belong to either the Clarno Formation or to the John Day Formation.

1.2 Regional Geology

The Clarno and John Day Formations each form a aomplex suite of basaltic to rhyolitic volcanic and volcaniclastic rocks. The Clarno Formation overlies pre-Cenozoic basement rocks and underlies the John Day Formation. The John Day Formation underlies flows of the Columbia River Basalt Group (Walker and Robinson 1990a).

The Clarno Formation consists of terrestrial volcanic, volcaniclastic, and epiclastic sedimentary rocks of Eocene to Oligocene age. Volcanic rocks from the Clarno Formation are primarily andesitic, but range in composition from basaltic to rhyolitic (Walker and Robinson 1990a). The Clarno Formation shows varying degrees of alteration.

The John Day Formation consists primarily of volcaniclastic rocks with some lava flows. The age of the John Day Formation ranges from Oligocene to early Miocene, and may be partially coeval with the Clarno Formation (Robinson et al. 1990). The volcanics range in composition from basaltic to rhyolitic, but consist mainly of intermediate to silicic air-fall tuffs. The

John Day Formation is typically less altered than the Clarno Formation.

1.3 Location of the study area

The Clarno Formation crops out primarily along the axis of the Blue Mountains Region in north central Oregon (Figs 1.1 and 1.2). The area of exposure is approximately 5000 square kilometres (Suayah and Rogers 1990). The John Day Formation exists in three distinct areas of northern and northeastern Oregon (Robinson et al. 1990) (Fig 1.2). Samples used in this study are from a variety of localities within both the Clarno and John Day Formations.

1.4 Objectives and scope

Isolated rhyolitic domes intrude or overlie typical Clarno volcanics. Some authors have assigned these rhyolites to the John Day Formation (Waters et al. 1951). However, isotopic ages indicate that these rhyolites are of Eocene age and therefore belong to the Clarno Formation (Walker and Robinson 1990a). A second problem is interlayered andesitic and rhyolitic rocks of typical Clarno lithology. These rocks display radiometric ages which place them in the John Day Formation (Robinson et al., 1990).

These examples show that some temporal overlap may exist between the Clarno and John Day Formations. As well, these rocks introduce the basic problem focused on in this report: what methods can distinguish between rhyolites from the Clarno and John Day Formations, and what is the origin of these two rhyolite suites? Lithology, age, and alteration are not sufficient in distinguishing the two formations (Walker, 1990).

Petrographic, mineralogical, and geochemical data may help distinguish between the two formations. Perhaps some chemical relation will universally apply when classifying a rhyolite from either the Clarno or John Day Formation. After identifying a method for distinguishing these rhyolites, a clearer picture of the origin of these units can be drawn.

The data which help distinguish between the two formations may help solve problems of age relations and may aid in determining the geologic history of both formations. A discussion of tectono-magmatic relations of the John Day and Clarno Formations follows, as well as a discussion of any further problems which arise from this study.

1.5 Previous work

The geology of the Blue Mountains Uplift has been studied since the turn of the century (Merriam 1901). Knowlton (1902), Merriam and Sinclair (1907), and Chaney (1924) studied plant fossils from the Clarno and John Day Formations and established the broad age range of each unit. Hergert (1961), Stirton

(1944), Mckee (1970), and Hanson (1973) expanded on these early works through plant and vertebrate studies. Fossil studies indicate that the Clarno Formation is primarily Eocene and that the John Day Formation ranges from latest Eocene to early Miocene age.

K-Ar radiometric studies of the area also appear in the literature (Everndon et al. 1964, Swanson and Robinson 1968, Enlows and Parker 1972, Walker 1973, and Brooks et al. 1976). Walker and Robinson (1990a) recalculated the dates from the previous studies, using decay constants acceptable in 1990. These studies largely support the Eocene and late Eocene to Miocene ages of the Clarno and John Day Formations, respectively, but show that some time overlap may exist between the two units.

Chemical studies of the Clarno Formation are presented by Rogers and Novitsky-Evans (1977), Rogers and Ragland (1980), and Noblett (1981). Noblett interpreted the Clarno Formation as a calc-alkaline suite of volcanics which erupted through a relatively thin continental crust, and relates it to subduction of oceanic crust beneath the continent.

This study will try to resolve problems uncovered by previous works. In particular, some method must be found to distinguish between rhyolites of the Clarno and John Day Formations. As well, this study investigates the origins of these rhyolites.

1.6 Organization

The first chapter of this thesis presents the basic geology of the Blue Mountains Region, and describes the main problems addressed by this study. The second chapter outlines the stratigraphy of the Clarno and John Day Formations, and describes the geologic setting. Chapter 3 details the petrography and mineralogy of rhyolites from the Clarno and John Day Formations. Chapter 4 presents geochemical data for these rhyolites and compares the geochemistry of Clarno and John Day rhyolites, eventually attempting to classify rhyolites of uncertain origin. Chapter 5 discusses the tectonic setting of the Clarno and John Day Formations. Finally, Chapter 6 presents the conclusions of this study.

CHAPTER 2 BACKGROUND GEOLOGY

2.1 Introduction

The Blue Mountains Region is underlain by thick sequences of sub-aerial volcanic rocks, incorporating the Clarno and John Day Formations. Historically, gross lithology and age have been used to distinguish the two formations. Rare fossil data provide the basis for the age of the units outlined in Chapter 1 (Walker 1990). Locally, however, there is considerable overlap in composition and perhaps in age. This creates problems when determining to which formation isolated flows and domes belong.

2.2 The Clarno Formation

Individual Clarno units are predominantly flows derived from local sources. Exposures of these units are commonly poor (Walker and Robinson, 1990). For these reasons, tracing units within the Clarno Formation laterally over large distances is not possible.

Typical Clarno rocks display varying degrees of alteration. This alteration affects the mineralogy, resulting in a secondary mineralogy overprinting the primary minerals. The alteration also affects the major and trace element geochemistry of these units. This is not true for all Clarno rhyolites; some unaltered samples are available.

Rhyolites in the Clarno Formation typically are untraceable over large areas, as they occur as laterally restricted flows or domes. Locally, pyroclastic rocks are abundant, and are generally more widespread than flow units. These pyroclastics are easily erodable, however, and thus exposures of these laterally extensive units are poor. Typical Clarno andesites do bound some rhyolites above and below, however, and therefore these units are assigned to the Clarno Formation. In contrast, localized rhyolite flows are not overlain by other units, as they represented stratigraphic highs during deposition of the andesites. In particular, many domes intrude typical Clarno andesites but are exposed at the surface (i.e. they are not overlain by anything). These domes may belong to either the Clarno or John Day Formation.

2.3 John Day Formation

The John Day Formation consists primarily of air fall tuffs, ash fall tuffs, and tuffaceous sediments of intermediate to silicic composition. Small mafic flows and rhyolite flows and domes also occur within the formation. The John Day Formation is distinguished from the Clarno Formation largely on the basis of age and lithology (Robinson et al. 1990).

Rhyolite flows from the John Day Formation typically display less alteration than those of the Clarno Formation. Secondary minerals are less highly developed in typical John Day samples than in typical Clarno samples. Much of the pyroclastic material has undergone weathering, however. The generally lower degree of alteration of John Day rocks implies that they are not as mineralogically nor chemically modified as Clarno rocks.

Rhyolite flows in the John Day Formation usually interfinger with ash flow tuffs, and their assignment is clear. However, classification of isolated domes which are completely surrounded by older or younger rocks is not easy. These domes may belong to either the John Day or the Clarno Formation (Fig 2.1).

2.4 Significance

Distinguishing between rhyolites of the Clarno and John Day Formations is essential in order to understand the tectono-magmatic evolution of the region. The Clarno Formation represents an arc complex that erupted through thin continental crust (Noblett 1981). Noblett's classification is based on a comparison of lithophile element abundances in both the Clarno Formation and in continental crust.

Well-defined vent complexes associated with locally erupted rocks are rare. These rocks are considered local despite the lack of an obvious source because they are rock types which are not easily transported, such as ash-flow tuffs and rhyolites flows. Conversely, the John Day Formation consists primarily of ash-fall tuffs, which can be transported significantly prior to deposition. These tuffs thicken to the west and southwest,

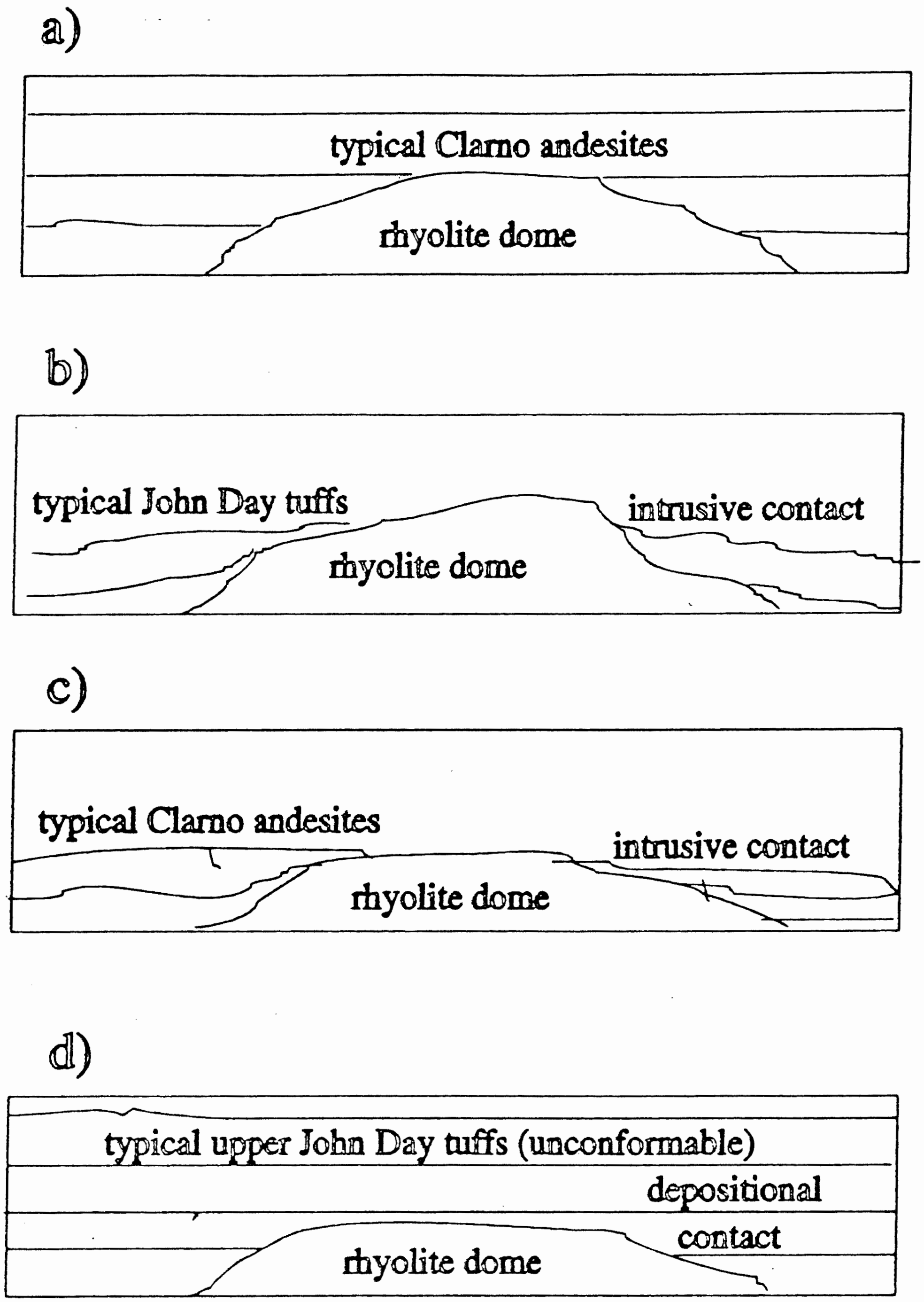


Figure 2.1 Possible field relations between rhyolite flows and domes and typical Clarno or John Day units: a) Rhyolite constrained as Clarno Formation, b) Rhyolite constrained as John Day Formation, c) and d) Rhyolite of unknown affinity.

suggesting that their sources were located in the Cascades (Robinson et al., 1990).

