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**MINERALOGY AND TRACE-ELEMENT COMPOSITION
OF ASH AND PUMICE SOILS IN THE PACIFIC
NORTHWEST OF THE UNITED STATES**

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MINERALOGY AND TRACE ELEMENT COMPOSITION OF ASH AND PUMICE SOILS IN THE PACIFIC NORTHWEST OF THE UNITED STATES*

M. E. Harward and G. A. Borchardt**

SUMMARY

Volcanic ejecta from the Cascade Range forms parent materials of large areas of soils in the northwestern United States. The widely distributed deposits are generally of dacitic composition. The largest deposit resulted from eruption of Mt. Mazama about 6600 years ago. The coarse Mazama pumice consists of glassy hypersthene-augite dacite with accessory hornblende. Although the pumice contains on the order of 15 percent minerals on a volume basis, the mineralogy varies within wide limits depending on direction and distance from the source as well as with particle size.

Parameters most useful for distinguishing different deposits are characteristic minerals, indices of refraction of phenocrysts and glass, and chemical composition of the glass. Problems associated with identification are variations in minerals of the deposit, presence of contaminants, variation in the amount and type of phenocrysts, and changes in composition by weathering.

Investigations are in progress at Oregon State University to characterize the trace element composition of volcanic glass by use of instrumental neutron activation analysis. Abundances of 19 nuclides belonging to the alkali and alkaline earths, rare earths, and transition metals are obtained directly with this technique. The trace element composition of glass was shown to be consistent within given deposits and to differ between sources. Weathering affects the composition of some elements, particularly the transition elements, but there appears to be little effect on the contents of rare earths. Trace element analyses determined by neutron activation are useful in investigations of depth of weathering, nature of alteration products, and profile discontinuities as well as for identification of the ash layers being investigated.

INTRODUCTION

General Geologic History of Cascades

The geologic history of the northwestern United States is intimately related to volcanism. The Cascade Range consists of a sequence of volcanic peaks extending from northern California across Oregon and Washington into British Columbia, Canada. Numerous vents exist in this area from which ejecta have been widely distributed. Active sources during the Quaternary include Lassen, Shasta, McLaughlin, Mazama, Newberry, Three Sisters, Jefferson, Hood, Adams, St. Helens, Glacier Peak, Baker and Bridge River (6, 17). There are also a number of recently active cinder cones in Oregon which are sources of locally distributed ash falls (13, 14).

Distribution of Different Ash Falls

The less silicious deposits (andesitic and basaltic) are darker colored and crystalline components may be dominant over glass (17). Although the individual deposits of basic ash are usually not extensive, they are more numerous and may be locally significant. The more silicious ejecta (rhyolite and dacite) are more widespread. They are generally light colored and phenocrysts such as feldspars, quartz, pyroxene, amphiboles, micas, and opaque oxides seldom exceed 10 - 15 percent by volume.

Detailed information on sources, chronology, and distribution is lacking for many of the deposits of the region. There are, however, encouraging developments in the Quaternary volcanology resulting from current interest by geologists, oceanographers, anthropologists, archeologists, and soil scientists. It is now possible to indicate some of the chronology and distribution of volcanic ash deposits (Table 1 and Figure 1). The ash falls from Glacier Peak and St. Helens were widely distributed but that from Mazama is the most extensive. It has been estimated that the volume of material deposited on the landscape by the catastrophic eruption of Mazama may be over 10 cubic miles (18). The area of deposition includes most of Oregon, Washington, northern Idaho, eastern Montana, and the southern parts of British Columbia, and Alberta, Canada. Mazama ash and pumices forms the parent material for large areas of present day soils in Oregon.

