BOREHOLE
DDH-3
 CORRELATIONS

Lawrence Berkeley Laboratory
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**CHEMICAL CHARACTERIZATION
 OF BASALT FLOWS**

Chemical Characterization of Basalt Flows

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Introduction

In the development of nuclear energy, the area of greatest public interest concerns the safe final storage of nuclear wastes. Extensive studies have been undertaken of the feasibility of storing such wastes in mined caverns in the basalt layers of the Columbia River Plateau. In order to guarantee the integrity of the stored material over periods of time long enough to allow its radioactivity to decay to acceptable levels it is necessary to anticipate water movement patterns within the Plateau basalts. An important facet in such hydrology is the identification, classification, and mapping of the basalts both in the vertical and horizontal directions. A considerable corpus of geophysical, petrographic and chemical data have been obtained by the Atlantic Richfield Hanford Company (ARHCO) from several boreholes in the central Plateau region and from many exposed flows. The present study was undertaken at the suggestion of ARHCO personnel to evaluate the ARHCO accumulated chemical data and determine their usefulness in identifying flows in the Plateau region. This paper is divided into three sections: in Part I the evaluation of the chemical data is given; in Part II a quantitative method is demonstrated of distinguishing between basalt flows with data selected from type locality, and other reference areas sampled by ARHCO; Part III shows the extent and degree of confidence with which the

criteria from Part II can be used to identify flow types as a function of depth in the borehole. Each section contains introduction, conclusion, and recommendation subsections.

Conclusions

The ARHCO chemical data which includes trace elements, can be used to distinguish, with a high degree of confidence, between flows in the upper (and part of the middle) Yakima basalts. They also can be used to distinguish between groupings of flows in the middle Yakima basalts, and between the lower basalts and the others.

The quality of the measurements, however, was not well-controlled. The atomic absorption measurements were generally useful, but contained a significant number of poor values. The quality of the neutron activation data, with the exception of the Cr values, was generally well below that which can presently be done. Almost all data was either poorly calibrated (Sc, Co, Eu, Ba), had variations in calibration over an extended group of samples (La, Sm, Th, Ta), or had poor precision (Tb). The poorly (but consistently) calibrated data were useful for the basalt characterization and in particular the Cr measurements were very useful. The gamma ray spectroscopy measurements, which determined K, U and Th abundances, were generally of poor precision and not very useful for characterization of the basalts. They were helpful, however, in evaluating K and Th data taken by other methods. The emission spectroscopy measurements, with few exceptions, were almost useless.

Recommendations

In order to accumulate reliable data, extensive chemical measurements in the future should be handled by a minimum number of laboratories, and one of these should coordinate and monitor the measurements. If more than one laboratory makes measurements, all participating laboratories should demonstrate they obtain the same values within specified limits when the same samples are measured. The monitoring program should also insure that variations in calibration do not occur with time. If one laboratory makes a significant number of measurements, some small fraction ($\sim 1-5\%$) of the measurements should be periodically checked by a second laboratory or an alternate technique.

The chemical measurements did not distinguish as well among a number of the middle Yakima flows as among the upper Yakima flows. Precise and accurate measurements of the abundances of selected trace elements in type locality samples from middle Yakima flows should permit assignments with less ambiguity. If this is successful it should be applied to borehole samples from the middle Yakima flows.

ARHCO could prepare a comprehensive compilation of the chemical elemental abundances for the various Plateau flows and of the spreads (root-mean-square deviations) of the abundances for many elements in each flow. The existing data base could be used, if it were systematically recalibrated by selected additional measurements. Other published reliable data could then be incorporated into this recalibrated data base, resulting in a compilation of the best data for chemically characterizing Plateau basalts.

PART I

Evaluation of ARHCO Chemical Data

Introduction

The chemical abundances used in this evaluation were supplied by the Atlantic Richfield Hanford Company in the form of (1) Lithology Logs for the boreholes DDH-1, DH-2, DDH-3, DH-4 and DH-5; (2) sheets of tabulated data for type locality and field section samples; and (3) several charts of data on type locality groups. In addition a publication of J.B. Tatman¹ was used which contained information for the boreholes.

Generally the information supplied by ARHCO was the same as in the publication ARH-ST-137 Vol. II.² There were some exceptions such as the Elephant Mountain major element data which were different in the latter publication. Data on Devils Canyon included in reference 2 were not available for this work.

The chemical data evaluated in this paper was taken by four techniques. Atomic absorption was used for the major elements and the results were expressed as abundances of SiO_2 , Al_2O_3 , FeO , MgO , Na_2O , CaO , K_2O , TiO_2 , and Ba. Other minor and trace elements were sometimes measured but those measurements were not evaluated. Neutron activation analysis was used on many samples and abundances of Na, La, Sm, Fe, Co, Sc, Cr, Eu, Th, and Hf were measured for many samples and abundances of Tb and Ta on a fewer number. Gamma ray spectrometry was

used on many samples to determine abundances of ^{40}K , ^{228}Th and ^{226}Ra , which can be used to calculate the abundance of K, Th and U. Emission spectroscopy was used for a number of samples and Ba, Cr, Ni, Rb, Sc, Sn, V, Zr and sometimes Zn, were measured. The evaluation of data was done principally on type locality and field section samples because more data was available for cross-checking different techniques.

One of the most effective methods of data evaluation used in this report was a comparison of the abundances of a given element as measured on the same samples by different techniques, e.g., Na as measured by atomic absorption and neutron activation analysis. The ratio of these values (expressed as either the elemental or oxide abundances) should be equal to 1 within the experimental uncertainties. If one or both of the techniques are improperly calibrated, but the calibrations are consistent throughout a group of data, then the ratio will be consistently equal to a number different from 1. Variations in the ratio reflect short term or long term errors in measurement. A comparison of the apparent precisions of measurement for two different techniques and the precision in their individual ratios can determine in favorable cases source variations as well as the actual precision of measurement for each technique.

In this work precision will refer to the root-mean-square deviation (RMSD) of a group of measurements on the same material presumably made in the same laboratory over a short period of time. Generally only

measurements on different rocks will be available and these will therefore give an upper limit to the precision. Also a concordance between group of samples and the laboratories which analyzed them was not available. It is therefore assumed that measurements on samples with sample numbers close to each other were made in the same laboratory at about the same time. Some apparent exceptions to this assumption are noted in the text. The root-mean-square deviation of the averages of measurements on groups of samples is one method of determining a calibration variation which presumably takes place over a relatively long period of time. If the average of ratios of measurements by different techniques for different sites are themselves averaged, and the RMSD determined, this latter value should be appreciably better than its overall RMSD. If not then it is an indication of calibration variations. Where measurements of the same element on the same samples by different techniques are not available, comparisons were sometimes made between different elements which are chemically similar. For example, if the precision of measurement was much better for Hf than for Zr, there was assumed to be a problem in the Zr measurement. Another type of comparison was made with measurements from other laboratories, i.e., the United States Geological Survey and the Lawrence Berkeley Laboratory. Data used from the U.S.G.S. came from two publications. One was an Open File Report³ which was used because it includes a large number of individual sherd analyses which permitted calculation of root-mean square deviations. The other was a journal publication which contained

average values for major element compositions. These values may be more accurate as they conformed to the Geological Survey standards. The LBL data are unpublished but appear in the form of graphs in an LBL report.⁵ Comparisons with other laboratories determine upper limits for calibration errors for specific flows. If both U.S.G.S. and LBL agree and ARHCO does not, the ARHCO measurements are assumed to have a calibration error. The variation in this error over a number of flows is a long term calibration variation.

When samples from different areas appear to belong to the same flow from geophysical arguments and from most of their chemical abundances, large deviations from the overall mean of the abundances of a specific element at a given site is regarded as suspicious. When the site behaves the same way for two or more flows, there is assumed to be calibration error in the measurements for that site.

PART I

Conclusions

The precision and calibration variations for various elements considered in this work are summarized in Table XXI of Part II. Most of the atomic absorption data for K_2O , Na_2O , SiO_2 , TiO_2 , FeO , Al_2O_3 , and CaO , which were evaluated in this report, were measured with a precision of better than 4%. The flow inhomogeneities amongst the sampled rocks are included in the 4% as well as measurement uncertainties. An attempt was made to evaluate variations in calibration caused by changes in chemical procedures or techniques.

Most of the elements discussed above had long term variations of less than 3% (one sigma values). CaO (5%), TiO_2 (8%) and possibly K_2O ($\leq 6\%$) were exceptions. The overall calibration for all of the above-mentioned elements was good and usually gave values within 3% of those obtained by other laboratories. MgO , on the other hand, was measured with poorer precision than the other elements and its overall calibration was about 11% different than that obtained by other laboratories. Ba as measured by AA gave values about 180 ppm too high regardless of whether there was a high or low barium content in the sample. The precision of the Ba measurement is unknown as the 11% RMSD could have been due to flow inhomogeneities. The above comments for all of the elements apply to the general body of data, but there were a number of examples of apparently bad values for most of the elements measured by AA.