The John Day Formation represents a depositional record of early Cascade volcanism (Robinson et al., 1990). Isolated rhyolitic flows and domes within the formation, however, were not transported as were the ash-fall tuffs. They must have erupted from local vents. These rhyolite flows are coeval with high-Ti alkali olivine basalts, suggesting a major shift in tectono-magmatic processes in the Blue Mountains between deposition of the Clarno and John Day Formations (Robinson et al., 1990). Thus, identifying the age and nature of locally erupted products is the key to understanding the change in tectonic regime which took place with the initiation of Cascade volcanism.

2.5 Summary

Age and lithology can distinguish the Clarno and John Day Formations on a large scale, however individual units within the formations can be difficult to distinguish, as they may display similar lithologic characteristics and have uncertain age relations. This is especially true for rhyolite flows and domes, which occur in both formations. Stratigraphic relations cannot always distinguish the units. In the case where a unit is not clearly overlain by typical rocks from the Clarno Formation or intruding typical John Day rocks, the assignment is unclear (Fig 2.1). Some other means must be found which will readily distinguish rhyolites from the Clarno and John Day Formations.

CHAPTER 3 PETROGRAPHY AND MINERALOGY

3.1 Introduction

This chapter summarizes the petrography and mineralogy of rhyolites from the Clarno and John Day Formations. Similarities and differences between rhyolites of the two formations yield significant clues to the tectono-magmatic evolution of the area. Detailed petrographic descriptions of each sample are given in Appendix 1.

3.2 Petrography of Clarno Formation Rhyolites

3.2.1 Primary mineralogy

Only three of the five Clarno rhyolites preserve primary mineralogy (648-592, 850, and 856). Alteration products completely replace the primary mineralogy in the other two samples. The samples which retain their primary mineralogies contain less than 3% phenocrysts. The preserved phenocrysts include plagioclase feldspar, sanidine, and quartz. All of these minerals occur in abundances of up to 1%. Feldspar-shaped cavities and casts in the Clarno thin sections indicate that feldspars were originally more abundant. This feldspar phase was subsequently removed by alteration.

Primary groundmass phases are much more abundant than phenocryst phases. Common groundmass phases include feldspar, quartz, and oxide phases. Devitrified phases are common, with only one sample (648-850) retaining primary volcanic glass.

3.2.2 Primary igneous textures

Clarno rhyolites dominantly display holocrystalline textures, although one sample (648-850) has a hypocrystalline texture, with 80% glass present. Trachytic textures are common, except in the most altered samples (648-812 and 850), and one sample also displays a spherulitic texture (648-856). Few rhyolites have porphyritic textures; those with phenocrysts contain only up to 3% by volume. The primary textures of the groundmass are cryptocrystalline to microcrystalline.

3.2.3 Alteration and secondary mineral growth

Clarno rhyolites typically display a high but variable degree of alteration. Alteration has removed the primary phenocryst phases from all samples except for 648-592 and 850. All the samples are highly altered except for 648-850.

Secondary mineral growth occurs to varying degrees in Clarno rhyolites. The least affected sample displays minor secondary quartz and hematite (648-850). All the other samples contain high abundances of secondary quartz and hematite, with lesser abundances of secondary carbonates, chlorite, and zeolite.

3.2.4 Summary

Clarno rhyolites display varying features in terms of primary mineralogy, texture, alteration, and secondary mineralogy. All Clarno rhyolites may have had similar primary mineralogies and textures when first deposited, but alteration has created diversity within Clarno samples. The Clarno Formation displays variable degrees of alteration, as evidenced by variable secondary mineral growth from sample to sample. This variable secondary mineral growth cannot be used to define Clarno rhyolites.

3.3 Petrography of John Day Formation Rhyolites

3.3.1 Primary mineralogy

The primary mineralogy of most John Day rhyolites is relatively well preserved. Phenocrysts, where present, commonly include quartz, sanidine, and sodic plagioclase. The occurrence and volume of each phenocryst varies widely. Phenocrystic quartz ranges from 0% (648-853) to 15% (648-623), whereas plagioclase and sanidine range from 0% (648-851) to 2% (648-607).

Groundmass phases invariably include quartz and oxide phases. Many John Day rhyolites include feldspar laths as well, although this feature is not present in every sample. Glass remaining as a groundmass phase ranges from 0% to 50%.

3.3.2 Primary igneous textures

Some John Day rhyolites contain well preserved primary igneous textures, but this is not true for all of the samples. All but one sample (648-653) are either porphyritic or contain feldspar-shaped cavities or casts (implying that they were once porphyritic). Some of the rhyolites are holocrystalline (648-862) while others are hypocrystalline with up to 50% glass (648-

852). Spherulitic and trachytic textures are common, although not present in all samples (648-852).

3.3.3 Alteration and secondary mineral growth

Alteration in John Day rhyolites is typically not highly developed, although the degree of alteration varies widely. Phenocrysts range from being completely unaltered to being completely removed, with many samples displaying intermediate phenocryst alteration between these two extremes.

Secondary mineral growth is more pronounced in the highly altered John Day samples than in the relatively fresh ones. Secondary quartz is present in all samples, although the abundance is low in less altered samples. Highly altered samples also display hematite growth, with the most altered samples having rare carbonate growth as well.

3.3.4 Summary

Rhyolites of the John Day Formation display varying primary mineralogies, textures, and degrees of alteration. Most of the rhyolites are porphyritic, containing phenocrysts of quartz, sodic plagioclase, and sanidine. Textures are commonly holocrystalline spherulitic, indicating that glass was once present. Primary glass is still present in some samples (642-862). Alteration and secondary mineral growth are not extensive in John Day rhyolites, although this feature varies widely. No one feature consistently describes all John Day Formation rhyolites.

3.4 Distinguishing Rhyolites on a Petrographic Basis

Distinguishing Clarno rhyolites from John Day rhyolites on a petrographic basis is impossible for several reasons. Both formations have widely varying, but generally similar, primary mineralogies, textures, and degrees of alteration. Although the Clarno Formation generally has a higher degree of alteration than the John Day Formation (Robinson and Walker, 1990a), fresh Clarno samples and highly altered John Day samples both exist. John Day rhyolites generally contain more phenocrystic quartz than Clarno rhyolites, but this feature varies widely in both formations. Because petrography cannot be used to distinguish rhyolites of the Clarno and John Day Formations, chemical methods must be employed. Petrographic features of rhyolites from the two formations are summarized in Table 3.1.

Petrographic Features	Clarno Formation	John Day Formation	Differences
primary phenocrysts	typically unpreserved, <3%, plagioclase, sanidine, quartz	well preserved, up to 15%, quartz, sanidine, plagioclase, (variable)	generally more abundant in John Day, but highly variable in each
primary groundmass	feldspar, quartz, oxides, glass rare	quartz, oxides, feldspar laths glass rare	feldspar laths more common in John Day, but present in both
textures	porphyritic, holocryst., trachytic, rarely spherulitic, crypto- to microcryst. groundmass	porphyritic, hypo- or holocrytalline spherulitic and/or trachytic, crypto- to microcryst. groundmass	some John Day samples hypocryst., John Day more commonly spherulitic
alteration and secondary minerals	variable, phenocrysts removed, quartz and hematite common, carbonates and chlorites minor	low but variable, quartz and hematite common, carbonates rare	generally higher alteration in Clarno, but highly variable in each.

Table 3.1 Summarized petrographic characteristics of rhyolites from the Clarno and John Day Formations.

CHAPTER 4 GEOCHEMICAL DISTINCTION

4.1 Introduction

Rhyolites of the Clarno and John Day Formations are not always distinguishable in the field, because of uncertain stratigraphic relations (Chapter 2). Similarly, these rhyolites are not distinguishable petrographically (Chapter 3). The only remaining option is to distinguish these rhyolites on a chemical basis.

4.2 Methodology

Some of the rhyolites used in this study were classifiable as belonging to either to Clarno or John Day Formation on the basis of stratigraphic relations (see Chapter 2 and Fig 2.1 for details). In this study, any rhyolite which was not identifiable as Clarno or John Day using stratigraphic relations was considered to be of unknown affinity.

The rhyolites which are identifiable using field relations and those which were not each formed a separate dataset. Each dataset was analyzed for major, trace, and rare earth element (REE) composition. Several geochemical plots were drawn using the identified rhyolite dataset in an attempt to find clear patterns for the chemistry of the Clarno and John Day Formations. The unknown dataset was used as a check to determine how well a given pattern could classify the unknowns. Because of the variable weathering found in these samples, a greater emphasis was placed on elements which tend to remain immobile under weathering conditions, such as the REE's.

4.3 Chemical Distinction

4.3.1 Major element chemistry

Rhyolites from the Clarno and John Day Formations show large variations in major oxide composition (Fig 4.1, Appendix 2). This may be a result of the variable degrees of alteration of these rocks. During alteration, certain reactions take place which mobilise elements such as Mg and Fe, while leaving behind Si and other less mobile elements, leading to a gradual change in the chemical make up of the rock. High alteration found in many Clarno and some John Day samples indicate that the major element geochemistry has likely been significantly altered over time.

Despite the effects of alteration, Na_2O appears to define discrete fields separating Clarno rhyolites from John Day rhyolites. Figure 4.2 shows plots of Na_2O against SiO_2, CaO, and Al_2O_3. All three of these plots have discrete fields for the Clarno and John Day samples.

4.3.2 Trace element geochemistry

Many of the trace elements behave similarly to the major oxides, in that they undergo differential transportation during alteration. To avoid problems created by varying degrees

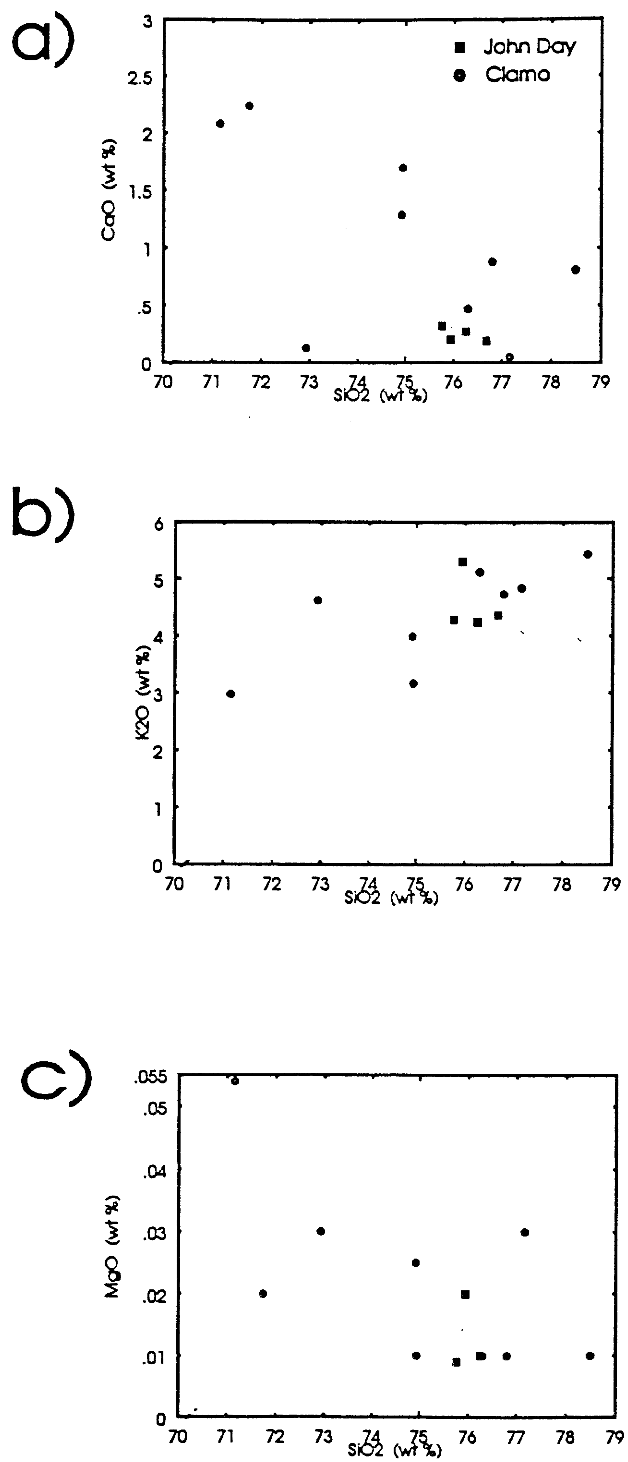


Figure 4.1 Plots of SiO_2 versus a) CaO, b) K_2O, and c) MgO. Clarno rhyolites show a wide range of major element composition.