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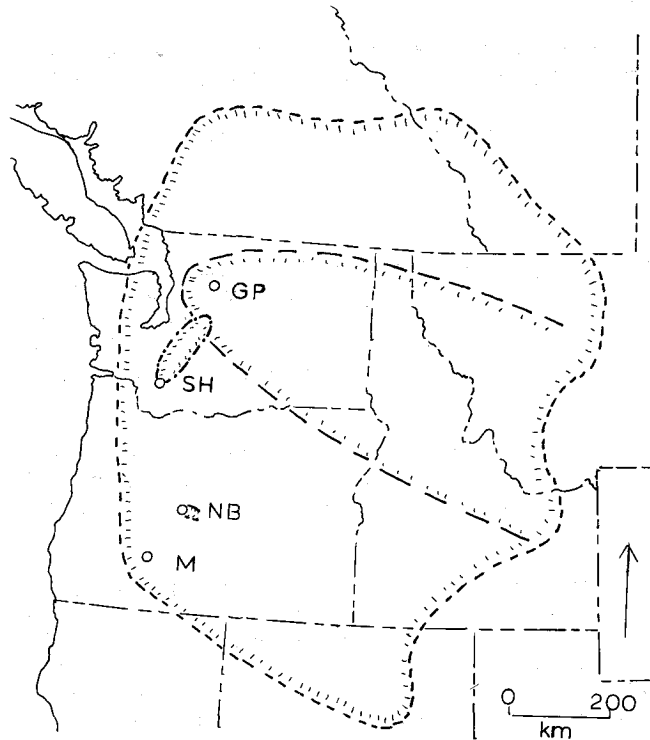


FIGURE 1. Distributions of some volcanic ash deposits in northwestern United States (after Crandell 'et al' (12) and Fryxell (4).

M: Manzana
 GP: Glacier Peak
 SH: St. Helens-Y
 NB: Newberry

Basis of Interest

The predominant interest in volcanic ash in the region has been for stratigraphic markers and correlation. Most of the research emphasis has therefore been on distribution, chronology, and identification of deposits where mineralogy and chemical composition are the characteristics most often used. There is some current interest from the standpoint of geochemistry and volcanic processes. Relatively little has been done so far from the standpoint of soil-parent materials and the influence of the ash on soil processes and properties. It was for this reason that an expanded research program on soils of volcanic ash was recently initiated at Oregon State University. The deposits from eruption of Mt. Mazama are receiving major emphasis. Present lines of investigation include:

- 1) Stratigraphy, redistribution and mixing in local environments
- 2) Identification on the basis of trace element composition determined by instrumental neutron activation analysis (INAA).
- 3) Weathering and genesis of crystalline and amorphous clays
- 4) Porosity of pumice and its relationships to movement of ions and weathering processes.

MINERALOGY

Glass: Mineral Ratios

The relative content of minerals in the glassy matrix will vary with conditions in the magmatic chamber at the

time of eruption. However, discrimination between deposits on the basis of glass:mineral ratios is not regarded as reliable. The ashes of andesitic or basaltic composition usually have a dominance of crystals over glass while the reverse is true for ashes of rhyolitic and dacitic composition (16). The widely distributed ashes tend toward similar compositions and mineral contents. Superimposed upon this are variations within a deposit due to sorting by wind and gravity and segregation by subsequent movement and redeposition. Williams (18) found the ratio of crystals to glass in the Mazama deposit to vary between wide limits. Close to Crater Lake where the deposit consists of large lumps, the volume of discrete crystals falls below 1 percent while at greater distances it may increase to more than 25 percent. In the region southeast of Klamath Marsh (east of the source), the volume percentage of crystals ranges from 1 to 11 percent. North of the source, the content of crystals generally increases with distance from Crater Lake. However, these differences may be related to different lobes of the deposit shown on his isopachytes diagram. The increase in crystal content with distance reported by Williams probably results from complex factors associated with conditions at the time of the eruption sequence. Crystal content normally decreases with distance due to segregation of heavier minerals. The complexity of the problem is illustrated by data of Borchardt* for samples taken along the northeast axis of the main lobe of the Mazama deposit (Table 2). The percentage of glass in 125 – 63 μ fractions of samples from the fine ash deposit increased from 40 to 72 percent as distance from the source increased. However, the coarse lump pumice closer to the source contained 82 percent glass.