The quality of the neutron activation data depended strongly on the element being measured. Na was done as well by NAA as by AA while Fe was not. Cr, a very important element for characterization, was measured with a precision of better than 6% as were Co, Sc, La, and Sm. Eu was measured somewhat more poorly. Long term variations were generally better than 4% for all of the elements just discussed although that for Cr could not be determined. Notable exceptions were Sm and La which had very large apparent changes in calibration from one sample group to another. Therefore these elements were not used in the characterization in spite of their high precision of measurement. Differences of 10% between the overall calibration of the ARHCO trace elements and other laboratories were common. One of the best ARHCO measurements for which other comparisons were available was on sample A1393 from Elephant Mountain whose trace element abundances agree closely with LBL results.

The gamma spectroscopy data on ^{40}K had a given precision of about 16% and a number of erroneous values. They were not generally good enough for characterization work but were useful in determining errors in the AA data. The work on ^{228}Th and ^{226}Ra was also of too poor precision for useful characterization of Th and U. The ^{228}Th results, however, were useful in determining errors in the NAA Th determinations.

Ba, Sc, Cr, Ni, Rb, Zr, and Zn data taken by emission spectroscopy were evaluated for many type locality and field section groups. These data were generally useless for characterization purposes. Exceptions worth noting were the Cr measurements on samples K5001-K5009 which appeared to be of high quality.

PART I

Recommendations

In future work, ARHCO should monitor its chemical measurements more effectively in order to obtain a consistently high quality of data. One method could be to have one laboratory responsible for all of the measurements, and the laboratory would be responsible for cross calibration for any measurements which it sub-contracted. ARHCO could monitor the operation by checking ~1% of the measurements in a second laboratory. The larger number of laboratories that make measurements for ARHCO the larger the fraction of the samples which should be checked. For trace element abundance measurements, neutron activation analysis is probably one of the most reliable methods which is generally available. Many of the trace elements measurable by this technique are useful for characterization (see Part II). X-ray fluorescence, when carefully done, can also be very effective for some trace elements, especially Zr, Sr, Rb, Nb, and Y. The effectiveness of these elements for basalt characterization is unknown but ARHCO might wish to determine this effectiveness for their program.

PART I

Discussion

K₂O by atomic absorption spectroscopy (AA)

Summary: Precision $\leq 4\%$, calibration variations $\leq 6\%$ (after modifications), ARHCO/others = 1.02.

Potassium (K) abundances were determined for many samples both by AA and by gamma ray spectroscopy measurements (γ) of the ^{40}K . The two measurements on each sample can be used to check each other and the ^{40}K values, when expressed in units of 10^{-3} μ curies of $^{40}\text{K}/\text{Kgm}$ which have been divided by 6.87, should give K₂O abundances expressed in percent.

The root-mean-square deviation (RMSD) of the ratios of K₂O measured by the two methods was 18.2% for 95 samples taken from 10 type locality or field section areas. The RMSD is defined as follows: $\text{RMSD} = \sqrt{\sum_i (r_i - \bar{r})^2 / (n - 1)}$ where r_i are the individual ratios, $\bar{r}$ is the average and n is the number of values. The average of the listed values for the one σ counting error in the K₂O abundance for 104 samples is 15.4% for the gamma spectra γ measurements. If the listed errors are correct then the one σ uncertainty in the K₂O AA measurements is $\sqrt{(18.1\%)^2 - (15.4\%)^2}$ or $\sim 10\%$.

A more sensitive determination can be made by averaging the ratios for each site. If all errors are random, then the RMSD of these average ratios should be smaller than the RMSD of the individual ratios by a factor of $\sqrt{\bar{n}}$ where $\bar{n}$ is the average number of samples in each group. If the resulting RMSD is not small enough, then there are non-random errors indicating calibration variations with a site dependence. Most samples at a given site have consecutive sample numbers and may have

been analyzed at about the same time in the same laboratory. Thus an apparent site dependence could be a dependence on time and place of analysis. For the 10 sites the RMSD in the average ratio was 13.8%, and it should have been closer to $18.2\% / \sqrt{9.5}$ or 5.9%. (As some of the groups have only 3 samples as shown in Table I, the expected RMSD would be somewhat larger than 5.9%). Thus, there are calibration variations of the order of $\sqrt{(13.8\%^2 - 5.9\%^2)}$ or $\sim 12\%$ (one σ value) in the AA or γ data or both.

The source of these variations can be determined by comparing the K_2O abundance for a given basalt flow or member at different sites or by comparing the ARHCO values with work done elsewhere on the same flow or member. The most pronounced deviations in Table I were in the Blair Point field section and the Pomona type locality samples.

By cross comparing AA abundances for two chemical groups (a Spukshowki Canyon Group and the Umatilla Group) in samples from a number of different sites (see Table II), it appears that nearly all of the Blair Point AA abundances are about 19% higher than those at other sites. This difference confirms the deviations indicated by Table I for Blair Point where the γ/AA ratios on the same samples are shown to be 24% lower than the average for other sites. As the AA results (excluding Blair Point values) on the Umatilla flow agree with U.S.G.S. and LBL values as shown in Table III it is very likely that nearly all of the Blair Point AA values are off $\sim 20\%$. As seen in Table III the Blair Point values in the sample series A1175 $\rightarrow$ A1183 should be

multiplied by .84 with an uncertainty of $\sim 5\%$. The samples A1184 $\rightarrow$ A1201 (except for A1187) group well (6.3% RMSD) and do not appear to have a systematic deviation within them. It seems likely that these data (A1184 - A1201) should also be multiplied by .84. The data for sample A1348 and for samples A1202 and up at Yellepit Pond appear to be valid and do not need a correction.

The Pomona type locality AA data are 10% higher than U.S.G.S. values and 8% higher than LBL values, but this difference can be due to the relatively low abundance of K_2O in the Pomona member and rounding errors coupled with uncertainties in all measurements. Compared to γ measurements on the same samples, the Pomona type locality AA results are 34% higher, which probably reflects an error in both AA ($\sim 9\%$) and γ spectra ($\sim 25\%$). Core samples of the Pomona type have AA average values of -17% (A2011 - A2014) -63% (A4005,7,9) and -15% (A5007,9,11) with respect to LBL-U.S.G.S. values. The A4000 series AA results are a good factor of 2 lower than the γ spectra results on the same samples so those AA results are suspect.

If the RMSD's of the AA abundances, the γ abundances and the individual ratios of the AA to γ results are all considered, in a statistically large sampling, the respective variations due to short term AA measurements errors, short term γ measurement errors and source differences can be separated. Although such a large sampling was not available, it was approximated by averaging the results of 8 groups totaling 63 samples. The relevant equations are:

Table I

Analysis of K₂O Measurements

	⁴⁰ K (expressed in curies 10 ⁻³ /Kgm) 6.86 (K ₂ O by AA expressed in %)	RMSD	Number of Samples
Pomona	0.82	0.21	5
Ward Gap	1.10	0.00	3
Umatilla	1.08	0.04	3
Huntzinger	1.27	0.14	5
Priest Rapids	1.27	0.17	15
Roza	1.17	0.09	4
Rush Canyon	1.04	0.12	13
Spukshowki Canyon			
Blair Point	0.88	0.14	20
Yellepit -Mound	1.08	0.08	12
Selah -Butte	1.16	0.14	15
Overall	1.076	.195 (18.1%)	95
Averages 10 groups	1.09	0.11	
RMSD	0.15(14%)		
Without Blair Point & Pomona			
Overall	1.150	0.151(13.1%)	70
Averages 8 groups*	1.146	0.10	
RMSD	0.087(7.6%)		

*Pomona and Blair Point values removed

Table II

Spukshowki Canyon Group		Umatilla Type Group	
Sample	AA K ₂ O abundance (%)	Sample	AA K ₂ O abundance (%)
Spukshowki Canyon		Silussi Butte	
A1253	1.5	A1214	2.8
A1251	1.3	A1215	2.8
A1252	1.4	A1216	2.5
A1250	1.2	A2117	2.6
A1249	1.0	A1237	2.6
A1248	1.3	A1238	2.7
		A1239	2.8
		A1283	2.6
Yellepit		Rush Canyon	
A1234	1.3	A1221	2.7
A1210	1.6	A1220	2.6
A1209	1.3	A1219	2.5
A1208	1.8		
A1207	1.3	Yellepit	
A1206	1.5	A1236	2.7
A1205	1.3	A1235	2.7
A1204	1.4	A1261	2.6
A1203	1.4	A1262	2.8
A1202	1.4	A1263	2.5
Selah Butte		A1264	2.6
A1298	1.3	A1265	2.5
A1297	1.4		
A1296	1.1	Blair Point	
Blair Point		A1348	2.6
A1177	1.7	A1175	3.0
A1178	1.5	A1176	3.1
A1179	1.6		
A1180	1.9		
A1181	1.8		
A1183	1.7		

1.28 ± .17

2.68 ± .12

1.39 ± .10

2.60 ± .10

2.70 ± .00

2.60 ± .12

3.05 ± .07

1.70 ± 0.14

Table III

Comparison of ARHCO K₂O data (AA)
with data from U.S.G.S. and LBL

Abundances of K₂O in %

Flow	ARHCO AA	U.S.G.S. ^{1,a}	LBL ⁵ XRF	ARHCO U.S.G.S.	ARHCO LBL
Umatilla ^b	2.68 ± .13 ^c (21) ^d	2.52 ± .10 (4)	2.69 ± .05 (5)	1.06	1.00
Elephant Mountain	1.26 ± .09 (5)	1.27 ± .14 (21)	1.22 ± .13 (12)	.99	1.03
Average values				1.023	1.015
RMSD				.035	.021
Overall average				1.020	
Overall RMSD				.027	

^aBest U.S.G.S.⁴ values normalized to 100% dry weight as of 1973: Umatilla, 2.59%,
Elephant Mountain, 1.25%.