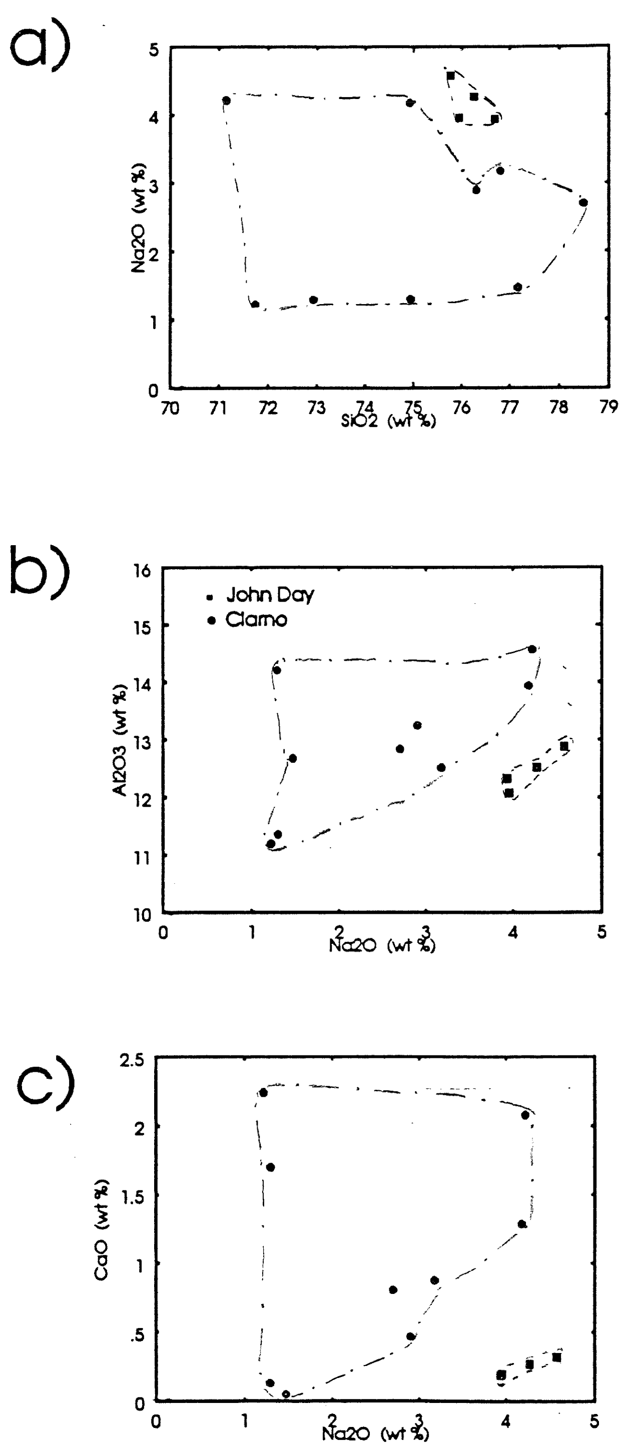


Figure 4.2 Plots of Na_2O against a) SiO_2, b) Al_2O_3, and c) CaO for Clarno and John Day rhyolites. Discrete fields exist for the Clarno and John Day Formations.

of alteration, elements which tend not to be mobilised during alteration are concentrated on in this report. Such elements tend to have a high valence charge and similar ionic radii, and therefore maintain their original ratios (relative to each other) in variably weathered rocks. Such elements include Y, Zr, Nb, Mo, Ta, and Hf (Hess, 1989). Each of these elements was analyzed. Of these elements, Nb, Y, and Mo define discrete fields for Clarno and John Day rhyolites when plotted against one another (Fig 4.3).

4.3.3 Rare earth elements

REE's can be used in the same capacity as the trace elements listed above. The above is true because the REE's behave as a coherent geochemical group (Hess, 1989). Figure 4.4 is a chondrite-normalized spider plot for the elements from La to Lu inclusive. Figure 4.4 reveals a distinct separation between Clarno and John Day rhyolites. The separation is most pronounced among the HREE's (Gd to Lu inclusive).

Figure 4.5 shows various relative plots for the HREE's. A clear chemical distinction exists between the Clarno and John Day rhyolites. The ratios of HREE's to each other remains constant, but the John Day samples are enriched in HREE's compared to the Clarno samples.

4.3.4 Classification of the unknowns

Figures 4.2, 4.3, 4.4, and 4.5 all apparently contain discrete fields for rhyolites from the Clarno and John Day Formations. In order to test the reliability of these fields,

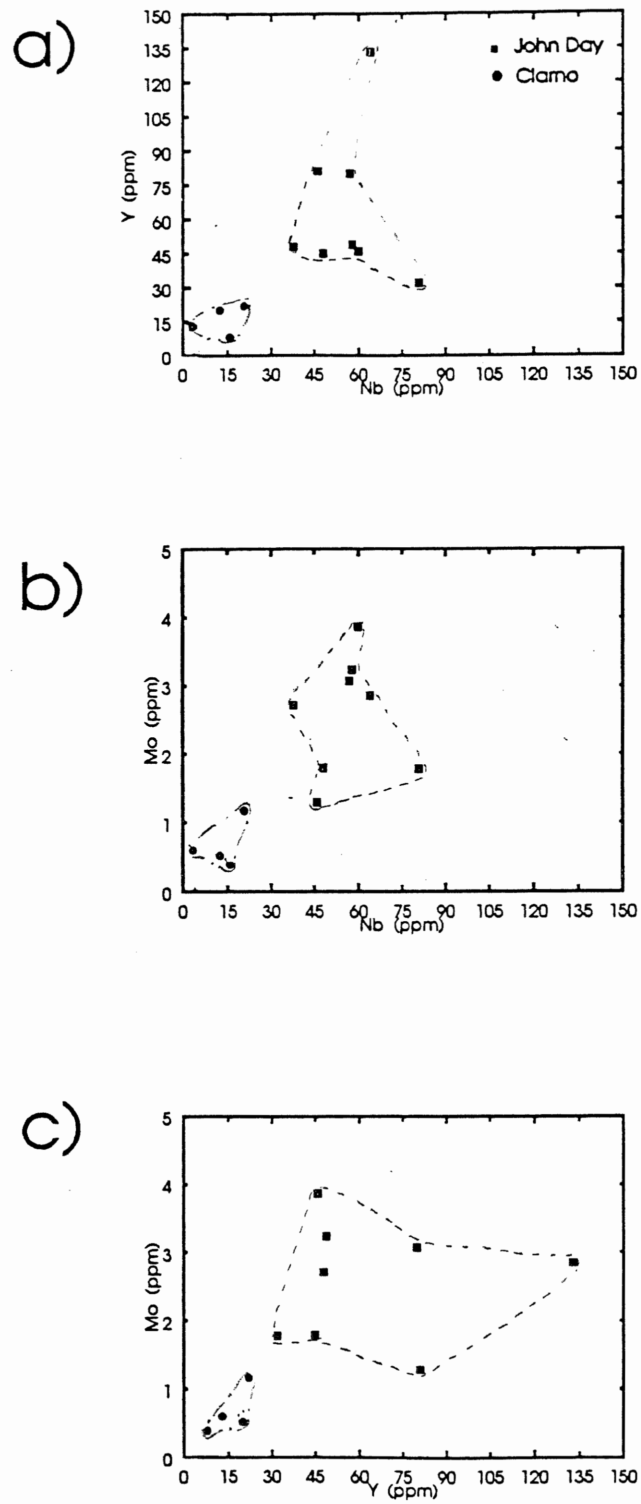


Figure 4.3 Plots of a) Nb-Y, b) Nb-Mo, and c) Y-Mo for rhyolites of known origin. Discrete fields exist for the Clarno and John Day samples.

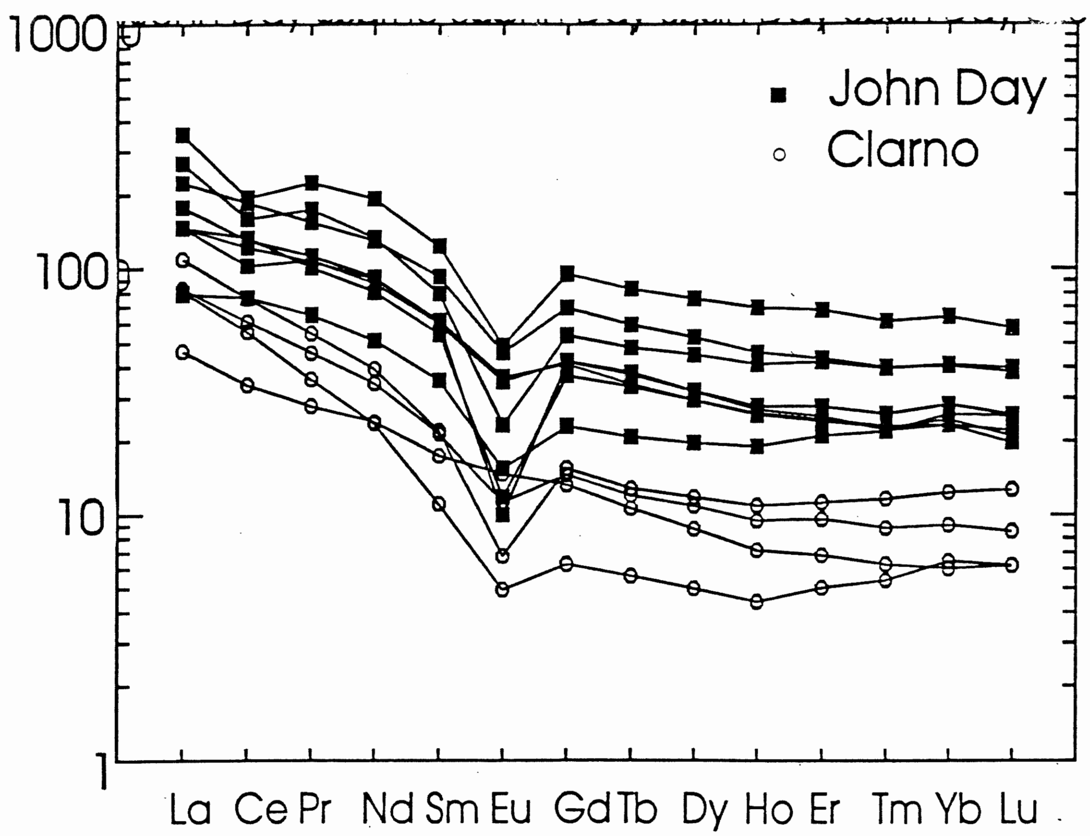


Figure 4.4 Chondrite-normalized REE spider plot for rhyolites of known origin. Distinct separation exists between Clarno and John Day HREE's, becoming less distinct for the LREE's.

a)

b)

c)

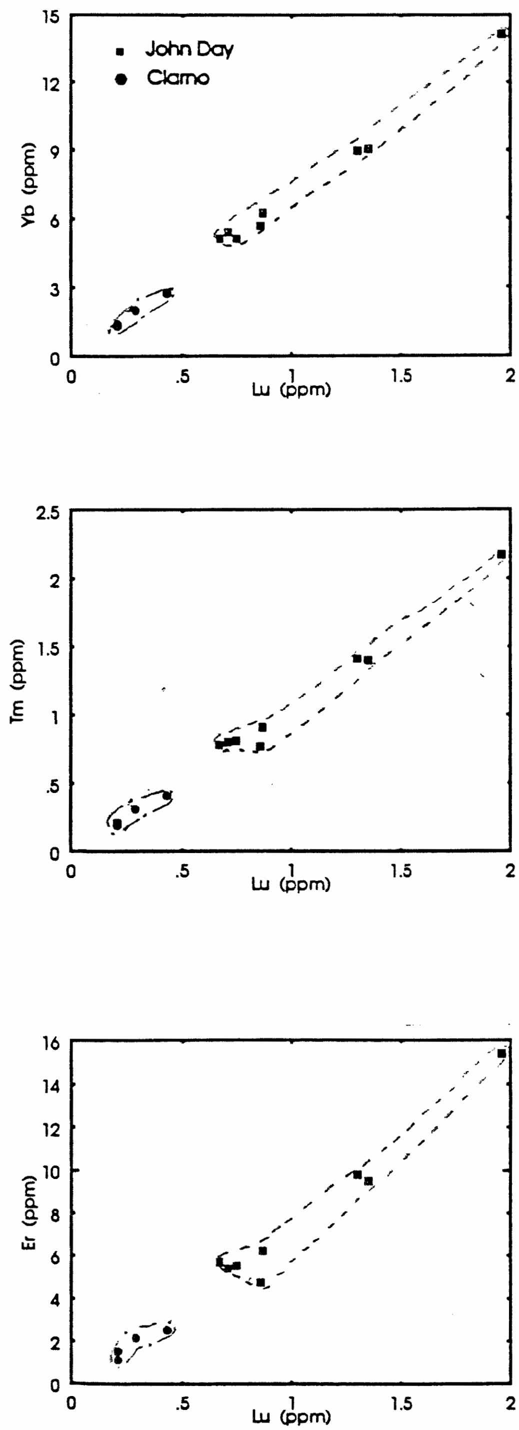


Figure 4.5 Plots of Lu against a) Yb, b) Tm, and c) Er. Well-defined fields exist for Clarno and John Day samples.