Primary Mineral Suites

Factors or Problems:

Suites of primary minerals have been used extensively to characterize and identify ash deposits in the region. Wilcox (17) has reviewed some of the problems of sampling and interpretation of data. The proportions of different minerals will vary within the deposit as discussed in the previous section. Although variation in proportion of constituents occurs, rarely will a primary constituent be totally lacking. Contamination or mixing of the deposit with the underlying material can lead to misleading or anomalous results. This problem is minimized by using phenocrysts with a complete or partial glass mantle as a criterion for volcanic origin. Distinctive crystals are therefore most useful in identification and relative abundances must be used with caution.

Mazama Deposits:

The coarse Mazama deposit has been described by Williams (18) as consisting of glassy hypersthene–augite dacite with accessory hornblende. The crystals consist of plagioclase, hypersthene, and smaller amounts of augite and hornblende. The ratio of light to heavy crystals is higher in the marginal parts of the pumice sheet than near the source. The ratio of feldspar to dark minerals is usually between two and three. Plagioclase is more abundant than all ferromagnesian minerals combined. Hypersthene is usually the chief dark constituent. The feldspars are intensely zoned and show a composition from labradorite at the center to oligoclase at the rims and they are highly fractured.

Other Deposits and Relations to Mazama'

The complexity of ash deposits in the region is demonstrated by the interlayered deposits of volcanic ash at Mt. Rainier, Washington. These have been shown to be from several sources including the eruption of Mt. Mazama in Oregon (2). Mineral abundances were used to aid in distinguishing the different layers (Table 3). The mineralogy of Mazama and other ash layers in Alberta are included for comparison. The analyses for the Mazama ash in Washington are in general agreement with the report by Williams (18). The Mazama layer is similar to St. Helens–W** except for the presence of augite and differs from Rainier–C only in the amount of hornblende. The Mazama ash in Alberta apparently differs from the other deposits of that area by a higher content of hornblende. The presence of cummingtonite in St. Helens–Y is distinctive (16, 17). The Mazama ash in Alberta differs from that in Washington by apparent absence of hypersthene. The St. Helens–Y in Alberta has lower contents of hornblende than that in Washington. Although these data illustrate the usefulness of mineralogy in distinguishing deposits in the same area, they also emphasize the problems of correlation over large distances and differences between petrographers. Wilcox (17) points out that to identify a particular ash in the laboratory, most effort should be placed on characteristics expected to be consistent throughout the deposit. In addition to mineral identification, he recommends the use of refractive indices of phenocrysts. These petrographic techniques have been used to aid in distinguishing Mazama from the Glacier Peak ash (9). Refractive indices of constituents in ash from eleven recent sources in the Cascades are given by Wilcox (16).

Refractive Index of Glass

The refractive index of volcanic glass has been applied widely to deposits in the region (2, 9, 12, 16, 17). Some of

* G. A. Borchardt. Preliminary data for Ph.D. thesis, Oregon State University

** See Table 1 for designation of ash layers.

the data are given in Table 3; additional data for a number of sources in the Cascades are given by Wilcox (17). This has proven to be a useful parameter when carefully determined. Problems associated with the parameter involve the small differences between the various sources or deposits. This requires determinations made with a sensitivity of 0.001 units and by counting a large number of particles to obtain modal values. Steen and Fryxell (12) report that weathering has little effect on the modal values although intuitively it would seem that this should be a factor. Wilcox (17) cautions that the glass of a particular ash may vary somewhat because of initial inhomogeneity or variation in degree of hydration and that deviations can be expected for glass that has been in an alkaline environment.

CHEMICAL COMPOSITION

Factors or Problems:

Chemical composition is one of the most widely used characteristics of volcanic ash. As in the case of primary minerals, a number of factors must be kept in mind in selection of samples and interpretation of data. It has been emphasized that the kind and amount of primary minerals vary within a given deposit. Consequently, analyses on whole samples containing different amounts and types of minerals have limited utility. The chemical composition of the glass is preferred for use as a distinguishing criterion. Even in the case when analyses are reported for glass, differences in degree of separation can result in discrepancies of data. Unfortunately, the literature is not always clear as to whether the analyses reported for a given volcanic ash or pumice is for glass only, for lumps with mineral inclusions or for glass with a given content of crystal contaminants.