^bA partial sample concordance is given in Tables XI and XVII.

^cRoot-mean-square deviation.

^dValues in parenthesis indicate numbers of samples measured.

$a^2 + c^2 = \text{RMSD}^2$ of the K_2O values in a chemical group measured by AA

$b^2 + c^2 = \text{RMSD}^2$ of the K_2O values in a chemical group measured by γ

$a^2 + b^2 + d^2 = \text{RMSD}^2$ of the individual ratios of AA to γ values

where a = RMSD due to short AA measurement error

b = RMSD due to short term γ measurement error

c = RMSD due to source inhomogeneity

d = RMSD due to calibration variations in AA, γ or both measurements.

The short term designation reflects the likelihood that samples in a given chemical group at a given site were measured in the same laboratory at about the same time.

The overall 15% difference between AA and γ measurements is due to errors in the latter. This can be seen in Table III where comparison of ARHCO AA measurements with U.S.G.S. and LBL determinations on the same members agree within 2%. The K_2O AA data is useful.

Na_2O by AA and Neutron Activation Analysis (NAA)

Summary:

AA: Precision < 3%, calibration variations (Modified) $\leq 2.2\%$.
ARHCO/others = 1.01

NAA: Precision < 3%, calibration variations $\leq 2.2\%$, ARHCO/others = 0.98

Na was measured on many samples both by AA and NAA. Comparison of the measurements on the same samples by both techniques can be used to evaluate the precision (short term variations) and calibration variations of the measurements.

For 32 samples the (long term) ratio of the AA to NAA values is 1.025 with a RMSD of 3.9%. Exceptions are the Blair Point data in which

tha AA results are 16% higher than the NAA (average for four groups), and the Pomona data in which the AA results are 9.8% higher. A cross comparison of the AA abundances of Na_2O within the Spukshowki group (which appears at different sites) in the same manner as discussed for K_2O indicates the Blair Point AA values are too high and should be multiplied by a factor of 0.90. With this factor the Blair Point AA data are then only 3.1% higher than the NAA data, and Blair Point is therefore consistent with other sites. Probably all Blair Point Na_2O AA data (A1175-A1201) should be multiplied by 0.90 to make them compatable with other ARHCO data. Samples A1202 & A1203 from Yellepit Pond have somewhat high AA values. The variation in the remaining Yellepit Pond samples is larger than normal. Samples A1200 and A1201 appear to have unusual Na values from NAA, almost as if the wrong samples were analyzed (e.g. the Spukshowki Canyon group).

The Pomona differences between AA & NAA probably are caused primarily by changes in calibration for the AA results. Comparisons between ARHCO, U.S.G.S. & LBL data on the same type of samples are given in Table IV. The ratio of ARHCO to LBL data is nearly constant (RMSD of only 2.0%) for 6 different groups, and the Pomona type locality samples have values higher by $4.1\% \pm 1.5\%$ from this value. With U.S.G.S. data the trend is in the same direction, but is more pronouced (7.7%). Pomona type locality AA data probably should be multiplied by a factor of 0.94 to make them compatable with other ARHCO data.

When the Blair point and Pomona data have been corrected, the ratio of ARHCO AA to NAA results for 11 different groups (including Blair Point

Table IV

Comparison of ARHCO Na₂O Data (AA)
with data from U.S.G.S. and LBL

Abundances of Na₂O (%)

Flow	ARHCO ^c AA	U.S.G.S.	LBL ^b NAA ⁵	ARHCO U.S.G.S.	ARHCO LBL
Pomona		2.16 ± .16 (10)	2.37 ± .07 (18)		
Cores	2.31 ± .11 ^e (10) ^a			1.07	.975
Umatilla		3.13 ± .10 (4)	3.31 ± .15		
Type Loc.	3.22 ± .18 (24)			1.02	.973
Cores	3.27 ± .14 (7)			1.04	.988
Elephant Mtn.	2.45 ± .10 (5)	2.38 ± .10 (20)	2.49 ± .11 (12)	1.03	.984
BCR-1 Type		3.27 ± .02 (11)	3.27 ^b		
DH-4	3.36 ± .09 (11)				1.028
DH-5	3.20 ± .14 (8)				.979
			Average values	1.040	.982
			RMSD	± .022	.020
Pomona					
Type loc.	2.42 ± .08 (5)			1.12	1.021

a. Values in parentheses are numbers of samples measured.

b. LBL values multiplied by factor of .968 to normalize to literature value of 3.27% for Na₂O abundance for BCR-1.

c. See Tables XI and XVII for sample concordance

d. Best U.S.G.S.⁴ values normalized to 100% dry weight as of 1973: Pomona, 2.42%; Umatilla, 3.22%; Elephant Mountain, 2.64%.

e. Entries after ± sign are root-mean-square deviations.

and Pomona) is 1.03 with a RMSD of 2.2%, which is good. The NAA work is of comparable precision to the AA work, which averaged 2.8% for 12 groups.

SiO₂ by AA

Summary:

Precision ~2.2% for 13 groups comprising 84 samples, calibration variations 2.7%, ARHCO/others = 1.03

Precision and accuracy in the SiO₂ measurement must generally be significantly higher than for other elements to be useful in characterization. This is because it is the major component and the total variation in SiO₂ amongst basalts in the ARHCO data is only about 15%. Errors in measurement of 10% do occur in the ARHCO data and errors of 5% are not uncommon. Some of the worst problems with SiO₂ measurements are in the Elephant Mountain, Gable Mountain and Priest Rapids data. In general, errors in SiO₂ measurement will be reflected by the material balance being unusually high, unusually low or variable.

The SiO₂ value, however, is redundant with the other major element data. If the total abundance of all the other components (with their errors) is subtracted from 100%, the result is often a more precise and accurate determination of the SiO₂ abundance than the directly measured values. This is demonstrated in Table V. for 4 groups of Columbia River Basalts measured both by ARHCO and by the U.S.G.S. The measured SiO₂ values average a factor of 1.032 higher than the U.S.G.S. values with a RMSD of 0.027.

Table V

Comparison of ARHCO SiO₂ data (AA)
with data from U.S.G.S.

Flow	No. of ARHCO ^a Samples	ARHCO AA	Abundances of SiO ₂ (%)			Lit. ⁶	ARHCO/ U.S.G.S. ^c	Modified ARHCO/ U.S.G.S. ^c
			Modified ^b ARHCO	U.S.G.S. ^{3,d}				
Elephant Mtn.	5	53.6 ^e ± 1.1	49.85 ± 0.40	49.94 ± 0.75		1.073		0.998
Pomona	5	51.6 ± 0.55 ^f	50.95 ± 0.58	50.86 ± 0.46		1.015		1.002
Umatilla	23	54.6 ± 1.3	53.82 ± 0.86	53.45 ± 0.72		1.022		1.007
BCR-1					54.50			
DH-4	11	56.91 ± 0.94	55.09 ± 0.87			1.044		1.011
DH-5	6	54.83 ± 0.04	54.94 ± 0.46			1.006		1.008
			Average values			1.032		1.005
			RMSD			0.027		0.005

^aA partial sample concordance is given in Tables XI and XVII.

^bAdditional corrections for MnO, P₂O₅ and BaO abundances were as follows: Elephant Mountain, 0.97%; Umatilla, 1.70%; Pomona 0.60%; and BCR-1, 0.78%. All Mg values except those in the DH-5 BCR-1 group were divided by 1.11 before incorporating into the SiO₂ determination.

^cU.S.G.S. value or literature value.

^dBest U.S.G.S. values⁴ normalized to 100% dry weight as of 1973: Pomona, 51.69%; Umatilla, 54.66%; and Elephant Mountain, 50.73%.

^eRevised ARHCO value = 52%

^fEntries after ± signs are root-mean-square deviations.

If instead one uses all the data on major elements and volatile components and makes additional corrections for P_2O_5 , BaO, MnO and other trace elements, the modified ARHCO abundances for SiO_2 are only a factor of 1.005 higher than U.S.G.S. values with a RMSD of only 0.005. The additional corrections are about 1% (0.6 → 1.7%) in the groups studied. Unfortunately in this method, very bad data on other elements reflect on the SiO_2 value also. Thus, this subtraction method has limited usefulness.

The SiO_2 measurements by AA were evaluated in the following way. The root-mean-square deviations were calculated for 13 groups of type locality samples. There were four from Priest Rapids, and one each from Elephant Mountain, Pomona, Ward Gap, Huntzinger, Sillusi Butte and Roza. The Umatilla flow samples from Sillusi Butte, Rush Canyon and Spukshowki Canyon were combined into one group and the Gable Mountain samples were also combined into one group. The average RMSD was 2.2% which represents both source variation and measuring errors. Calibration variations were determined from U.S.G.S. measurements on the same flows, as shown in Table IV.