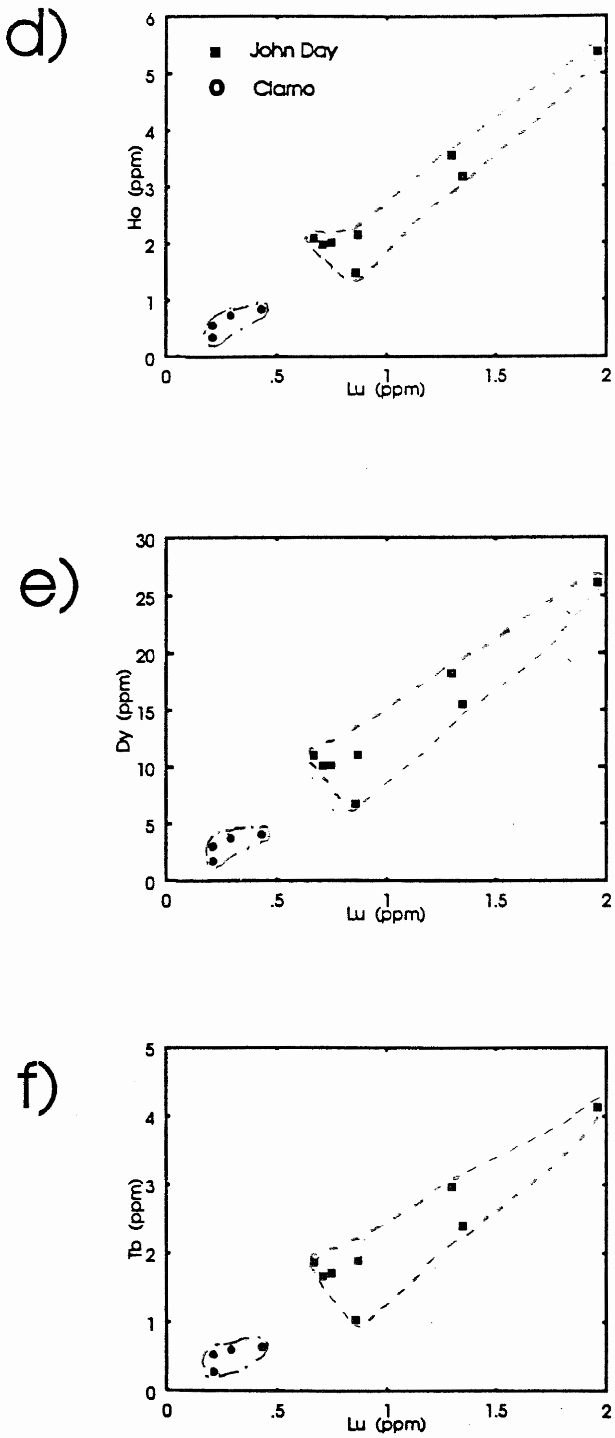
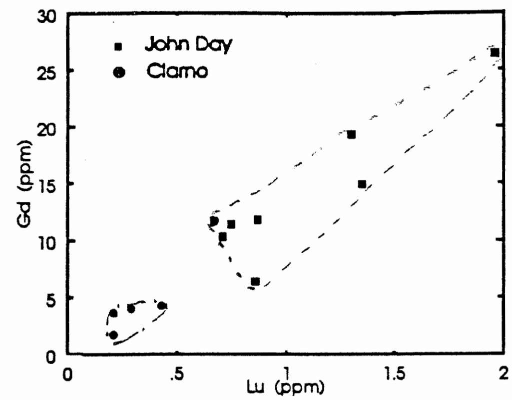


Figure 4.5 (continued) Plots of Lu against d) Ho, e) Dy, and f) Tb. Well-defined fields exist for the Clarno and John Day Formations.

g)



h)

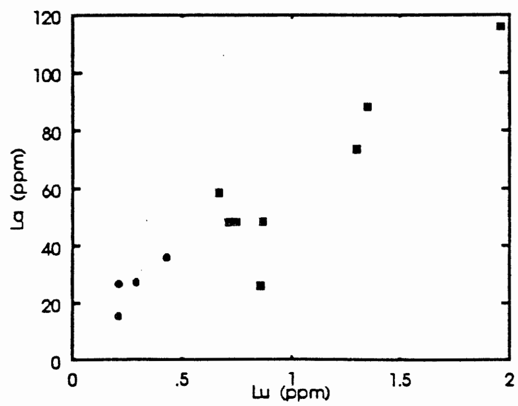


Figure 4.5 (continued) Plots of Lu against g) Gd and h) La. Well-defined fields exist between Clarno and John Day samples.

the same plots were produced for the unclassified samples, with the fields from the original plots superimposed. Plots which reveal contradictory or unreliable information for the unknowns can then be discarded. The plots were produced and are discussed in the same order as the known samples (majors, trace, REE's).

Figure 4.6 shows the distribution of unknown samples for Na_2O versus SiO_2, Al_2O_3, and CaO. None of the samples plots consistently as a John Day rhyolite, whereas samples 648-660 and 648-822 plot as Clarno rhyolites. The remainder of the unknowns plot inconsistently, indicating that this classification scheme has limited usefulness.

Figure 4.7 contains the relative plots of Nb-Y-Mo for the unknown samples, with superimposed fields from Figure 4.3. Sample 648-922 consistently plots in the Clarno field, while none of the samples plots in the John Day field. The remaining seven unknowns plot inconsistently. This inconsistency indicates that Nb-Y-Mo relative plots are not ideal for distinguishing rhyolites of the Clarno and John Day Formations.

Figure 4.8 is a chondrite-normalized REE spider plot for the unknown samples. Figure 4.9 shows plots of various HREE's against Lu. Using these figures together reveals a consistent classification for the unknowns. Sample 648-922 plots as a Clarno rhyolite, and samples 648-568, 570, and 917 all plot within the John Day field. The remaining four unknowns consistently plot between the fields defined for the Clarno and John Day Formations. These four samples may represent

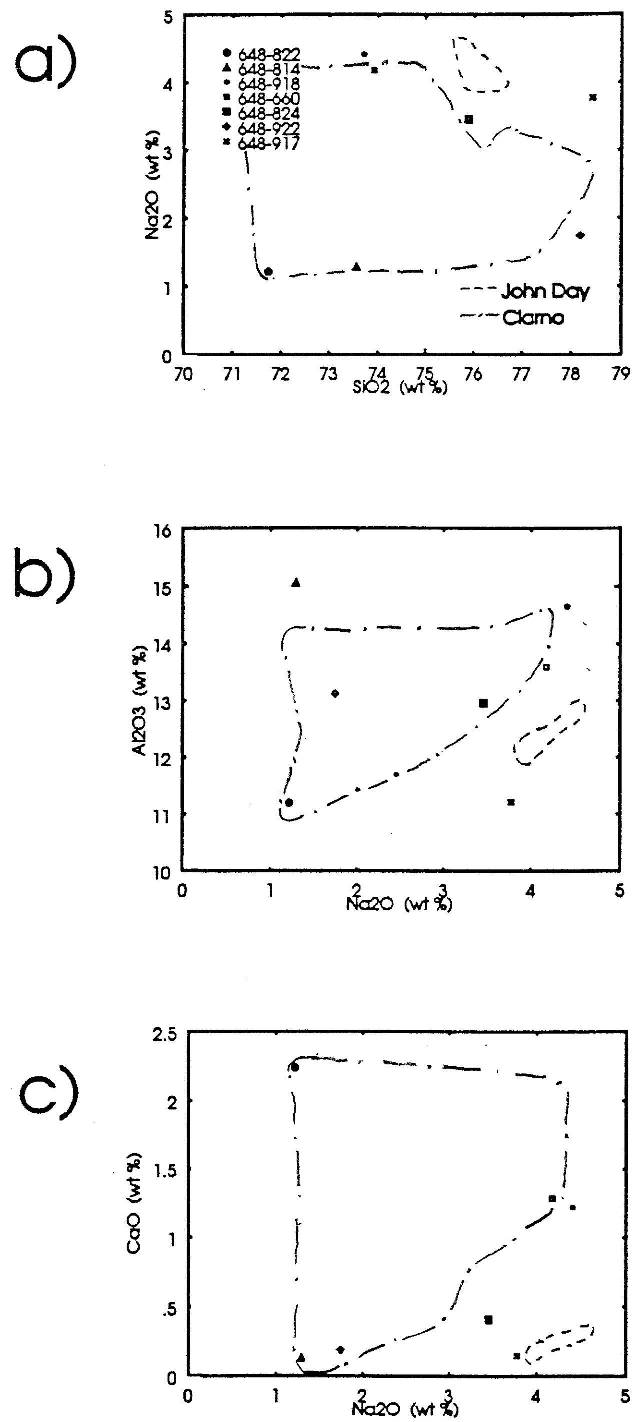


Figure 4.6 Plots of Na_2O against a) SiO_2, b) Al_2O_3, and c) CaO for unknown samples. Several samples lie outside the fields defined in Figure 4.2.