Contamination of the sample with detrital or non-volcanic components is minimized by separation of volcanic glass. The presence of carbonates or hydrous oxides may require "cleaning" treatments. For precise analysis, removal of surface contaminants is required. Mixing of different volcanic deposits is a much more difficult problem to recognize and handle. This may be indicated by stratigraphy of the area and deviations from the composition norms.

A factor which has received less attention is weathering or alteration of the deposit. Variations are expected in relation to depth and environment. Borchardt (3) has shown that samples of Mazama pumice from upper soil horizons are lower in Si, Ca and K and higher in Al, Ti and Fe relative to lower horizons. Similar effects have been reported by Czamanske and Porter (3) for "fresh" and "weathered" lumps of pumice. The importance of weathering to trace element compositions will be illustrated later.

Major Element Composition

The Mazama pumice has been classed as dacite on the basis of its chemical composition (18). These analyses were made on the lump pumice. Other analyses for the Mazama ash as well as for Glacier Peak ash are given by Powers and Wilcox (9), Czamanske and Porter (3) and Smith and Westgate (10). The data of Smith and Westgate were chosen for presentation here (Table 4) since they include averages of a larger number of samples with precise control of the glass component being analyzed. The general similarity in composition of the different glasses is apparent and consistent with the dacitic composition of widely distributed ash falls. Within this gross similarity, characteristic differences are usually observed. The Glacier Peak ash is higher in silica and lower in most other constituents in comparison with Mazama. Components of St. Helens-Y are generally intermediate between Mazama and Glacier Peak except for Ca which is higher. The Bridge River ash is most like Mazama and would be difficult to distinguish on the basis of these data.

The technique of Smith and Westgate (11) deserves special comment since their data were obtained by the use of an electron probe. The merit to this approach is the degree of control for analysis of glass. Conditions of operation were such that the material could be viewed during analysis and the microlites and bubbles in the shards or pumice fragments could be avoided. Although 12 elements were determined, it was reported that as few as 3 elements such as Ca, K and Fe or Ca, K and Na would distinguish their samples. An apparent limitation of major element analysis involves the influence of weathering. All of the elements determined may vary depending on the environment since deposition. They are fortunate in that the ash in the Edmonton area occurs as buried layers and apparently little alteration has occurred. This contrasts with the situation in Oregon in which much of the Mazama pumice is surficial and alteration has occurred in upper horizons. The extent to which the method can be applied for samples of diverse environments and success of pretreatments to obtain a residue of "clear, fresh" glass needs to be determined. Nevertheless, it is obvious that the technique has great merit for eliminating the contribution of phenocrysts.

The content of titanium by X-ray emission spectroscopy also has been used to aid in the identification of Cascade Range pyroclastics (3). The contents of TiO₂ for Mazama and Glacier Peak lump pumice were 0.58 and 0.43 percent respectively; the contents in the glass fractions of Mazama and Glacier Peak were 0.42 and 0.28

respectively. However, the composition was affected considerably by enrichment of Ti by weathering which resulted in overlap in values for some samples of the two sources. In addition, titanium contents of other ash layers such as those of St. Helens overlap those of Glacier Peak and Mazama.

Trace Elements

Information in the literature on trace element composition of different ashes of the region is scarce. The contents of yttrium, ytterbium and zirconium in Glacier Peak pumice have been reported to be lower than in Mazama pumice (9).

Instrumental Neutron Activation Analysis

Pedological studies across a transect of a given deposit require the ability to recognize the deposit over distance and to distinguish it from others. As previously discussed, determinations to accomplish this include kinds and amounts of primary minerals, indices of refraction of glass and phenocrysts, and chemical composition. Chemical analyses generally have been restricted to the more common major elements. Trace element composition by wet chemical methods has not been extensively used because the techniques are laborious. Each of the different approaches has some limitations due to overlapping parameters, bimodal frequency distributions and problems of mixing or contamination. There is generally no single method that will determine source. Rather, several methods are used to complement each other.