The SiO_2 measurements are generally not as useful as those on other elements for source characterization.

TiO₂ by AA

Summary:

Precision 3.8% (or ± 0.08 absolute %) for 13 groups, calibration variations 8%, ARHCO/others = 0.97.

In 13 groups of samples, the average RMSD was 3.8% of the value or 0.08 in absolute percent units as shown in Table VI. These values are the limits for the precision of the TiO_2 measurements.

The calibration of different sets of data is not easily evaluated for the TiO_2 measurements. As seen in Table VII, there are differences in means of 6% for Pomona flow type locality and core samples, 15% between different Umatilla type locality samples and 15% between two core series which may correspond to the U.S.G.S. BCR-1 standard. LBL and U.S.G.S. data for three flows are in nearly exact agreement and do not reflect these variations. In all cases individual values have been removed which are anomolous with respect to the means. This is usually less than 20% fo the samples analyzed. In the course of the ARHCO measurements, the U.S.G.S. BCR-1 standard was measured periodically, and these data do not show large variations. Unfortunately the available data on the standard measurements does not cover the time period when most of the samples considered in this treatment were measured.

Both the U.S.G.S. and LBL have TiO_2 data on a number of flows measured by ARHCO. As shown in Table VII for 8 groups of data the average RMSD in the ARHCO to others ratio is 8.0%. This is taken as the calibration uncertainty. The ARHCO calibrations on the average give answers which are 97% of the LBL and U.S.G.S. values. TiO_2 is a useful element for the characterization of basalt flows. The ARHCO data on TiO_2 is valuable although less calibration variation is desirable.

Table VI

Precision of ARHCO TiO₂ measurements by AA

Groups	No. of Samples	Mean Abundance	RMSD	% RMSD
Sillusi Butte (Pomona)	15	1.560	0.091	5.8
Spukshowki Canyon	25	2.668	0.080	3.0
Elephant Mountain Type locality	5	3.60	0.12	3.3
Umatilla	15	2.59	0.12	4.6
Type locality	9	2.27	0.07	3.1
Cores	5	2.30	0.07	3.0
BCR-1 Type Cores				
series DH-4	11	1.86	0.09	4.8
series DH-5	6	2.00	0.06	3.0
Pomona				
Type locality	5	1.58	0.05	3.2
Cores	10	1.67	0.07	4.0
Flow Cores				
DH-5	10	1.58	0.08	5.1
DH-4	8	1.65	0.05	3.0
Blair Point	9	2.56	0.10	3.9
Ave RMSD			0.081	3.83
RMSD in RMSD			± 0.023	± 0.96

Table VII

Comparison of ARHCO TiO₂ data (AA)
with data from U.S.G.S. and LBL

	Abundance of TiO ₂ (%)							
	ARHCO AA	LBL ^a NAA ⁵	6. Lit.	U.S.G.S. ^{3,f}	ARHCO/ LBL	ARHCO/ Lit.	ARHCO/ U.S.G.S.	LBL/ U.S.G.S.
Pomona		1.60 ± 0.05		1.61 ± 0.09				
Type locality	1.58 ± 0.05 (5)				0.987		0.981	0.994
Cores DDH-3, DH-4 DH-5	1.67 ± 0.07 (10)				1.044		1.037	
Umatilla		2.54 ± 0.15		2.57 ± 0.15				0.998
Type locality	2.59 ± 0.12 (15) ^b				1.020		1.008	
Cores DDH-3	2.22 ± 0.07 (9) ^c				0.874		0.864	
	2.30 ± 0.07 (5)				0.906		0.895	
Elephant Mountain		3.47 ± 0.09		3.43 ± 0.07				0.994
Type locality	3.60 ± 0.12 ^g (5)				1.037		1.050	
BCR-1 type		2.20 ± 0.04	2.20					
Cores DH-4	1.86 ± 0.09 (11) ^h					0.845		
DH-5	2.16 ± 0.04 (8)					0.982		
ARHCO BCR-1 Calibr.	2.26 ± 0.06 (20)			Average values	.0978		0.973	0.992
				RMSD	± 0.072		± 0.077	± 0.003 ^d

^aAll LBL values were multiplied by 1.018 to give literature value of 2.20% for BCR-1.

^bSilusi Butte, Rush Canyon, Spukshowki Canyon, Blair Point Al348.

^cBlair Point, Yellepit Pond and Mound.

^dAgreement is this good by coincidence.

^eA partial sample concordance is given in Tables XI and XVII.

^fBest USGS values normalized to 100% dry weight as of 1973 are: Pomona, 1.62%; Umatilla, 2.63%; Elephant Mountain, 3.47%.

^gRevised ARHCO values = 3.2%.

^hValues in parenthesis are numbers of samples in groups.

FeO by AA and NAA

Summary:

AA: Precision $\leq 2\%$, calibration variations $< 2\%$ (some exceptions) ARHCO/others = 1.00

NAA: Precision $\sim 4\%$, calibration variations $< 2\%$ ARHCO/others = 0.96

Fe was measured in many samples by both AA and NAA and the results serve as a check on each other. The AA measurements are 4.8% higher than NAA measurements on the same samples for 48 comparisons. The RMSD is 4.1% i.e., the factor is 1.048 ± 0.041 . As shown in Table VII for seven groups, with the largest RMSD in the ratio of the AA to NAA values, the AA results cluster more tightly than the NAA. Therefore most of this error of 4.1% is probably in the NAA measurements. For the samples considered the precision of the NAA measurements should be $\sim 4\%$ and that of the AA measurements $\leq 2\%$. The calibration variations in the ratio can be evaluated as was done with K_2O data and are less than 1.2%. This probably applies to both AA and NAA results (see Table VIII).

In another type of treatment the calibration appears to vary less than 2.5% by comparison with LBL data for 7 different groups as shown in Table IX. The Pomona core data seems to be unusually high. The calibration data for BCR-1 from 1969 to 1972 gave unusually high ($\sim 13\%$) Fe values but these may not necessarily apply to the cores. The Elephant Mountain type locality data appears to be somewhat low. Gable Mountain data seems to shift by $\sim 10\%$ between the A1000 and the A2000 series. The Priest Rapids data seems to have a calibration shift between sample PR-08 and PR-23.

Table VIII

Comparisons of ARHCO AA and NAA abundance measurements of FeO

<u>Site or flow</u>	<u>No. of Samples</u>	<u>AA/NAA</u>	<u>AA value (%)</u>	<u>RMSD%</u>	
				<u>AA</u>	<u>NAA</u>
Ward Gap	3	$1.058 \pm .015$	14.6	4.2	5.3
Pomona	5	$1.041 \pm .032$	10.8	1.6	1.9
Huntzinger	5	$1.028 \pm .015$	10.6	1.2	2.1
Roza	3	$1.066 \pm .031$	14.3	1.2	3.1
Sillusi Butte	7	$1.050 \pm .052$	10.7	3.4	4.1
Spukshowki Canyon	3	$1.021 \pm .033$	12.6	.5	3.6
	6	$1.056 \pm .037$	14.6	1.9	3.1
Blair Point	6	$1.051 \pm .052$	14.7	1.3	4.2
	10	$1.051 \pm .057$	13.7	3.4	5.6
Averages		1.048		2.1	3.7

RMSE 0.041

RMSE/ $\sqrt{48/9}$ 0.018

RMSE in average values 0.014

Calibration variations (1σ) <.02

Table IX

Comparison of ARHCO FeO data (AA) with data from U.S.G.S. and LBL

Flow	FeO abundances (%)				
	ARHCO AA ^b	LBL ^a NAA ⁵	U.S.G.S. ^{3,c}	ARHCO LBL	LBL U.S.G.S.
Pomona		10.47 ± .56	10.39 ± .17		1.008
Type local,	10.76 ± .17 (5)			1.028	1.036
Cores	11.10 ± .30 (10)			1.060	1.068
Umatilla		12.42 ± .14	12.23 ± .12		1.016
Field section	12.48 ± .33 (23)			1.005	1.020
Cores	12.32 ± .33 (5)			.992	1.007
Elephant Mtn.		14.37 ± .71	14.60 ± .42		.984
Type local.	13.80 ± .14 ^d (5)			.960	.945
BCR-1 type		12.06 ± .11 ^e			
DH-4	11.72 ± .30 (11) ^f			.972	
DH-5	11.77 ± .25 (6)			.976	
Averages					1.003
RMSD					± .017
Averages without Pomona Cores					1.002
RMSD					± .040

^aAll LBL results have been multiplied by a factor of .991 to give the literature value of 12.06% for BCR-1.^bA partial sample concordance is given in Tables XI and XVII.^cBest USGS values⁴ normalized to 100% dry weight as of 1973: Pomona, 10.54%; Umatilla, 12.51%; Elephant Mountain, 14.84%.^dRevised ARHCO values = 14.46 ± .21%.^eEntries after ± signs are root-mean-square deviations.^fValues in parentheses are number of samples in groups.