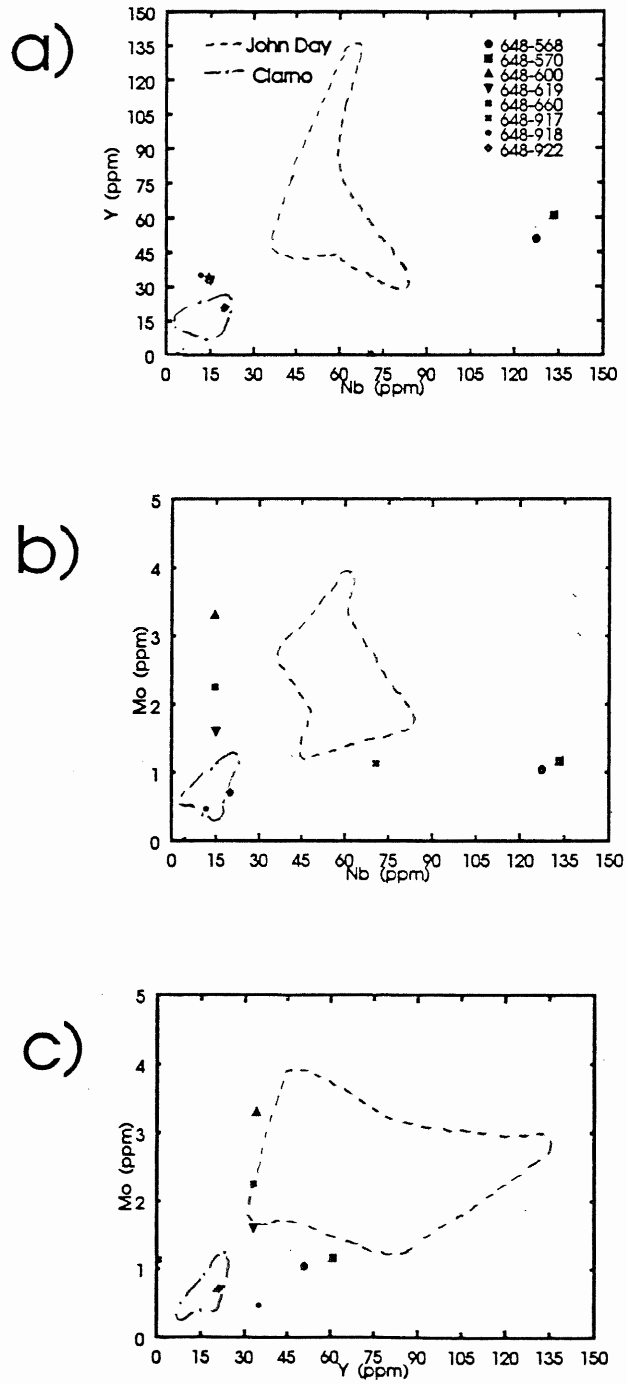


Figure 4.7 Plots of a) Nb-Y, b) Nb-Mo, and c) Y-Mo for unknown samples. Only three samples consistently plot in either the Clarno or John Day fields defined from Figure 4.3.

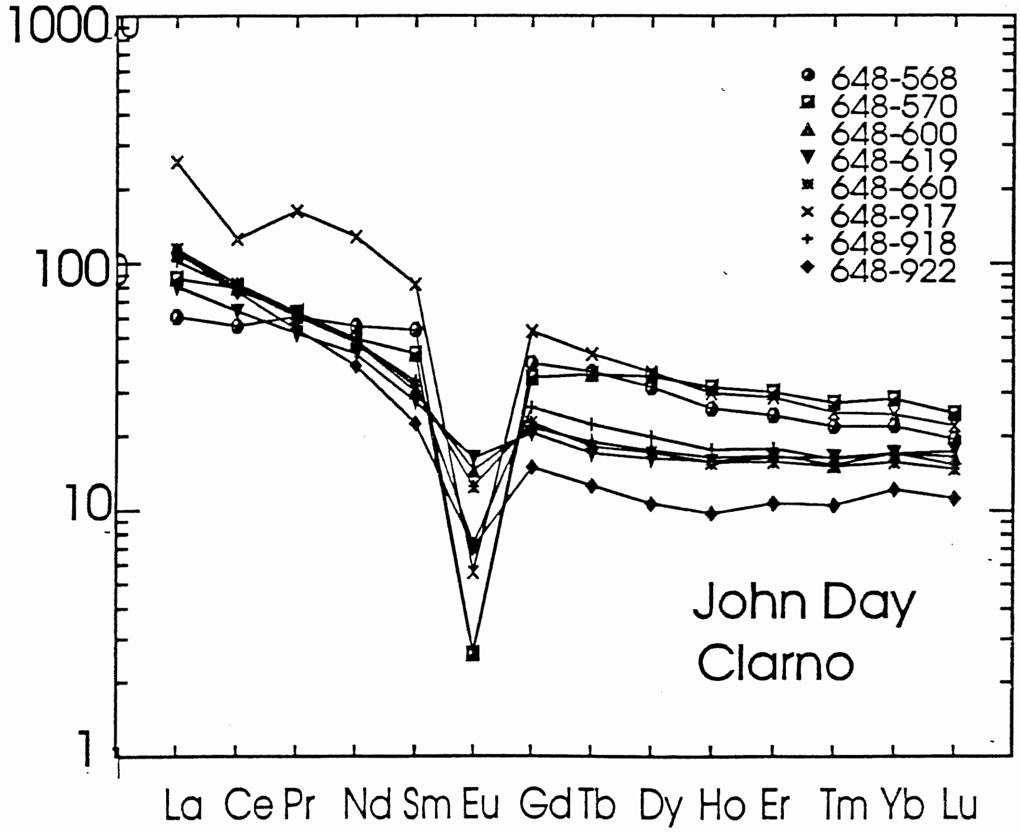


Figure 4.8 Chondrite-normalized REE plot for unknown samples. Sample 648-922 plots in the Clarno field defined in Figure 4.4. Samples 648-568, 578, and 917 plot in the John Day field. The remaining unknowns plot between the two fields.

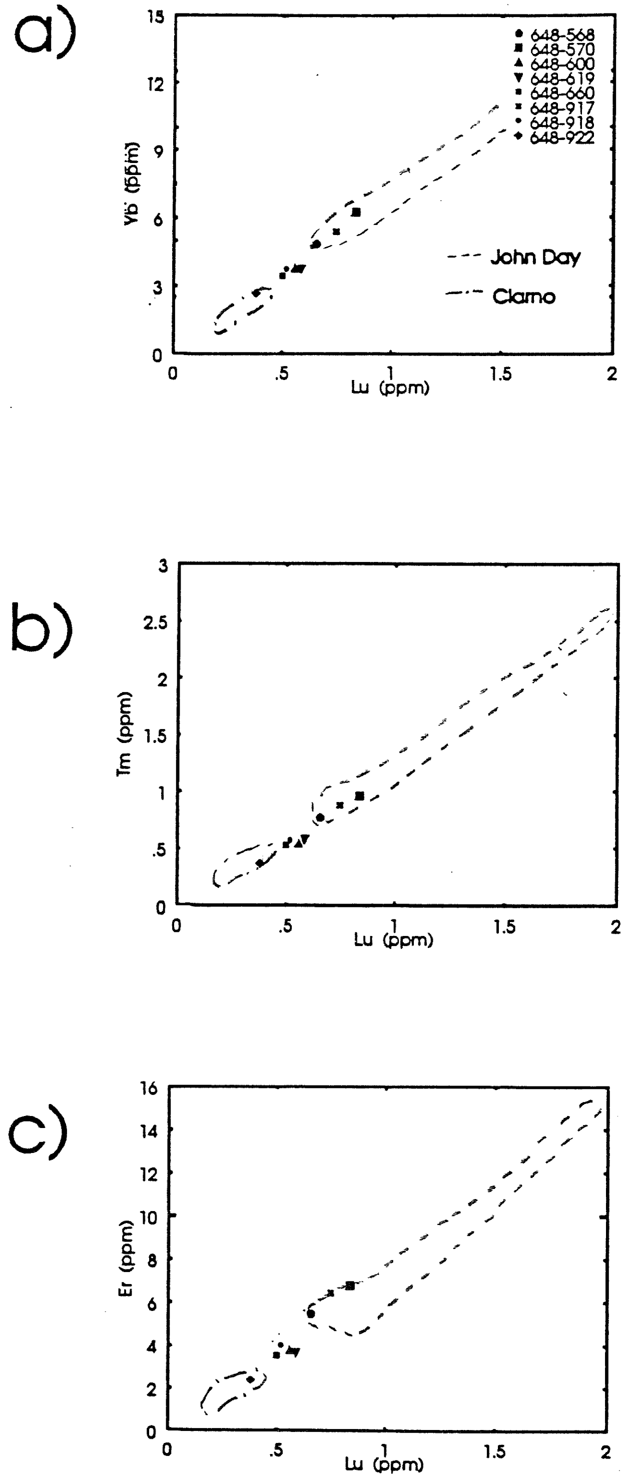


Figure 4.9 Plots of Lu against a) Yb, b) Tm, and c) Er for unknown samples. Similar distribution for the unknown samples is found as in Figure 4.8.

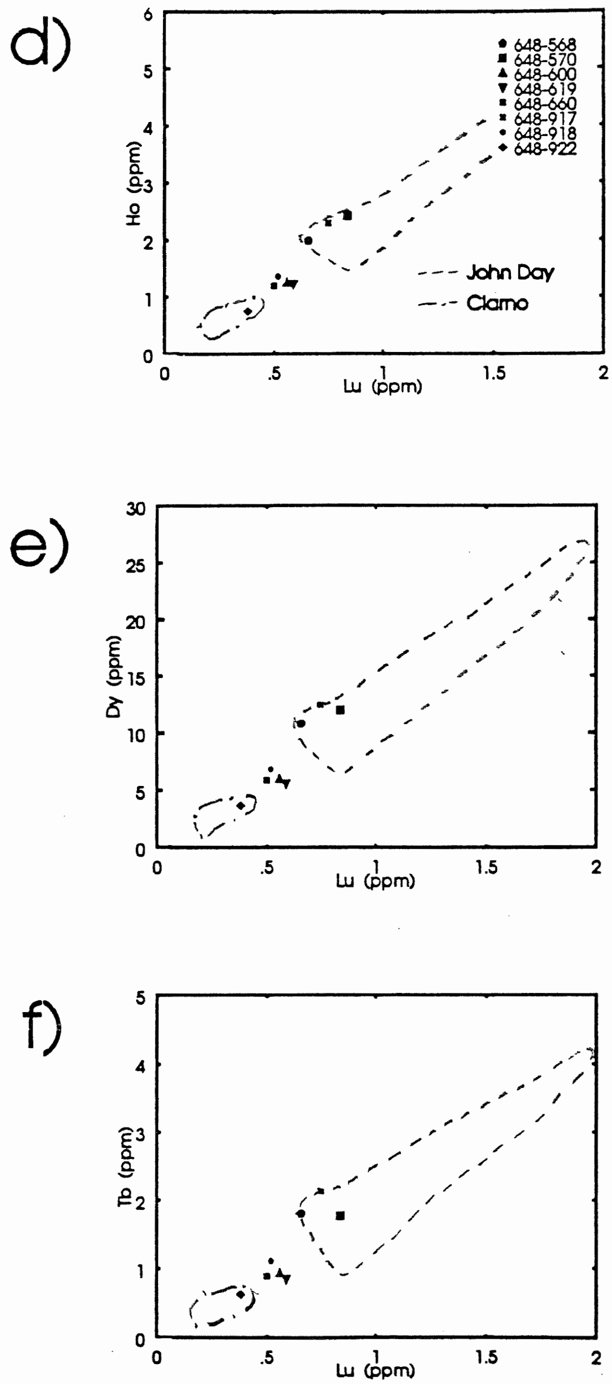


Figure 4.9 (continued) Plots of Lu against d) Ho, e) Dy, and f) Tb for unknown samples. similar distribution is found as in Figure 4.8.

g)

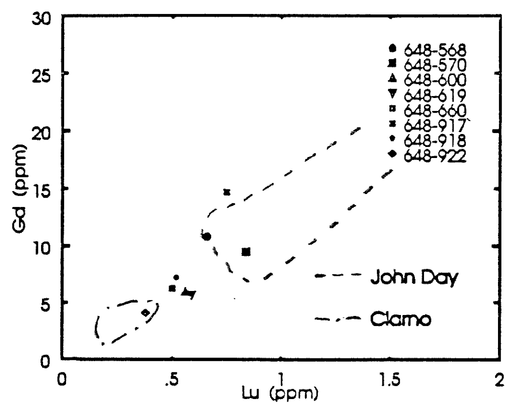


Figure 4.9 (continued) Plot of Lu against g) Gd for unknown samples. Similar distribution is found as in Figure 4.8.

transitional rhyolites between the Clarno and John Day rhyolites.

4.4 Summary

Classification of rhyolites from the Clarno and John Day Formations on the basis of chemistry presents two problems. The first problem is which elements to choose when attempting to distinguish between the two formations. Generally, elements which are relatively immobile during weathering are ideal in such variably altered rocks. In this case, the rare earth elements appear to best distinguish between the two formations. The second problem is that many of the unknowns plot consistently between fields defined for the Clarno and John Day Formations. This problem may indicate that certain unknowns represent transitional products between Clarno and John Day rhyolites. Alternatively, the true fields for Clarno and John Day rhyolites may not be accurately defined in this study because of the small number of representative samples.