Activation analysis has been successfully applied to analysis of meteorites and other geologic material (5, 10). Although not previously used for distinguishing volcanic ash deposits, activation analysis should offer considerable promise for this purpose. The merit for the approach lies in the ability to obtain analyses for a large number of trace elements more rapidly than is possible with wet chemical procedures. A "finger print" of many elements should increase the reliability of identification.

A preliminary study indicated the potential usefulness of instrumental neutron activation analysis (INAA) in distinguishing different deposits of volcanic ash (15). Ash samples of known origin were used to develop the general methodology and determine the magnitude of differences between samples.

Detailed investigations using INAA of samples of soils developed on volcanic ash are now in progress at Oregon State University. Data from the present study will form the basis of the Ph.D. thesis of G. A. Borchardt. Although analysis and interpretation of the data are not yet complete, summaries of the preliminary data are presented here to illustrate the kinds of problems studied with the technique. In addition, they will provide a perspective of trace element compositions of some of the ash deposits of the region. The final data are scheduled to be published in scientific journals.

Procedures:

Horizon samples were obtained along a southeast to northwest transect from the vicinity of Crater Lake to the northeastern corner of Oregon. This corresponds to the axis of the main lobe of the Mazama deposit. Sites were selected on broad plateaus or ridge tops under forest vegetation in an effort to minimize contamination by movement and redeposition. Samples of preserved ash layers in bogs were obtained for reference and correlation with upland sites.

It was recognized that contamination of layers of pyroclastics by primary minerals and possible differences due to mineral sorting might contribute to geochemical variability and confound the interpretations. Therefore, glassy components were isolated from fine sand size (125 to 63 μ) fractions using bromoform-bromobenzene, $\rho = 2.4 \text{ g/cm}^3$. An additional separation at 2.2 g/cm^3 may be used to remove fragments of plant residues. The separates were then irradiated in the Oregon State University TRIGA Reactor and analyzed using the method of Gordon 'et al', (5). The counting equipment consists of a 30 cm^3 Ge(Li) semiconductor detector and a 4096 Nuclear Data Multichannel analyzer.

Analysis of the gamma ray spectra emitted from the irradiated sample and comparison with suitable standards yields elemental abundances down to the range of parts per million. The glassy separates yielded 19 nuclides measureable directly with these techniques. These include the alkali and alkaline earth elements Na, Rb, Ca and Ba; the rare earth elements La, Ce, Nd, Sm, Eu, Tb, Yb and Lu; and the transition elements Th, Hf, Ta, Co, Fe, Sc and Cr.

Variation within Deposits:

The basic assumptions in this approach are that the elemental compositions of ashes of various sources differ and that these differences can be measured. This requires that one must first evaluate the accuracy of determinations and the variability within the deposit. The average elemental compositions for 21 samples of Mazama pumice and ash and the associated statistics are given in Table 5. The accuracy of determination (based on counting statistics) varies with the different elements. A number of elements can be determined within a few percent and most of them within 5 to 20 percent of the amount present. The variability within the deposit appears to be no greater than the accuracy of determination.

Differences Between Sources:

The average compositions of samples from known sources are given in Table 6. The Mazama deposit is characterized by a particle size discontinuity (C1 - C2 horizon boundary) at a number of locations where coarser materials overlie the finer. The data show that the trace element compositions of these horizons are much alike. The Newberry samples are generally higher in trace elements than in Mazama samples. The Glacier Peak ash has significantly lower trace element contents than Mazama. The St. Helens-Y samples are similar to Glacier Peak.

For distinguishing or correlating ash deposits, it is desirable to have a smaller number of parameters which will represent the composition of a sample. The extent to which compositions differ can be expressed in terms of relative concentrations. The data in Table 7 summarize the difference between samples of known origin. The means (Column 1) were obtained from the ratios of each of the 19 elements determined relative to the average composition of 21 different samples of Mazama. For a sample like Mazama, the ratio for a given element should be near 1. The mean of the ratios for all elements in the sample should also be near 1 and the coefficient of variation (% C. V.) should be low. The deviation in mean ratio from a value of 1 and the larger values for % C. V. reflect the lack of agreement with Mazama.