Fe is a very useful element in basalt characterization and the ARHCO data is valuable. Although the average calibration variation is not large (<2%), there are isolated examples of much larger errors. Because of its importance in characterization, more reliable data would be useful.

Al₂O₃ by AA

Summary:

Precision < 3%, calibration variations $\leq 2.2\%$, ARHCO/others = .96

The average RMSD in the Al₂O₃ value for five groups of rocks comprising 93 samples is 2.9%. Thus the precision of the AA measurements was good. ARHCO values for Al₂O₃ abundances of 6 groups of rocks are shown in Table X along with LBL and U.S.G.S. measurements of the same flow types. The U.S.G.S. and LBL values agree well, and the ARHCO results are 4% lower. Al is a moderately useful element for basalt characterization and the ARHCO determinations are good.

CaO by AA

Summary:

Precision $\leq 3.3\%$, calibration variations = 4.7%, ARHCO/other = .97

For 6 groups of rocks comprising 105 samples the average RMSD was 3.3%. Thus the precision (one sigma) should be better than this.

The ARHCO values for 7 groups of rocks are shown in Table XI along with LBL, U.S.G.S. and literature values for the same flow types.

Table X

Comparison of ARHCO Al_2O_3 data (AA) with data from U.S.G.S. and LBL

<u>Al_2O_3 abundances (%)</u>						
Flow	ARHCO AA	LBL ^a NAA ⁵	U.S.G.S. ^{3,b}	ARHCO LBL	ARHCO U.S.G.S.	LBL U.S.G.S.
Pomona		$14.9 \pm .5^c$	$14.58 \pm .23$			1.022
Type local.	$14.36 \pm .24$ (5) ^d			.964	.985	
Cores	$13.74 \pm .30$ (10)			.922	.942	
Umatilla		$13.8 \pm .7$	$13.50 \pm .14$			1.022
Field section	$13.33 \pm .34$ (24)			.966	.987	
Cores	$31.23 \pm .61$ (7)			.959	.980	
Elephant Mtn.		$13.4 \pm .4$	$13.14 \pm .43$			1.020
Type Local.	$12.48 \pm .15^e$ (5)			.931	.950	
BCR-1		$13.6 \pm .4$				
Cores	$13.20 \pm .24$ (17)			.971		
			Averages	.952	.969	1.021
			RMSD	.020	.020	.001 ^f

^aAll LBL values were multiplied by 1.03 to normalize to 13.6% value for BCR-1.

^bBest USGS average values (normalized to 100% dry weight) from a published 1973 paper⁴ are: Pomona, 14.80%; Umatilla, 13.81%; Elephant Mountain, 13.27%.

^cEntries after $\pm$ signs are root-mean-square deviations.

^dValues in parentheses are number of samples in groups.

^eRevised ARHCO values = $12.42 \pm .08\%$.

^fAgreement is this good by coincidence.

Table XI

Comparison of ARHCO CaO data (AA) with data from U.S.G.S. and LBL

CaO abundances (%)								
FLOW	ARHCO AA	LBL ⁵ XRF	Lit. ⁶	U.S.G.S. ^{3,f}	ARHCO	ARHCO	ARHCO	LBL
					LBL	Lit.	U.S.G.S.	U.S.G.S.
Pomona		10.8 ± .3 ^g		10.66 ± .21 (10)				1.013
Type Local.	10.02 ± .24 (5) ⁱ				.928		.940	
Cores, CCH-3, DH-4, DH-5	9.72 ± .48 (10) ^a				.900		.912	
Umatilla		6.05 ± .16		6.10 ± .24 (4)				
Type local.	5.82 ± .28 (24)				.962		.954	
Cores DDH-3	5.84 ± .17 (5) ^b				.965		.957	.992
Elephant Mtn.		8.76 ± .59		8.44 ± .26 (20)	1.018		1.056	1.038
Type local.	8.92 ± .13 ^h (4) ^c							
BCR-1			6.92			1.003		
Cores DH-4	6.94 ± .14 (11) ^d							
DH-5	6.92 ± .10 (6) ^e							
Averages					.955		.964	1.014
RMSD					.044		.054	± .023
Overall average					<u>.967</u>			
Average RMSD					0.046			

^fBest USGS average values (normalized to 100% dry weight) from a published 1973 paper⁴ are: Pomona, 10.82%; Umatilla, 6.24%; Elephant Mountain 8.50%.

^gEntries after ± signs are root-mean-square deviations.

^hRevised ARHCO values are 8.56 ± .21%.

ⁱValues in parentheses are numbers of samples in groups.

The LBL and U.S.G.S. values agree well, and the ARHCO values are 3.3% lower. The RMSD of the ratios (ARHCO/other)[†] is 4.7% and this probably reflects a variation in calibration.

The Elephant Mountain ARHCO values seem to be somewhat high. This is particularly evident as one value of 12.0% was excluded. One cannot definitely state these values are wrong, however, as a measurement of the CaO content in BCR-1 samples (7.0%) taken at about the same time as the Elephant Mountain samples, show no evidence of any error. The revised ARHCO Elephant Mountain values however, are 5% lower and the resulting ARHCO/others ratio is more consistent with other flow types.

MgO by AA

Summary:

Precision 5.6%, calibration variations (some exceptions) $\leq 2.7\%$
ARHCO/others = 1.11

Six chemical groups, comprised of 101 rocks, had an average RMSD of 5.6%. As shown in Table XII, nearly all of the ARHCO values are high by about a factor of 1.11. A possible, but not certain, exception are the core samples A4117 - A4127. These samples appear very similar to BCR-1 in trace elements but differ slightly in some of the major elements. In the analyses of BCR-1 made by the analytical laboratories working for ARHCO, the MgO abundance, $3.73 \pm .14\%$ for 20 samples measured between 12-09-69 and 5-02-74, was 7.8% higher than the listed value (3.46%). The value for standard diabase, $7.27 \pm .14\%$ for 3 samples measured

Table XII

Comparison of ARHCO MgO data (AA) with data from U.S.G.S. and LBL

Flow	MgO Abundance (%)						
	ARHCO AA	LBL ⁵ XRF	Lit	U.S.G.S. ^{3,a}	ARHCO LBL	ARHCO Lit	ARHCO U.S.G.S.
Pomona		6.81±.48 ^b		6.71±.20			
Type Local.	7.74±.29(5) ^c				1.14		1.15
Cores DDH-3, DH-4, DH-5	7.44±.16(10)				1.09		1.11
Umatilla		2.53±.34		2.62±.10			
Field section	2.89±.38(23)				1.14		1.10
Cores	2.90±.12(5)				1.15		1.11
Elephant Mtn.		3.93±.32		4.17±.22			
Type Local.	4.32±.18 ^d (5)				1.10		1.04
BCR-1 type			3.46				
Cores DH-4	3.39±.08(11)					.98	
DH-5	3.73±.12(6)					1.08	
Average Values					1.124		1.102
RMSD					±.027		± .040

^aBest U.S.G.S. average values (normalized to 100% dry weight) from a published 1973 paper⁴ are: Pomona, 6.82%; Umatilla, 2.69%; Elephant Mountain, 4.22%.

^bEntries after ± signs are root-mean-square deviations.

^cValues in parentheses are numbers of samples measured.

^dRevised values are 3.98 ± .11%.

between 6-20-72 and 5-2-74, was 9.8% higher than the listed value (6.62%). Thus, these values, and the independently arrived at factor of 1.11, are consistent and indicate a general calibration error of about 11%. Such a large error, even though consistent through most of the body of data, could cause difficulty if more accurate values were included. For example, the revised Elephant Mountain MgO abundances which appear in reference 2 would appear to be ~11% different than MgO abundances from the borehole samples corresponding to the Elephant Mountain flow.

Mg is a very useful element for basalt characterization. The ARHCO data is valuable, but better reliability should be achieved.

Ba by AA

This is covered in the emission spectroscopy section.

Evaluation of Neutron Activation Analysis Data

Na and Fe (see atomic absorption section)

Scandium by NAA

Precision < 3.7%, calibration variations < 1.4%, ARHCO/LBL = 0.879

For 77 samples in 9 groups, the average RMSD was 3.7%, and the precision of measurement must be better than this. The average LBL RMSD for 6 groups of Columbia River basalts is 3.8%, most of which is due to source variation. For the six best groups, the average ARHCO RMSD was 3.0% which is probably closer to the precision of measurement.

The ARHCO data are calibrated differently from LBL data, but the ratio is very consistent for the samples in Table XIII. There is a small difference between the literature values for BCR-1 and the LBL values. Care must be taken in incorporating more accurate data (possibly that at Elephant Mountain) with the body of ARHCO data. To be comparable with other work all ARHCO Sc data taken by neutron activation analysis (and studied in this report) should be divided by a factor of 0.879. Sc is a useful element in basalt characterization and the ARHCO data is valuable.

Cobalt by NAA

Precision < 4.9%, calibration variations < 1.2%, ARHCO/LBL = 0.922

For 77 samples in 9 groups the average RMSD was 4.9%, and the precision of measurements must be better than this. For the five best groups comprising 35 samples, the average RMSD was 3.1% which is probably closer to the precision of measurement. Source variations in six LBL Columbia River basalt groups average 5.4%, slightly larger than the ARHCO variations.