CHAPTER 5 DISCUSSION

5.1 Introduction

The change from Clarno volcanism to John Day volcanism represents an important change in volcanic regime. The Clarno Formation is largely composed of locally erupted flows and ash-fall tuffs, whereas the John Day Formation is largely composed of transported air-fall tuffs (Walker 1990). There may be some age overlap between the cessation of Clarno volcanism and the beginning of John Day volcanism (Robinson et al., 1990), indicating that local volcanics (Clarno) and transported volcanics (John Day) are partially coeval. Chapter 5 discusses these ideas in relation to the data gathered in this study.

5.2 Tectonic History

5.2.1 The Clarno Formation

Volcanic rocks of the Clarno Formation vary widely in composition and include diverse assemblages ranging from basalt to rhyolite. The most voluminous rocks in the formation are andesites and basaltic andesites (Walker and Robinson, 1990). Chemical analyses are available for all suites of Clarno volcanics (Rogers and Novitsky-Evans, 1977, Noblett, 1981, Walker and Robinson, 1990). Chemical analyses indicate that the assemblage is predominately calc-alkaline (Noblett, 1981). This indicates a volcanic arc origin for the Clarno Formation

(Noblett, 1981).

The Nb-Y content of Clarno rhyolites (Fig 5.1) indicates that the Clarno Formation is of volcanic arc origin. The Clarno samples all plot within the VAG field of the Nb-Y discrimination diagram from Pearce et al (1984). Noblett (1981) also describes the Clarno Formation as being arc-related volcanism through a thin continental margin. This conclusion is based on the abundance of lithophile elements in Clarno lavas relative to abundances on island arcs and continental margins.

5.2.2 The John Day Formation

The John Day Formation consists largely of ash-fall tuffs which thicken westwards towards the Cascade Range (Robinson et al., 1990). Rhyolite flows and domes are less voluminous than tuffs, and are localised in the western portion of the Blue Mountains Region (Fig 1.2). Localised flows to the east are largely alkali-olivine basalts and trachyandesites.

The origin of rhyolite flows and domes in the John Day Formation remains unclear. The Nb-Y plot shows that these rhyolites are a result of within-plate volcanism (Fig 5.1). Arc-related volcanism, caused by the subduction of the Pacific Plate, shifted westwards between the Eocene and Oligocene, focusing in the present-day Cascade Range (Robinson et al., 1990). The Blue Mountains region experienced volcanism from other sources, perhaps as a result of foreland basin development.

Rare earth elements are highly enriched in the John Day rhyolites. Pronounced Eu anomalies are evident as well. The

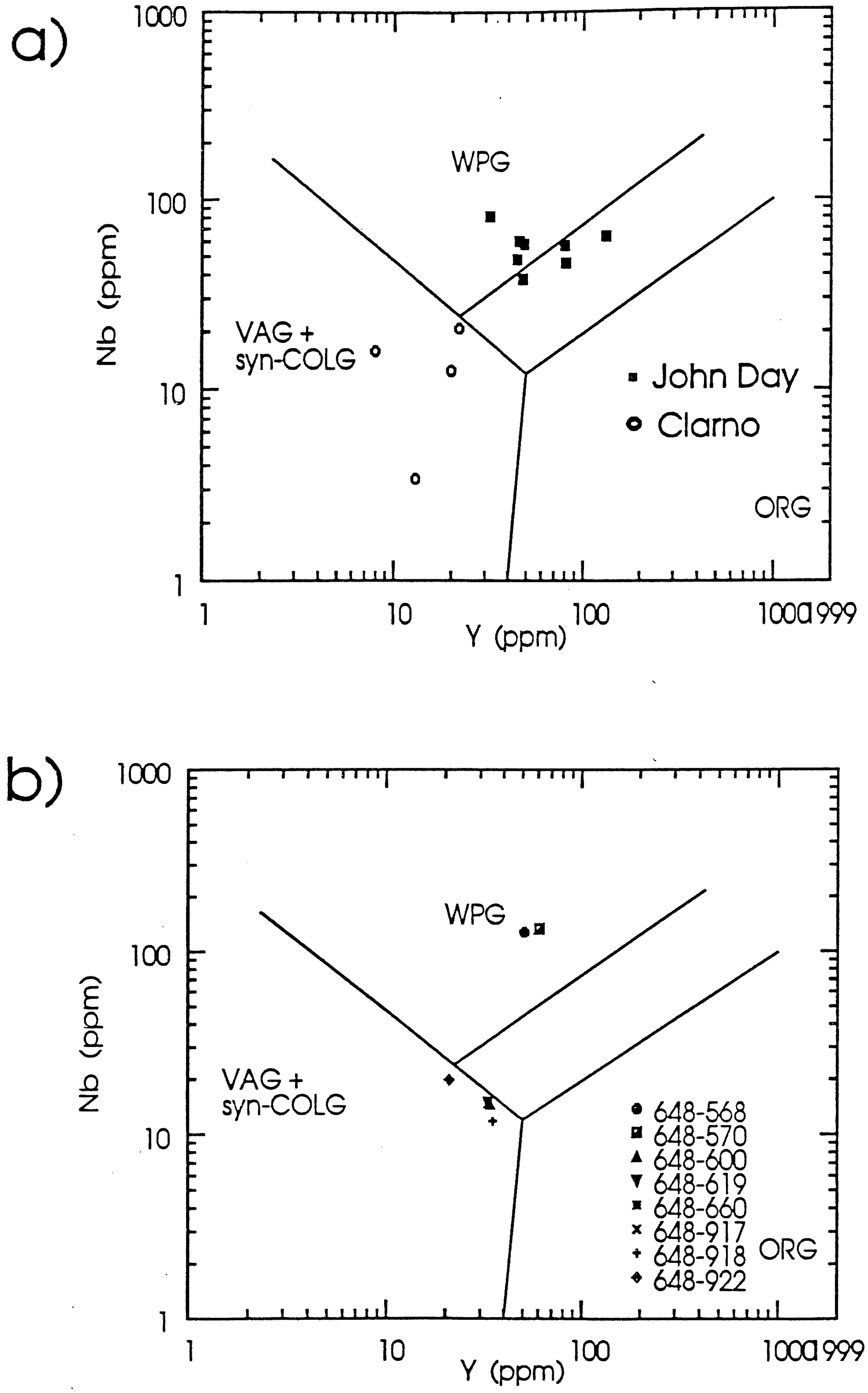


Figure 5.1 Tectonic discrimination plot using log (Nb) versus log (Y) for a) known samples and b) unknown samples. Clarno rhyolites plot within the volcanic arc field (VAG) whereas John Day rhyolites plot within the within-plate field (WPG) (from Pearce et al, 1984).

enrichment of REE's may indicate fractionation of a number of mafic minerals, such as amphibole or hypersthene. The negative Eu anomaly indicates fractionation of plagioclase. High Na_2O and K_2O supports the idea of fractionating hypersthene or a similar mineral. Fractionation of Ca-rich plagioclase could also lead to an enrichment in Na_2O and K_2O.

5.3 Age Relations

One of the most pressing problems of volcanism in the Blue Mountains Region is whether the Clarno and John Day Formations are partially coeval (Robinson and Walker, 1990). The age of the Clarno Formation ranges from about 55 to 40 Ma. Several authors report dates younger than 40 Ma, possibly suggesting temporal overlap with rocks of the John Day Formation (Fiebelkorn et al., 1983, Enlows and Parker, 1972, Everndon et al., 1964, Walker, 1973, Brook et al, 1976, Brown and Thayer, 1966, Robinson and Walker, 1990). Many of the younger Clarno ages are suspect because they are whole rock K-Ar dates of altered basalts and andesites, which can be inaccurate (Robinson and Walker, 1990).

The tectonic history of the Blue Mountains Uplift region shows that the transition from Clarno to John Day volcanism involved a westwards shift in arc related volcanism from the Blue Mountains to the Cascades. This implies a westwards shift in subduction of the Pacific Plate. The portion of the subducting plate beneath the Blue Mountains may have lingered while subduction was occurring beneath the Cascades. This could explain the apparent partially coeval nature of the Clarno and John Day Formations. A model which would predict the time between the westward shift in subduction and the cessation of local arc-related volcanism is needed to further test this theory.

Proof that the Clarno and John Day formation are coeval is largely circumstantial. Age dates which appear to prove temporal overlap are suspect. However, some of the unknown samples tested in this study plot consistently between fields for Clarno and John Day rhyolites (Fig 4.9). These samples may be transitional between the two Formations, and may indicate a gradual change from Clarno to John Day volcanism. This would imply a partially coeval nature for the two Formations.

An extensive age and chemical study of the suspect age rocks is needed before any temporal overlap can be unequivocally proven. Such a study would involve classifying andesites of typical Clarno lithology and comparing them to rocks of the John Day Formation. The ages of local rhyolites would also help in determining whether the formations are partially coeval. Different dating techniques should be used as well. Such techniques should include K-Ar and Ar-Ar dating of individual minerals and U-Pb and Pb-Pb dating methods.

5.4 Summary

The Clarno and John Day Formations are different in terms of bulk chemistry and tectonic environment. The Clarno Formation is a volcanic arc sequence, likely erupted though a continental margin or a transitional continental-oceanic crust (Noblett, 1981). The John Day Formation is largely derived from volcanic centres to the west of the Blue Mountains, and locally erupted flows were formed from a within-plate environment. The change in tectonic regimes and eruptive sources imply a westward shift in subduction, or at least in partial melting as a result of subduction.

The change in volcanism described above allows temporal overlap to occur between the Clarno and John Day Formations. Evidence for a partial temporal overlap may exist in some of the unknown samples (specifically 648-600, -619, -660, and -918). These samples have a transitional REE chemistry between typical Clarno and John Day rhyolites. They may represent late-stage Clarno volcanics, or they may actually imply a transitional period between the two tectonic environments. Alternatively, the apparent transitional character may be a result of the small number of samples used in this study; analyses of a larger number of samples would help in determining a transitional character. K-Ar age data of individual minerals would also help define which case applies.

CHAPTER 6 CONCLUSIONS

Study of the chemical relations of rhyolites from the Clarno and John Day Formations allows new interpretations regarding the Cenozoic history of the Blue Mountains. Distinguishing these units is complicated by the effects of variable alteration on the chemical compositions of the rhyolites. The information gained from analyses of the rhyolites permits the following conclusions:

1) Rhyolites from the Clarno and John Day Formations can be best distinguished by their rare-earth element content, specifically using comparative plots of the elements Lu, Yb, Tm, Er, Gd, Dy, and Ho.

2) The Clarno Formation represents arc-related volcanism, while the John Day Formation represents within-plate volcanism.

3) Some rhyolites of uncertain origin are transitional between Clarno rhyolites and John Day rhyolites used in this study; this may indicate temporal overlap between the units.

REFERENCES

Baldwin EM (1964) Geology of Oregon, 2nd Edition. Edwards Brothers, Inc, Ann Arbor, Michigan: 165 pp.

Brooks HC, McIntyre JR, and Walker GW (1976) Geology of the Oregon part of the Baker 1° by 2° quadrangle. Oregon Department of Geology and Mineral Industries Geologic Map Series Map GMS-7, 25 p., scale 1:250,000

Brown CE and Thayer TP (1966) Geologic map of the Canyon City quadrangle, northeastern Oregon. USGS Misc Geologic Investigations Map I-447, scale 1:250,000

Chaney RW (1924) Fossil floras of the John Day Basin. Carnegie Institute of Washington Year Book 22: 349-350 (from Walker, 1990).

Enlows HE and Parker DJ (1972) Geochronology of the Clarno igneous activity in the Mitchell Quadrangle, Wheeler County, Oregon. Ore Bin 34: 104-110.

Everndon JF, Savage DE, Curtis GH, and James GT (1964) Potassium-argon dates and the Cenozoic mammalian chronology of North America. Am J Science 262: 145-198.

Fiebelkorn RB, Walker GW, MacLeod NS, McKee EH, and Smith JG (1983) Index to K-Ar determination for the State of Oregon. Isochron/West 37: 60pp.

Hanson CB (1973) Geology and vertebrate faunas in the type area of the Clarno Formation, Oregon. Geol Soc of Am Abstracts with Programs 5: 50.

Hergert HL (1961) Plant fossils in the Clarno Formation, Oregon. Ore Bin 23: 55-62.