Composition Across a Transect:

Mean trace element ratios for volcanic ash from C horizons across the transect generally verify our initial assumption that the sample sites represent the Mazama deposit (Table 8). Mean ratios are close to 1 and C. V.'s are low. The South Ice Cave site deviates from the other four sites. The field description for this site indicates some mixing of horizons. Weathering changes the trace element composition and decreases the agreement with the standard Mazama composition. Examination of the individual element compositions for this sample suggests mixing with some of the weathered horizons. The possibility of contamination from local sources in the area should also be considered.

Depth of Weathering:

Weathering results in accumulation of some trace elements in upper horizons. This is reflected in higher values of the mean ratio and percent C. V. (Table 9). Higher concentrations in weathered horizons than in lower ones were particularly evident for Cr and Co and to a lesser extent for Sc and Fe. The rare earth elements do not vary appreciably with depth. For purposes of correlation or identification it will be necessary to use criteria other than mean ratios of all elements. The use of rare earth compositions or certain element ratios such as Fe/Sc or La/Sm are needed for correlating weathered materials. On the other hand, variation of certain trace elements with depth provide a means of determining the extent of weathering.

Alteration Products:

Amorphous components dominate the clay fraction of soils developed on Mazama pumice. The question arises as to whether this is merely fine glass or a weathering product. An alteration product would be indicated by differences in chemical composition. Comparison of $< 2\mu$ fractions with the average composition of the glass show that the clay fraction is different and suggest that it is indeed an alteration product (Table 10). The abundances in the clay fractions exceed that of the glass by factors of 2 - 10 times depending on the element.

Bog Sites Versus Uplands:

Samples of preserved ash layers in bogs generally correlate with samples from the uplands. For example, samples were obtained from a bog at Tollgate Summit which is near the Dick Springs soil location. The mean ratio for the

bog sample is 0.93 and the C. V. is 15 percent. These values may be compared with the C horizon sample of Dick Springs listed in Table 8. Samples from some bogs resulted in values somewhat higher than expected for Mazama. These effects appear to be related to weathering as noted for upper soil horizons.

Profile Discontinuities:

Activation analysis techniques have application to study of profile discontinuities. In our case, we wanted to know if the particle size discontinuity (C1 - C2 horizon) was also correlated with differences in chemical composition. Preliminary analysis of the data indicate that the compositions are the same within the accuracy of determinations.

Inclusion of Phenocrysts (Glass vs. Whole Samples):

Glass separates were used in most of our investigations to avoid possible confounding with different mineral contents. The effect of mineral inclusions was checked by comparing whole samples with glass separates of Mazama and Glacier Peaks pumices. Although the presence of minerals in the Mazama sample did not materially change the mean ratio, the abundances of particular elements were affected (Table 11). The content of rare earths remained the same while there were increases in Fe, Sc and Cr. The Mazama lump pumice contains on the order of 15 percent minerals on a volume basis. The effects of mineral inclusions would be more pronounced in fine ash samples containing higher mineral contents (Table 2). Glacier Peak pumice has higher contents of phenocrysts than Mazama and the increases in composition were very marked.

Regional Distribution

Deposits of volcanic ash from as far away as Edmonton, Alberta, Canada and from ocean deposits in the Astoria fan off the Columbia River have been reported to be from Mazama (8, 16). Analysis of samples from these deposits yielded values which agree very well with the standard composition of Mazama. This illustrates the usefulness of INAA techniques for correlating ash deposits over large distances.

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TABLE 1. Source and chronology of some quaternary ash deposits of the northwestern United States.