Table XIII

Comparison of ARHCO Scandium (Sc) data (NAA) with LBL data

Flow	Sc abundances (ppm)		Lit ⁶	LBL/ARHCO	Lit/ARHCO
	ARHCO NAA	LBL ⁵ NAA			
Pomona		37.9±0.7			
Type local.	33.0±0.7(5) ^a			1.148	
Cores DDH-3, DH-4, OH-5	33.1±1.1(10)			1.145	
Umatilla		28.0±0.9 ^b			
Type local.	25.1±1.6(15)			1.116	
Cores	25.0±1.2(7)			1.120	
BCR-1 type		34.4±0.4	33		
Cores DH-4	30.0±1.0(5)			1.147	1.100
DH-5	29.9±1.0(3)			1.151	1.104
		Averages		1.138	1.102
		RMSD		0.016	

^aValues in parentheses are number of samples measured.

^bEntries after ± signs are root-mean-square deviations.

The ARHCO data is calibrated differently from LBL but the ratio is very consistent for all of the samples shown in Table XIV. The LBL and literature values are essentially identical. To be comparable with other work the ARHCO Co data taken by neutron activation analysis should be divided by factor of 0.922. Care must be taken in incorporating more accurate data with the body of ARHCO values because of the large values of ARHCO/others. Co is somewhat useful for basalt characterization and the ARHCO data is of good quality.

Europium by NAA

Precision < 8.4% or < .19 ppm, calibration variations < 3.6%, ARHCO/LBL = 0.901

For 77 samples in 9 groups the average RMSD was 8.4%. The RMSD expressed in ppm did not change much for the different groups and averaged 0.19 ppm. For the seven best groups the RMSD was 0.16 ppm, and this is probably close to the precision. For 6 groups of Columbia River basalts the average LBL RMSD is 0.14 ppm, ~5.9%, and most of this is due to the counting uncertainties. Some (not many) of the Eu values in the ARHCO core samples look anomolous.

As shown in Table XV the ARHCO data is calibrated differently from the LBL data, and the LBL data for BCR-1 is calibrated slightly differently (3%) from the literature value. There is a variation in the ARHCO calibration of 3.6%. To be comparable with other work all ARHCO Eu data taken by neutron activation analysis should be divided by a factor of 0.901. Care must be taken in incorporating more accurate data into the ARHCO body of values. Eu is a useful element for basalt characterization, but should be measured with higher precision than in this work.

Table XIV

Comparison of ARHCO Colbalt (Co) data (NAA) with LBL data

Flow	Co abundances (ppm)		Lit ⁶	LBL/ARHCO	Lit/ARHCO
	ARHCO NAA	LBL ⁵ NAA			
Pomona		45.2±2.6			
Type local	41.6±1.3 ^a			1.087	
Cores DDH-3 (DH-4,DH-5)	41.9±1.2			1.079	
Umatilla		28.6±2.9			
Type local	25.9±2.1			1.104	
Cores	26.1±1.9			1.096	
BCR-1		37.6±0.5	38		
Cores DH-4	35.0±1.0			1.074	1.086
DH-5	35.1±1.1			1.071	1.083
Averages				1.085	1.084
RMSD				0.013	

^aEntries after ± signs are root-mean-square deviations.

Table XV

Comparison of ARHCO Europium (Eu) data (NAA) with LBL data

Flow	Eu abundances (ppm)		Lit ⁶	LBL/ARHCO	Lit/ARHCO
	ARHCO NAA	LBL ⁵ NAA			
Pomona		1.63±0.11 ^a			
Type local.	1.54±0.22			1.058	
Cores DDH-3, DH-4, DH-5	1.44±0.08			1.132	
Umatilla		4.62±0.24			
Type local.	4.19±0.31			1.103	
Cores	4.24±0.20			1.090	
BCR-1		2.00±0.06	1.94		
Cores DH-4	1.82±0.08			1.099	1.066
DH-5	1.70±0.20			1.176	1.142
Averages				1.110	
RMSD				0.040	

^aEntries after ± signs are root-mean-square deviations.

Chromium by NAA

Precision is the larger of 5.4% or 3.4 ppm, calibration variations were not determined, ARHCO/LBL = 0.953, ARHCO/literature ~ 1.063

Chromium is very abundant in some ultramafic materials and small impurities of these can cause large percentage changes in the chromium abundance in low-chromium lavas. Eleven groups of samples in the A1000 - A5000 series were evaluated. Five of these, with Cr abundances ranging from 85 to 175 ppm, had an average RMSD of 5.4%. The other six, which ranged from 0 to 45 ppm, had an average RMSD of 3.4 ppm. The ppm variation (which is not so sensitive to abundance) is more significant for low-chromium lavas than the percentage variation. The precision of the measurements is then better than 5.4% or 3.4 ppm whichever is larger.

Comparisons with other data are difficult because of the low abundance of Cr. Pomona material has been analyzed at LBL, and the LBL and ARHCO results agree within 5% as shown in Table XVI. On other samples with larger Cr abundances, LBL obtained values 11.6% higher than literature values for two U.S.G.S. standard rocks (PCC-1 and DTS-1). It appears then that the ARHCO results give Cr values 6.3% higher than measurements calibrated with literature values for U.S.G.S. standard rocks. As the latter are averages and not recommended values and as the cross comparisons are so meager, no changes are recommended in the ARHCO numbers at this time.

The variation in Cr reported for the Umatilla flow range from 12 ± 1 ppm (A1283) to <1 (A1254). Although it is possible that measurement

Table XVI

Comparison of ARHCO chromium (Cr) data (NAA) with LBL data

Flow	Cr abundances (ppm)		Lit ⁶	LBL/ARHCO	LBL/Lit
	ARHCO NAA	LBL ⁵ NAA			
Pomona		108±6			
Type local.	103.0±2.2 (5) ^a			1.049	
Cores	102.9±7.7 (10)			1.050	
Field section ^b	107.6±4.6 (9)			1.004	
Umatilla		3.3±3.1			
Field section	8.4±3.5				
Cores	7.3±5.9				
BCR-1		12±3	17.6		
Cores DH-4	26±11				
DH-5	26±9				
DTS-1		4457±89 (7)	4000		1.114
PCC-1		3052±9 (3)	2730		1.118

^aValues in parentheses are numbers of samples measured

^bGroup comprises samples: A1241 - A1247, A1257, A1282.

errors may be responsible for the variation, impurities may also account for some of the variation as mentioned before. Cr is an extremely useful element in basalt characterization. For the data under discussion either 5.4% or 3.4 ppm, whichever is larger, should be used as the minimum RMSD that can be expected for a group. The ARHCO data in Cr taken by NAA appears to be well-measured for type locality samples and many core samples.

Lanthanum and Samarium by NAA

Lanthanum

Precision < 4.1%, calibration variations = 10% (unmodified), possibly < 4.8% after modification; ARHCO/LBL = 1.15 for A1100 and A1200 series. ARHCO/LBL = 0.95 for A2000, A4000, and A5000 series.

Samarium

Precision < 2.8%, calibration variations, 7.1% (unmodified), possibly < 3.3% after modification; ARHCO/LBL = 0.91 for A1100 and A1200 series. ARHCO/LBL = 1.05 for A2000, A4000, and A5000 series.

Five type locality samples of Pomona basalt give abundances for Sc, Cr, Co, and Eu which are nearly identical with the abundances for the same elements in 10 core samples from holes DDH-3, DH-4, and DH-5. The La and Sm, however, show respective variations of 22% and 15% in opposite directions. This suggests something was wrong in the La and Sm measurements. Tatman's¹ compilation of ARHCO data shows different values of La and Sm abundances in the core samples than are in the Lithology Logs.² It seems likely Tatman was using different data than was available for this work. Tatman's abundances for Sc, Cr, Co, and usually Eu, on the other hand, are the same as in the Lithology Logs (reference 2, Vol II, Appendix C).

It is probable there are large calibration variations in the La and Sm data. One can compensate for these variations to some extent for some of the data by using different calibration factors as shown in the Tables XVII and XVIII. These should be valid for the samples encompassed by the ranges shown in the Tables.

The precision of the measurements, 2.8% for Sm and 4.1% for La is good. In Table XIX is an example of what the ARHCO data would have looked like if all measurements were well calibrated. Calibration factors were developed for each element, and the factor for a given element (core measurement) included the ratio of the abundance of that element in the Pomona flow as measured by ARHCO to the abundance as measured at LBL.

Also included in the calibration factors were the ratios of LBL trace element measurements on the U.S.G.S. Standard Rock, BCR-1 to the literature values.⁶ Thus, the factors, shown in Table XIX, serve to calibrate the ARHCO borehole measurements against U.S.G.S. standard rocks. The calibration factors were applied to data from 5 DH-4 borehole samples for which trace element analyses were available, and whose major element abundances were consistent with those of BCR-1 Standard Rock. These samples were part of a group of 11 collected from a depth of 2700 feet to 3840 feet. As can be seen in Table XIX, the agreement is excellent, within 1% on the average for the 5 elements.

Table XVII

Comparison of ARHCO lanthanum (La) data (NAA) with LBL data.