Hess PC (1989) Origins of Igneous Rocks. Harvard University Press, Cambridge Massachusetts: 336 pp.

Knowlton FH (1902) Fossil flora of the John Day Basin, Oregon. USGS Bulletin 204: 153pp.

McKee TM (1970) Preliminary report on fossil fruits and seeds from the mammal quarry of the Clarno Formation, Oregon. Ore Bin 32: 27-32.

Merriam JC (1901) A contribution to the geology of the John Day Region. University of California Publications, Department of Geology Bulletin 2: 269-314.

Merriam JC and Sinclair WJ (1907) Tertiary faunas of the John Day Region. University of California Publications, Department of Geology Bulletin 5: 171-205.

Noblett JB (1981) Subduction-related origin of the volcanic rocks of the Eocene Clarno Formation near Cherry Creek, Oregon. Oregon Geology 43: 91-99.

Pearce JA, Harris NBW, and Tindle AG (1984) Trace element discrimination diagrams from the tectonic interpretation of granitic rocks. J Pet 25: 956-983.

Robinson PT, Walker GW, and McKee KH (1990) Eocene (?), Oligocene, and Lower Miocene rocks of the Blue Mountains Region. US Geological Survey Professional Paper 1437: 29-62.

Rogers JJW and Novitsky-Evans JM (1977) The Clarno Formation of central Oregon, USA - Volcanism on a thin continental margin. EPSL 34: 56-66.

Rogers JJW and Ragland PC (1980) Trace elements in continental margin magmatism - Pt. I, Trace elements in the Clarno Formation of central Oregon and the nature of the continental margin on which eruption occurred. Geol Soc Am Bull 91: 1217-1292

Stirton RA (1944) A rhinoceros tooth from the Clarno Eocene of Oregon J Paleon 18: 265-267.

Suayah IB and Rogers JJW (1990) Evidence of multi-process petrologic evolution in the Tertiary Clarno Formation in north-central Oregon. Unpublished manuscript (?).

Swanson DA and Robinson PT (1968) Base of the John Day Formation in and near the Horse Heaven mining district, north-central Oregon, in Geological Survey Research, 1968; USGS Professional Paper 600-D: 254-161.

Walker GW (1973) Reconnaissance geologic map of the Pendleton quadrangle, Oregon and Washington. USGS Misc Investigations Series Map I-727, scale 1:250,000

Walker GW (1990) Overview of the Cenozoic geology of the Blue Mountains Region. USGS Professional Paper 1437: 1-11.

Walker GW and Robinson PT (1990a) Palaeocene (?), Eocene, and Oligocene (?) rocks of the Blue Mountains Region. USGS Professional Paper 1437: 13-27.

Walker GW and Robinson PT (1990b) Cenozoic tectonism and volcanism of the Blue Mountains Region. USGS Professional Paper 1437: 119-135.

Waters AC, Brown RE, Compton RR, Staples LW, Walker GW, and Williams H (1951) Quicksilver deposits of the Horse Heaven mining district, Oregon. USGS Bull 969-E: 105-149.

APPENDIX 1 PETROGRAPHY

A) Clarno Formation Rhyolites

648-592

Phenocrysts: Porphyritic (.5-2 mm size), euhedral. Some cavities bear the shape of feldspar laths. Zoned sanidine (2%), Plagioclase (<1%). **Groundmass**: Holocrystalline, trachytic; plagioclase laths (30%), oxides (10%), quartz (15%), interstitial cryptocrystalline area (40%, devitrified glass?). **Alteration**: Some feldspar? grains completely replaced by hematite; carbonate, quartz growth, alteration of phenocryst rims.

648-812

Phenocrysts: None, some large areas (2-3 mm) filled with cryptocrystalline secondary minerals and dendritic hematite (may be phenocrysts casts). **Groundmass**: Remnant holo- or hypocrystalline texture evident, original igneous texture destroyed by alteration. **Alteration**: Extensive secondary quartz and hematite growth. Also chlorite, carbonate and zeolite? growth. No primary igneous minerals remain.

648-850

Phenocrysts: None. **Groundmass**: Hypocrystalline, 80% glass. Vesicular (8%), with rare quartz amygdules. Plagioclase laths (2%) only original crystalline phase. **Alteration**: Some quartz and hematite growth in amygdules. 10% devitrified. Plagioclase laths variable altered to sericite(?).

648-856

Phenocrysts: Porphyritic, euhedral (.5-1 mm); sanidine (<1%), plagioclase (1%), quartz (1%). Plagioclase highly altered, may have been more abundant before alteration. **Groundmass**: Holocrystalline, largely cryptocrystalline, trachytic, rarely spherulitic; no original groundmass crystals remain. **Alteration**: Extensive quartz and opaque growth; minor carbonates and chlorite. Plagioclase phenocrysts variably altered. Glass 100% devitrified.

648-876

Phenocrysts: None. **Groundmass**: Holocrystalline, trachytic. Feldspar laths rare (<1%), most groundmass is cryptocrystalline. **Alteration**: Extensive quartz infill of flattened vesicles; minor carbonate growth; rare chlorite. Glass 100% devitrified.

B) John Day Formation Rhyolites

648-607

Phenocrysts: Porphyritic, sub- to euhedral (1-5 mm). Plagioclase (2%), sanidine (1%), quartz (<1%); plagioclase and sanidine highly altered. **Groundmass**: Holocrystalline, trachytic, strongly spherulitic. Rare feldspar laths (<1%). **Alteration**: Plagioclase highly altered, sanidine slightly altered. 15% secondary quartz growth, 3% opaques. Glass 100% devitrified.

648-623

Phenocrysts: Porphyritic, subhedral (2-5 MM). Quartz (15%), sanidine (2%), plagioclase (<1%), altered remnants of pyroxene (?)(<1%). **Groundmass**: Holocrystalline, microcrystalline, vesicular; layered texture. Small opaques (.1 mm) and quartz present. Mostly cryptocrystalline. **Alteration**: Quartz and opaque infill some vesicles, rare mantling of lithic fragments.

648-653

Phenocrysts: None. **Groundmass**: Holocrystalline, rare spherulitic textures; some compositional banding (may be secondary). Microcrystalline quartz, opaques, and rare feldspar laths. **Alteration**: Quartz infill common; oxides and biotite (?) present; rare carbonate. Glass 100% devitrified.

648-845 (brecciated rhyolite)

Phenocrysts: Porphyritic, subhedral (1-4 mm). Quartz (5%) and sanidine (2%). **Groundmass**: Hypocrystalline (20% glass), flow banded; quartz and oxides common (more common in brecciated portions), no feldspar laths. **Alteration**: Quartz infill not pronounced, more common in brecciated sections, secondary oxides rare. Sanidine phenocrysts highly altered (and brecciated), quartz less so. Glass 60% devitrified.

648-851

Phenocrysts: None; feldspar shaped cavities may be moulds of original phenocrysts. **Groundmass**: Holocrystalline, spherulitic, microcrystalline to cryptocrystalline crystals; quartz and feldspars common, oxides present. **Alteration**: Extensive quartz and oxide growth outside spherulitic aggregates, rare hematite growth. Glass 100% devitrified.

648-852

Phenocrysts: Porphyritic, sub- to euhedral (1-3 mm). Quartz (3%), sanidine (1%) and plagioclase (1%). Many lath-shaped cavities imply phenocrystic content was higher. **Groundmass**: Hypocrystalline, microcrystalline; flow-banded. Quartz and oxides present, rare feldspar laths. **Alteration**: Quartz infill common, oxides rare. Phenocrysts highly altered. Glass 50% devitrified.

648-853

Phenocrysts: Anhedral quartz (.5-1 mm). **Groundmass**: Holocrystalline, microcrystalline; trachytic, vesicles and amygdules prominent. Quartz and oxides common, rare feldspar laths. **Alteration**: Quartz infills amygdules, with minor hematite. Phenocrysts have altered exteriors. Glass 100% devitrified.

648-860

Phenocrysts: Porphyritic, euhedral; sanidine (1%) only phase. **Groundmass**: Hypocrystalline, microcrystalline to cryptocrystalline, with spherulitic textures. Quartz and oxides common, feldspar absent. **Alteration**: Quartz and oxides rare, sample is relatively fresh. Phenocrysts very slightly altered around rims. Glass 80% devitrified.

648-862

Phenocrysts: None; some cavities may be feldspar moulds. **Groundmass**: Holocrystalline, cryptocrystalline; dominantly spherulitic. Quartz and oxides common, feldspar absent. **Alteration**: Abundant quartz and hematite (?) infill. Phenocrysts completely removed/replaced. Glass 100% devitrified.

648-908

Phenocrysts: Porphyritic, euhedral (.1-1 mm). Sanidine (2%), plagioclase (1%), oxides (<1%). **Groundmass**: Holocrystalline, trachytic; microcrystalline oxides and quartz, with common feldspar laths. **Alteration**: Minor quartz growth, phenocrysts slightly altered.

C) Unknown Rhyolites

648-600

Phenocrysts: Glomeroporphyritic, eu- to subhedral (2-4 mm). Zoned sanidine (5%), pyroxene (2%), and plagioclase (1%). Pyroxene is surrounded by sanidine in some cases, and reacts to form biotite (?). **Groundmass:** Hypocrystalline (95% glass), vitrophyric, with perlitic cracks. Feldspar laths present. **Alteration:** Only associated with pyroxene grains. Glass less than 5% devitrified.

648-619

Phenocrysts: Glomeroporphyritic, euhedral (2-5 mm). Zoned plagioclase (15%), zoned sanidine (3%), pyroxene (2%). **Groundmass:** Holocrystalline, trachytic, with micro- and cryptocrystalline phases. Feldspar laths abundant, with minor oxides and quartz. **Alteration:** Pyroxenes mantled by opaque overgrowths; feldspars fresh. Glass 100% devitrified.

648-660

Phenocrysts: Glomeroporphyritic, subhedral (3-5 mm). Zoned plagioclase (10%), zoned sanidine (3%), pyroxene (1%). **Groundmass:** Holocrystalline, cryptocrystalline crystals, with rare microcrystalline feldspar laths. Largely oxides and quartz. **Alteration:** Pyroxenes mantled by opaque overgrowth, sanidine slightly replaced by sericite, plagioclase fresh. Glass 100% devitrified.

648-865

Phenocrysts: Porphyritic, euhedral (1-3 mm). Quartz (<1%) and sanidine (<1%); some cavities may be feldspar moulds. **Groundmass:** Holocrystalline, cryptocrystalline, abundantly spherulitic. Feldspar laths absent. **Alteration:** Several phenocrysts removed, sanidine highly altered, minor quartz growth. Glass 100% devitrified.

648-866

Phenocrysts: Porphyritic, subhedral (2-3 mm). Plagioclase, sanidine, and quartz (total <1%). **Groundmass:** Holocrytalline, cryptocrystalline, spherulitic texture; feldspar laths absent. **Alteration:** Feldspar phenocrysts moderately altered; rare opaque growth. Glass 100% devitrified.

648-917

Phenocrysts: Glomeroporphyritic, subhedral (1-4 mm). Quartz (5%), oxides (<1%). Many vesicles may be feldspar moulds. **Groundmass:** Holocrystalline, trachytic; cryptocrystalline with 10% microcrystalline feldspar laths. **Alteration:** Extensive oxide growth, minor quartz and carbonate (?) growth. Glass 100% devitrified.

648-918

Phenocrysts: Porphyritic, euhedral (2-5 mm). Quartz (25%) and plagioclase (10%). **Groundmass**: Holocrystalline, micro- and cryptocrystalline with quartz, oxides, and rare feldspar laths. **Alteration**: Core and mantle textures on some plagioclases, plagioclases variably altered; rare secondary oxide and quartz growth (<5%). Glass 100% devitrified.

648-922

Phenocrysts: None. **Groundmass**: Holocrystalline, micro- and cryptocrystalline with quartz and oxides present. Feldspar laths absent. **Alteration**: Extensive secondary quartz and oxide growth, secondary carbonate common; rare chlorite and zeolite (?).