Ash fall or layer	Source	Approx. age (yrs. B. P.)	Reference
T	Mt. St. Helens, Washington	167	Mullineaux (7)
W	Mt. St. Helens, Washington	300	Crandell 'et al' (2)
C	Mt. Rainier, Wwashington	1,000 – 3,000	Crandell 'et al' (2)
Newberry	Newberry Crater, Oregon	2,000	Higgins and Waters (6)
Y	Mt. St. Helens, Washington	3,200	Crandell 'et al' (2) Westgate and Dreimanis (16)
O	Mt. Mazama, Oregon	6,600	Williams (18) Crandell 'et al' (2) Powers and Wilcox (9) Wilcox (16) Allison (1)
R	Mt. Rainier	8,750	Crandell 'et al' (2)
Glacier Peak	Glacier Peak, Washington	12,000	Powers and Wilcox (9) Fryxell (4)

TABLE 2. Relationship of distance to content of glass in very fine sand size fractions of Mazama ash. (Samples of C horizons)

Location	Distance from Source (km)	% glass
South Ochoco Butte	222	40
Day Creek	304	59
Dick Springs	445	72
Huckleberry Springs (lump pumice)	50	82

TABLE 3. Mineralogy of volcanic ash deposits from northwestern United States (%)

	Washington*					Alberta**		
	O Mazama	Y St. Helens	W St. Helens	R Rainier	C Rainier	Mazama	Y St. Helens	Bridge River
Hypersthene	> 50	R	> 50	V	> 50			
Hornblende	5 – 50	> 50	5 – 50	V	< 5	> 50	10 – 50	10 – 50
Augite	5 – 50			V	5 – 50			
Oxyhornblende				V		5 – 10	R	< 5
Orthopyroxene						< 5	R	10 – 50
Clinopyroxene						R		< 5
Biotite						R?	R	< 5
Apatite						R		R
Cummingtonite							10 – 50	
Refractive Index of glass	1.50–1.51	1.50–1.51	1.49–1.50	1.52–1.57	1.50–1.53	1.504–1.514	1.502–1.520	1.496–1.504

* Crandell 'et al' (2) Samples from vicinity of Mt. Rainier, Washington.
 ** Westgate and Dreimanis (16). Samples from Alberta, Canada.
 R Rare
 V Variable

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TABLE 4. Average compositions (%) of volcanic glasses. (Data of Smith and Westgate, 11).

	M a z a m a	Glacier Peak	St. Helens—Y	Bridge River
SiO ₂	72,27	76,51	74,80	72,95
TiO ₂	,49	,24	,17	,44
Al ₂ O ₃	14,85	13,44	14,70	14,64
Fe ₂ O ₃ + FeO	2,02	1,11	1,39	1,85
MnO	,04	,03	,03	,05
MgO	,53	,28	,46	,54
CaO	1,61	1,32	1,81	1,65
Na ₂ O	5,23	3,92	4,45	4,77
K ₂ O	2,67	2,96	2,01	2,86
P ₂ O ₅	,06	,02	,04	,04
Cl	,18	,18	,11	,15
F	,05	—	,02	,07

TABLE 5. Average elemental composition, counting statistics, and field variability of Mazama ash (21 samples)

Element	Concentration* ±s		Coefficient of Variation (%)	
			Counting	Field
Na	3,47%	,07	2	5
Rb	55	11	20	20
Cs	3,73	,52	14	14
Ba	679	48	17	16
La	21,6	1,5	7	9
Ce	42,4	1,3	3	5
Nd	25,5	9,9	39	34
Sm	4,99	,10	2	7
Eu	,81	,09	11	13
Tb	,87	,26	30	21
Yb	3,49	,49	14	16
Lu	,58	,10	17	15
Th	5,88	,29	5	13
Hf	6,30	,19	3	4
Ta	,25	,06	23	39
Co	2,51	,48	9	15
Fe	1,46%	,03	2	5
Sc	6,24	,12	2	5
Cr	1,6	1,2	73	36

* ppm except for Na and Fe which are in percent.

B.5.11

TABLE 6. Average trace element compositions of pyroclastics from several sources in the Cascade Range. (ppm unless otherwise indicated).