Flow	La abundance (ppm)		ARHCO Type / Loc / LBL		ARHCO Cores / LBL	
	ARHCO NAA	LBL ⁵ NAA				
Pomona		18.1±1.1 ^j (18)				
Type local. ^a	21.4±1.1(5) ^m			1.18±0.03 ^k		
Umatilla		46.7±1.4 (5)				
Field section ^b	52.33±2.35(15)			1.12±0.02		
Pomona						
DDH-3 ^c	17.0±0.8(4)				0.94±0.03 ^k	
DH-4 ^d	17.0±1.0(3)				0.94±0.04	
DH-5 ^e	18.0±1.0(3)				0.99±0.04	
Umatilla						
DDH-3 ^f	40.7±1.0(7)				0.87±0.01	
BCR-1 type		25.9±0.8(11)				
DH-4 ^g	25.4±0.55(5)				0.98±0.01	
DH-5 ^h	25.7±0.6 (3)				0.99±0.02	
Average RMSD 4.1%		Averages	1.15		0.952	
		RMSD	0.043		0.046	
		Overall:				
		Average		1.00		
		RMSD		0.10		

^aA1266-70.^bSillusi Butte, A1237-9, A1283, Spukshowki Canyon, A1254-6, Blair Point
A1175-6, Yellepit, A1235, A1261-5.^cA2011-4.^dA4005,7,9.^eA5007,9,11.^fA2022, A2024-9.^gA4119, A4121, A4122, A4124, A4126.^hA5135, A5137, A5139.^jRoot-mean-square deviation = σ .

$$^k \text{Deviations in the mean} = \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}} \times \text{mean}.$$

^mValues in parentheses are numbers
of samples measured.

Table XVIII

Comparison of ARHCO samarium (Sm) data (NAA) with LBL data.

Flow	Sm abundance (ppm)		ARHCO Type / Loc / LBL	ARHCO CORES / LBL
	ARHCO NAA	LBL NAA		
Pomona		4.76 ± 0.16		
Type local.	4.30 ± 0.23		0.903 ± 0.023	
Umatilla		10.18 ± 0.40		
Field section	9.35 ± 0.28		0.918 ± 0.018	
Pomona				
DDH-3	5.20 ± 0.16			1.092 ± 0.019
DH-4	4.83 ± 0.06			1.015 ± 0.011
DH-5	4.83 ± 0.15			1.015 ± 0.020
Umatilla				
DDH-3	11.10 ± 0.10			1.090 ± 0.020
BCR-1 type		6.39 ± 0.04		
DH-4	6.64 ± 0.11			1.039 ± 0.008
DH-5	6.80 ± 0.26			1.064 ± 0.024
<hr/>				
Average RMSD	2.8%	Averages	0.911	1.053
		RMSD	0.011	.035
			<hr/>	
Overall			1.017	
Average				
RMSD			0.072	

^aGroups and terms have the same meaning as in Table XVII.

Table XIX

Calibration of ARHCO trace element data in BCR-1 type material.

	La	Sm	Sc	Co	Eu
ARHCO normalized averages ^a	26.7±0.6	6.57±0.11	33.0±1.1	38.3±1.1	1.94±0.09
Literature values ⁶	26	6.6	33	38	1.94
Calibration factors	1.054	1.023	1.055	1.105	1.036

^aAverages and RMSD for data from core samples A4119, -21, -22, -24 and -26.

Sm and La are useful elements for characterization but the calibration variations exhibited in the ARHCO data are unacceptable. The data outside the sample ranges shown in Tables XVII and XVIII may have unknown errors due to calibration variations.

Th by NAA

Thorium was measured both by NAA and by gamma-ray measurements on ^{228}Th daughter products which are part of the ^{232}Th decay chain. The Th abundances expressed in parts-per-million (ppm) equal $\mu\text{Ci } ^{228}\text{Th}/(10^3 \text{ kgm})$ divided by 0.109. In the Al000 series below Al300, Th values determined by NAA vary by factors ranging from 0.75 to 3 from those measured by γ spectroscopy. On measurements of Umatilla material, Th values obtained by γ spectroscopy agreed with NAA values measured at LBL whereas the ARHCO NAA values were lower by almost a factor of 3. Therefore the γ spectroscopy results are probably correct and the NAA results are probably in error. The precision of the γ spectroscopy measurements, however, is too poor to be very useful.

Th is a useful element for characterization of basalts but in the present work the Th values are not reliable enough.

Evaluation of Emission Spectroscopy (ES) data
on ARHCO basalts

The samples used in this evaluation are shown on the chart below.

Information supplied by ARHCO as data
sheets for the following sites.

	<u>Sample Numbers</u>
Priest Rapids	PR -01, -02, -21 → 24, -04, -05, -08 → 13, -27A, -30
Sillusi Butte	A1211 → A1217, A1237 → A1245
Rush Canyon	A1219 → A1221, A1247
Spukshowki Canyon	A1248 → A1257
Blair Point	A1175 → A1181, -83, -84 A1186 → A1188, A1194 → A1201
Yellepit-Mound, Pond	A1202 → A1210, A1231 → A1236
Selah Butte	A1286 - A1300

Information supplied by ARHCO in chart form for the following type locality groups.

Ice Harbor	A1423 - A1427
Ward Gap	A1276 - A1278
Elephant Mountain	A1393 - A1397
Pomona	A1266 → A1270
Huntzinger	A1301 → A1305

Ba by AA and ES

Summary:

AA: Precision $\leq 11\%$, Calibration variations ~ 43 ppm

ARHCO minus others = 182 ppm

For 14 groups totaling 122 samples, the average RMSD in the AA measurements was 10.6% and this is taken as an upper limit to the precision for AA.

For 5 groups, with Ba of 500-1000 ppm both ES and AA measurements were made, and the average of the ES RMSD was 45% compared to 12.2% for AA measurements on the same samples. Thus, the precision of these ES measurements is very poor and the data are almost useless. When compared with LBL values as shown in Table XX ARHCO AA values average 182 ppm higher than LBL values, and it appears as if the 182 ppm was a threshold for the AA measurements. The RMSD in the average is 43 ppm and this is taken as the calibration variation. Ba is a somewhat useful element for basalt classification and the ARHCO AA data is valuable.

Sc by ES

The ES data is sometimes high by over a factor of 3 relative to the NAA results and sometimes low by nearly the same factor. For 10 groups the average RMSD of the Sc is 59% for ES and for 4 groups of NAA measurements it was 3.3%. For the same 2 groups of rocks the ES average RMSD was 50% and the NAA was 6.0%. The average NAA values for 10 Umatilla type rocks are a factor of 1.12 smaller than the LBL values. ES Sc data is neither precise nor well-calibrated and should not be used.

TABLE XX

Comparison of ARHCO Ba data
(AA and ES)
with LBL and Literature Values

FLOW	Abundances of Ba in ppm				Difference between Column II and Column IV
	ARHCO AA	ARHCO ES	LBL ⁵ NAA	Lit. ⁶	
Pomona			297 ± 108 (18)		
Type locality	497 ± 102 ^b (5) ^a				200
Field sections	537 ± 113 (15)	268 ± 14 (13)			240
Cores DDH-3,	420 ± 43 (10)				123
Elephant Mountain					
Type locality	771 ± 57 (5)		555 ± 70 (12)		216
Umatilla					
Type locality	3617 ± 326 (24)	>2500 (12)			
Field sections		2500 (2) 1617 ± 76 (3)	3420 ± 217 (5)		197
BCR-1 type			679 ± 19 (11)	675	
DH-4					
A4117 - A4127	830 ± 59				151
DH-5					
A5135 - A5140	821 ± 78				142
			Average		182
			RMSD		43

^aValues in parentheses are number of samples measured.

^bEntries after ± sign are root-mean-square deviations.

Cr by ES

Blair Point and Yellepit - all Blair Point ES data look only qualitative or semiquantitative and should be ignored; Cr sensitivity is 50 ppm and values are given in blocks of 50 ppm. The values cannot be relied on to better than a factor of 4. The Yellepit data is the same type as that at Blair Point except a higher quality measurement was made on A1234 and possibly A1235 and A1236.

Ice Harbor, Ward Gap, Elephant Mountain, Pomona, Huntzinger, Priest Rapids, Sillusi, Butte, Rush Canyon - The ES data represents a somewhat better type of measurement than that at Blair Point. Many ES values deviate about a factor of two from the NAA results. For the Pomona type material, the Cr NAA average for 5 samples is 5% lower than the LBL value and should be considered much better than the ES results. These ES data should not be used for characterization of the basalts as they are poorly calibrated and not precise.

Samples K5001 → K5009 - These appear to be the best Cr measurements by ES and appear comparable to NAA. Six values by ES agree with the NAA measurements within 2% on the average and the root-mean-square deviation is 12%.

Ni by ES

The ES nickel values for samples A1175 - A1210 are not useful. They are comparable to the Cr data. For samples A1211 - A1427, the data are of better quality. The RMSD for 9 samples from Sillusi Butte is 14%. Four (Sm, Cr, Co, Sc) of the other trace elements have an average RMSD of only 3.9% and it is likely that the 14% Ni value represents the

measurement uncertainty. The data from Selah Butte (A1296 → A1300) look comparable as the average RMSD for 3 groups is 14%. One of the six groups measured at LBL (Umatilla) is represented in this series but the value, 35 ± 23 , is not good enough to check the ES value of <10 .