APPENDIX 2 CHEMICAL DATA

A) Major element oxides - Determined using XRF analysis at the Geochemical Analytical Laboratory in Washington State University, Pullman, Washington.

i) Clarno Formation rhyolites

Element	648-621	648-665	648-667	648-672	648-804
SiO2	72.93	76.30	71.15	74.92	74.94
TiO2	0.26	0.10	0.25	0.14	0.08
Al2O3	14.21	13.25	14.57	13.94	11.36
Fe2O3	0.00	0.00	0.00	0.00	0.00
FeO	2.13	1.17	2.90	1.26	0.78
MnO	0.08	0.00	0.40	0.00	0.87
MgO	0.03	0.01	0.05	0.03	0.01
CaO	0.13	0.47	2.08	1.29	1.70
Na2O	1.29	2.90	4.22	4.18	1.30
K2O	4.62	5.12	2.98	3.99	3.17
P2O5	0.02	0.01	0.09	0.06	0.02
Totals	95.70	99.33	98.69	99.81	94.23

Element	648-808	648-812	648-822	648-856
SiO2	77.16	78.49	71.74	76.80
TiO2	0.08	0.21	0.13	0.07
Al2O3	12.68	12.84	11.20	12.52
Fe2O3	0.00	0.00	0.00	0.00
FeO	1.17	0.45	2.05	0.87
MnO	0.40	0.45	1.15	0.09
MgO	0.03	0.01	0.02	0.01
CaO	0.05	0.81	2.24	0.88
Na2O	1.47	2.70	1.22	3.18
K2O	4.84	5.44	2.00	4.73
P2O5	0.03	0.05	0.03	0.01
Totals	97.91	101.45	91.78	99.16

ii) John Day Formation rhyolites

Elements	648-607	648-851	648-852	648-853
SiO2	75.77	76.26	76.68	75.95
TiO2	0.24	0.23	0.19	0.15
Al2O3	12.88	12.52	12.33	12.08
Fe2O3	0.00	0.00	0.00	0.00
FeO	1.12	1.45	1.32	2.05
MnO	0.00	0.00	0.00	0.00
MgO	0.01	0.01	0.00	0.02
CaO	0.32	0.27	0.19	0.20
Na2O	4.58	4.27	3.94	3.96
K2O	4.28	4.24	4.36	5.30
P2O5	0.03	0.00	0.04	0.04
Totals	99.23	99.25	99.05	99.75

iii) Rhyolites of uncertain origin

Elements	648-660	648-814	648-822	648-824
SiO2	73.92	73.57	71.74	75.89
TiO2	0.26	0.20	0.13	0.08
Al2O3	13.60	15.06	11.20	12.96
Fe2O3	0.00	0.00	0.00	0.00
FeO	2.18	2.02	2.05	1.24
MnO	0.00	0.34	1.15	0.34
MgO	0.03	0.03	0.02	0.01
CaO	1.29	0.13	2.24	0.41
Na2O	4.18	1.29	1.22	3.46
K2O	3.99	4.62	2.00	4.63
P2O5	0.00	0.02	0.03	0.00
Totals	99.45	97.28	91.78	99.02

Elements	648-917	648-918	648-922
SiO2	78.42	73.71	78.18
TiO2	0.11	0.20	0.07
Al2O3	11.22	14.65	13.13
Fe2O3	0.00	0.00	0.00
FeO	1.65	0.67	1.18
MnO	0.00	0.01	0.00
MgO	0.03	0.00	0.03
CaO	0.15	1.22	0.15
Na2O	3.78	4.41	3.78
K2O	4.46	4.52	4.46
P2O5	0.00	0.00	0.00
Totals	99.82	99.39	100.98

b) Trace and REE data - Trace elements determined using XRF analysis at the Geochemical Analytical Laboratory in Washington State University, Pullman. REE's determined using neutron activation analysis at the Department of Earth Sciences, University of Waterloo, Waterloo, Ontario.

i) Clarno Formation rhyolites

Sample	648-592	648-602a	648-812	648-856
Cr	3	18	2	3
Sc	5	17	3	4
V	5	222	3	4
Cu	22	1172	8	7
Pb	9	12	12	16
Zn	52	98	29	39
Bi	0.02	0.04	0.06	0.01
Mo	0.52	0.60	1.17	0.39
Rb	69	41	141	150
Cs	1.33	1.04	2.32	4.33
Ba	656	645	868	992
Sr	183	503	21	52
Tl	0.21	0.03	0.71	0.75
Li	23.12	24.09	32.91	50.30
Ta	1.16	0.28	2.48	1.92
Nb	12.40	3.40	20.70	15.80
Hf	3.14	0.56	4.19	3.41
Zr	113	20	105	84
Y	20	13	22	8
Th	6.90	2.77	13.54	11.60
U	2.40	0.76	3.11	2.30
La	27.32	15.31	35.96	26.70
Ce	53.01	29.36	65.99	48.23
Pr	5.95	3.61	7.15	4.65
Nd	21.66	15.04	24.85	14.84
Sm	4.36	3.54	4.46	2.24
Eu	0.87	1.13	0.52	0.38
Gd	4.03	3.67	4.30	1.73
Tb	0.60	0.53	0.64	0.28
Dy	3.74	3.01	4.06	1.72
Ho	0.73	0.55	0.84	0.34
Er	2.16	1.53	2.53	1.13
Tm	0.31	0.22	0.41	0.19
Yb	2.00	1.32	2.72	1.42
Lu	0.29	0.21	0.43	0.21
Be	2.79	2.42	2.97	3.38

Appendix 2

ii) John Day Formation rhyolites

Sample	648-607	648-623b	648-625a	648-626	648-653
Cr	2	4	5	2	2
Sc	3	1	2	2	4
V	1	7	2	2	4
Cu	5	7	9	4	4
Pb	15	8	9	10	12
Zn	196	80	99	69	82
Bi	0.02	0.02	0.01	0.03	0.07
Mo	3.07	1.29	2.71	1.78	3.23
Rb	131	113	117	140	94
Cs	2.22	0.99	2.13	2.30	1.45
Ba	1059	260	589	823	963
Sr	51	10	16	17	94
Tl	0.49	0.27	0.26	0.47	0.47
Li	8.55	15.26	12.78	33.79	20.03
Ta	3.60	2.25	2.42	4.02	3.05
Nb	57.0	46.0	37.8	80.9	57.9
Hf	12.66	17.67	1.04	15.01	5.78
Zr	416	670	23	492	177
Y	80	81	48	32	49
Th	13.75	11.48	9.87	15.79	8.50
U	4.37	1.02	2.56	5.05	2.31
La	73.60	88.20	58.51	25.98	48.23
Ce	160.70	137.70	112.76	66.14	105.09
Pr	20.09	22.55	14.63	8.48	13.91
Nd	81.42	83.87	58.05	32.34	57.45
Sm	18.80	16.05	12.34	7.16	12.57
Eu	3.54	1.79	0.77	1.19	2.82
Gd	19.28	14.90	11.68	6.38	11.38
Tb	2.97	2.40	1.87	1.04	1.71
Dy	18.22	15.51	11.03	6.76	10.16
Ho	3.55	3.18	2.08	1.47	2.00
Er	9.80	9.49	5.70	4.75	5.53
Tm	1.41	1.40	0.78	0.77	0.81
Yb	8.95	9.03	5.12	5.68	5.12
Lu	1.30	1.35	0.67	0.86	0.75
Be	4.54	4.76	5.48	4.53	3.70

ii) John Day Formation rhyolites (continued)

Sample	648-851	648-852	648-853	648-908
Cr	3	3	3	5
Sc	3	3	2	11
V	3	3	2	11
Cu	4	6	9	11
Pb	11	12	18	9
Zn	95	128	153	173
Bi	0.04	0.05	0.01	0.02
Mo	3.86	2.85	1.79	7.44
Rb	134	136	171	105
Cs	2.77	2.55	3.10	4.00
Ba	1028	816	406	1123
Sr	40	24	14	194
Tl	0.39	0.49	-	0.32
Li	24.54	23.89	39.03	32.70
Ta	3.52	3.41	2.47	1.90
Nb	59.9	64.1	48.0	44.2
Hf	12.25	7.96	2.94	9.14
Zr	409	240	85	349
Y	46	133	45	61
Th	14.14	14.13	12.75	7.63
U	3.44	4.62	2.42	1.71
La	48.36	115.92	48.02	56.47
Ce	88.80	167.57	115.22	98.65
Pr	14.04	29.06	13.13	15.98
Nd	54.94	120.82	50.79	64.94
Sm	12.19	25.00	11.01	14.02
Eu	2.70	3.79	0.91	4.29
Gd	11.77	26.40	10.29	13.87
Tb	1.90	4.13	1.67	2.04
Dy	11.05	26.12	10.11	11.99
Ho	2.14	5.38	1.93	2.37
Er	6.23	15.40	5.42	6.39
Tm	0.91	2.17	0.80	0.86
Yb	6.24	14.13	5.40	5.59
Lu	0.87	1.96	0.71	0.85
Be	4.55	5.48	6.14	4.25

iii) Rhyolites of uncertain origin

Sample	648-568	648-570	648-600	648-619
Cr	1	1	4	6
Sc	1	0	6	8
V	4	2	9	22
Cu	5	5	11	32
Pb	22	25	12	9
Zn	144	135	60	60
Bi	0.11	0.02	0.15	0.03
Mo	1.05	1.17	3.31	1.61
Rb	213	289	145	59
Cs	3.32	5.07	5.38	1.22
Ba	19	30	732	837
Sr	18	11	119	268
Tl	0.79	0.24	1.55	0.18
Li	13.66	40.28	2.82	52.93
Ta	6.87	7.38	1.53	1.28
Nb	127.6	133.5	14.6	15.0
Hf	10.43	16.03	5.62	7.10
Zr	219	343	201	269
Y	51	61	34	33
Th	18.36	20.93	12.93	5.51
U	4.65	7.90	4.38	1.81
La	19.97	28.67	36.32	26.59
Ce	48.13	68.95	69.24	55.37
Pr	7.91	8.23	7.92	6.76
Nd	35.02	31.10	29.91	26.96
Sm	10.86	8.67	6.10	5.58
Eu	0.20	0.20	1.12	1.25
Gd	10.85	9.48	5.98	5.69
Tb	1.81	1.77	0.94	0.85
Dy	10.84	11.97	6.01	5.57
Ho	1.99	2.42	1.26	1.22
Er	5.48	6.77	3.77	3.69
Tm	0.77	0.96	0.54	0.58
Yb	4.84	6.22	3.76	3.74
Lu	0.66	0.84	0.56	0.59
Be	9.76	10.74	3.44	2.79

iii) Rhyolites of uncertain origin (continued)

Sample	648-660	648-917	648-918	648-922
Cr	3	3	8	3
Sc	6	2	7	4
V	6	2	7	4
Cu	8	7	9	5
Pb	13	11	20	12
Zn	49	153	42	34
Bi	0.05	0.23	0.03	0.04
Mo	2.26	1.14	0.47	0.71
Rb	136	163	159	136
Cs	3.29	3.48	4.63	2.70
Ba	835	17	905	855
Sr	99	5	83	24
Tl	0.62	0.25	0.76	0.71
Li	24.26	53.36	42.70	35.37
Ta	1.71	3.67	1.54	1.71
Nb	14.7	70.7	11.8	19.9
Hf	4.29	9.63	3.16	3.88
Zr	133	251	62	98
Y	33	62	35	21
Th	13.50	13.28	12.11	13.65
U	4.79	4.27	3.84	3.16
La	37.55	84.50	33.64	36.55
Ce	71.66	109.01	67.64	66.40
Pr	8.23	21.15	8.13	7.01
Nd	30.49	80.78	30.22	24.13
Sm	6.47	16.69	6.78	4.57
Eu	0.96	0.43	0.56	0.54
Gd	6.27	14.69	7.21	4.12
Tb	0.90	2.14	1.11	0.63
Dy	5.90	12.46	6.84	3.66
Ho	1.20	2.30	1.36	0.75
Er	3.55	6.45	4.02	2.41
Tm	0.53	0.88	0.57	0.37
Yb	3.45	5.39	3.76	2.68
Lu	0.50	0.75	0.52	0.38
Be	3.90	7.48	3.84	4.36