Element	Mazama C1 (4 samples)	Mazama C2 (4 samples)	Newberry (3 samples)	Glacier Peak (3 samples)	St. Helens-Y (2 samples)
Na(%)	3.26	3.54	3.71	2.12	2.29
Rb	52.	48.	96.	41.	34.
Cs	3.73	3.39	4.85	2.54	1.90
Ba	611.	659.	625.	346.	217.
La	22.	20.5	33.5	15.3	16.6
Ce	44.5	42.4	43.7	25.9	22.5
Nd	28.3	29.6	22.4	7.9	16.6
Sm	5.09	4.99	7.09	2.05	2.64
Eu	.90	.75	.72	.49	.45
Tb	.79	.86	1.22	.23	.53
Yb	3.59	3.49	6.56	.80	.70
Lu	.55	.57	.94	.23	.22
Th	6.35	5.94	12.93	6.41	3.59
Hf	6.55	6.24	8.95	2.52	2.14
Ta	.30	.17	1.02	.28	.33
Co	2.81	2.48	1.18	2.86	2.83
Fe(%)	1.52	1.46	1.52	1.02	1.18
Sc	6.61	6.24	6.24	3.12	2.50
Cr	1.62	1.47	2.53	1.99	2.20

TABLE 7. Mean elemental ratios for different sources of volcanic ash relative to Mazama.

Source of Ash	Mean Ratio*	Percentage C. V.
Mazama C1	1.03	15
Mazama C2	.97	16
Newberry	1.47	52
Glacier Peak	.65	53
St. Helens-Y	.65	48

* $\frac{\sum (C_x)_Z}{(C_x)_M} / \text{No. elements}$

where $(C_x)_Z$ is composition of element x for sample being compared to Mazama ash.

$(C_x)_M$ is average composition of element x for 21 samples of Mazama ash.

TABLE 8. Mean elemental ratios for C horizon samples of volcanic ash across a transect of soils.

Location	Distance from source (km)	Mean ratio*	C.V. %
Huckleberry Springs (Sec. 36, T.27S, R9E., W.M.)	50	0.99	10
South Ice Cave (Sec. 13, T.23S., R.13E., W.M.)	107	1.38	34
South Ochoco Butte (Sec. 11, T.13S., R.20E., W.M.)	222	1.05	22
Day Creek (Sec. 24, T.11S., R.30E., W.M.)	304	.92	15
Dick Springs (Sec. 11, T.3N., R.37E., W.M.)	445	.99	15

* Mean of trace elements relative to standard composition of Mazama.

B.5.12

TABLE 9. Changes in trace element composition of volcanic ash with soil depth: Weathering effect. (Day Creek site).

Horizon	Depth (cm)	Mean ratio*	Percentage C.V.
A1	0-25	1.28	78
AC	25-45	1.29	55
C1	45-60	1.13	26
C2	60-72	.92	15

* Mean of trace elements relative to standard composition of Mazama.

TABLE 10. Trace element compositions of $< 2\mu$ fractions of soil horizons relative to 123-63 μ glass. (Day Creek site).

Horizon	Depth (cm)	Mean ratio*	Percentage C.V.
A1	0-25	2.92	100
AC	25-45	2.95	91
C1	45-60	2.54	66
C2	60-72	2.22	44

* Mean of trace element ratios of $< 2\mu$ fraction relative to standard composition of Mazama glass.

TABLE 11. Effect of mineral inclusions on trace element compositions. (Whole samples vs. glass separates).

	Mazama		Glacier Peak	
	Glass	Lump Pumice	Glass	Lump Pumice
Mean Ratio*	1.05	1.09	0.36	1.02
% C. V.	14	22	49	91
Rare Earth Elements*	1.13	1.12	.38	.83
Co (ppm)	3.05	2.36	1.40	5.94
Fe (%)	1.49	2.13	.52	1.85
Sc (ppm)	6.82	7.78	1.77	6.12
Cr (ppm)	1.00	2.80	.80	7.00

* Relative to the standard composition of Mazama glass.