The data for samples in the A1200, A1300, A1400, and Priest Rapid series on the chart are of poorer quality. The Priest Rapids data on the chart are different from that on the sheets for Ni and particularly Cr. The Ni data on the chart seem to have at most limited usefulness. Data of the quality given in the sheets for samples A1211 - A1300 might be of some use but there is not enough information to evaluate them properly.

Rb by ES

Rb often follows K in its behavior. If K is homogeneous in a chemical group and other well-measured trace elements are also homogeneous, the Rb should be homogeneous.

Blair Point and most of Yellepit - The ES data for samples A1175 - A1210 are very bad.

Priest Rapids - The RMSD of Rb in the 4 Priest Rapids groups averages 63%, which is much worse than that of K_2O , which averages 12%. As the other trace elements are fairly homogeneous, these Rb data are not useful for characterization.

Sillusi Butte, Rush Canyon, Spukshowki Canyon, Yellepit (after A1234) - for samples A1211-17, A1219-21, and A1235-A1256 the

average RMSD is 35% for Rb (for four groups) and 9.0% for K_2O . The 35% RMSD is too large for most characterization work.

Selah Butte - For samples A1286-A1300 the average RMSD is 38% for 4 groups (15 samples) while the K_2O variation is only 5.7%. If we exclude one Rb measurement (A1288) the 38% drops to 21%. The 21% still is rather large for characterization work.

The ES rubidium measurements generally would have only limited usefulness for characterization purposes.

Zr by ES^{7,8}

Zirconium chemically follows hafnium in its behavior. If the Hf is homogeneous and the other trace elements are homogeneous, Zr should probably be homogeneous.

Blair Point - These ES data are nearly useless as all values are either 200 or 500 ppm.

Yellepit Pond - A1202-A1210 data are like the Blair Point data. A1234-5 is perhaps better but possible typographical errors cause uncertainties.^{7,8}

Sillusi Butte, Rush Canyon, Spukshowki Canyon, Yellepit Pond A1235, Selah Butte - Samples A1211-17, A1219-21, A1234-57^{7,8} and A1289-95 fall into 4 groups for which Zr has an average RMSD of 26%. Hf as measured by NAA for three of the groups has an average RMSD of 19%. Neither of these is very good. About 10% of the samples seem to have

measuring errors for Zr of a factor of two or more. With this uncertainty and the large RMSD, the ES Zr data seem of rather limited usefulness for characterization purposes. Better measurements, on the other hand, would make Zr a very useful element.

Zn by ES

Priest Rapids - There are variations of an order of magnitude. If the two worst cases are removed (PR-22 and PR-13) the average RMSD is 41% for four Priest Rapids groups.

Sillusi Butte etc. (as given for Zr) - Samples A1211-17, A1219-21, A1234-45, A1247-57, A1280-A1300 were divided into four chemical groups; Umatilla type, a Sillusi Butte type, a Spukshowki Canyon type and a Selah Butte type. The average RMSD for the 4 groups was 49%. The RMSD for the Umatilla group was 41% compared to 12% for an Umatilla group measured by LBL.

These ES Zn data are nearly useless for characterization.

V by ES^{7,8}

For the eight groups discussed under Zn, V has an average RMSD of 16%. This is after excluding two measurements. The ES abundance for the Umatilla group is 299 ppm with a RMSD of 67 ppm, after excluding the same two bad values for A1236 and A1255. The LBL value for an Umatilla group is 181 ± 38 ppm, and LBL measurements of V give values 13% higher than literature values for BCR-1. Therefore the ES calibration gives V values which are probably over 50% too high.

These V data are of questionable usefulness.

Sn by ES

For the same 8 groups discussed under Zr and averaged RMSD was 31%. With such a large variation, these Sn ES data are not useful for characterization purposes.

PART II - Type Locality Statistical Characterizations

Introduction

In determining by chemical comparisons if a rock is part of a given volcanic flow, two criteria must generally be met. The first is that the given flow must be sufficiently homogeneous in certain of its chemical abundances that a characteristic pattern can be established in which there are relatively small variations in those abundances throughout the flow. The other criterion is that all other possible flows or sources of the rock must have a chemical abundance pattern which is distinguishable from the given flow. This pattern involves not only the major elements but also the trace elements with abundances in the parts-per-million range and lower. It is possible that some flows may be so nearly unique in the abundance of one or more elements that only the second criterion is of importance.

In determining the chemical variability of a flow it is desirable to have samples which encompass the geographic region of interest. In addition enough samples should be measured so that a statistically significant variation (expressed in this work as a root-mean-square deviation) can be obtained for each element of interest.

In this section the relative merit for characterization purposes of different elements as measured by ARHCO is evaluated. The chemical data on the type locality groups proposed by ARHCO as references for the Plateau basalts are compared statistically and the degree to which these groups can be chemically distinguished from each other is determined. The applicability of this treatment to identification of flows is presented in Part III.

PART II

Conclusions

The most important elements for basalt characterization as measured by ARHCO were Cr, a trace element measured by NAA, and secondly Fe, a major element, as measured by AA. The next most important elements were Sc, Eu, K, Mg, and Ti, followed closely by Ba, Ca, Co, Al, and Na. The least useful was Si. The mean abundances and the root-mean-square deviations for these 13 elements were calculated for 19 type locality, field section, or borehole groups proposed by ARHCO plus one group arbitrarily formed from field section samples. One sample from each group was compared statistically with everyone of the 20 groups to determine the ambiguities in assignment by chemical methods. For these samples a single number represented the extent of the agreement for each flow for all 13 elements. There was no ambiguity between the Ice Harbor I, Ice Harbor II, Ward Gap, Elephant Mountain, Pomona, Gable Mountain, Huntzinger and Priest Rapids IV groups and any of the other groups considered. There was some ambiguity between the Priest Rapids II, III, and IV groups, between Roza, Sentinel Gap, Gingko, and Sand Hollow groups, and between the Museum and Rocky Coulee groups. It is likely that reliable measurements made on more trace elements would resolve many of these ambiguities. Extension of such measurements to lower Yakima basalts as found in the boreholes might distinguish between these as well.

PART II

Recommendations

ARHCO should obtain reliable and accurate measurements by neutron activation for a larger number of trace elements in its type locality groups of the Priest Rapids I, II, III, Roza, Sentinel Gap, Sand Hollow, Ginkgo, Museum, and Rocky Coulee flows. These elements could include Cr, Sc, La, Sm, Eu, Yb, Ta, Hf, Co, Th, U and Ba. Fe and perhaps Ti could also be included in this group and be measured in the same analysis. Cs, Ni, and Rb can also be measured in these analyses but the precision is poorer than for the other elements. A reanalysis of the major elements particularly Mg and K would be desirable. These could be measured by soft x-ray fluorescence which would detect other major elements as well. Probably about 5 rocks per flow would be the minimum number necessary if both NAA and soft XRF measurements (for 20 elements) are used, although a large number is desirable. These measurements should determine the extent to which these middle Yakima flows can be distinguished chemically.

The ARHCO data could serve as a base for a comprehensive tabulation of chemical data taken on Columbia River Plateau basalts. To combine measurements usefully it is necessary that they be of comparable quality with respect to accuracy. The ARHCO data could be combined with U.S.G.S. and LBL data and that of others if it were recalibrated. A considerable amount of the ARHCO type locality and field section data was sufficiently precise for characterization purposes, but had calibration problems. If one sample in each type locality group determined by

ARHCO was remeasured by carefully calibrated techniques, these values could represent the group profile. Then the root-mean-square deviations could be taken directly from the existing data on all members of the group. This technique could also be applied to the field section samples. These averages and associated root-mean-square deviations can be combined with the work of others to give overall averages and root-mean-square deviations, which would be applicable to any characterization work on the basalts.

A study of the elements measured by different methods could be made by ARHCO to determine how effective they are for basalt characterization. Some of the elements well determined by hard x-ray fluorescence are Rb, Sr, Zr, Nb, and Y. Many other elements can be measured by this technique and Ni in particular might be quite useful. Phosphorous may also be a useful element if well measured, e.g., by wet chemical methods or alpha particle activation analysis.

Some flow members might be separable into their respective flows from the chemical data if more extensive trace element measurements were made on type locality samples representing the individual flows. Examples would be careful measurements on the Ward Gap flow to insure distinction from the Elephant Mountain flow. Although these were distinguishable from the ARHCO data, that may have been due to differences in measurement calibration. The two Sillusi-Umatilla flows discussed in reference 2, might also be distinguishable by this method. The measurements should probably include nearly all of the trace and minor elements discussed in this section as well as the major elements.

PART II

Discussion

A summary of the precision of measurements (or limits) and calibration variations (or limits) for the various elements studied in Part I is shown in Table XXI. The relative value for characterization purposes of the elements measured by ARHCO and found useful in Part I is shown in Table XXII. For each element (except Ba) the limits of precision and the calibration variation shown in Table XXI were combined by taking the square root of the mean of the squares, which gave an overall percentage uncertainty. This was multiplied by the average abundance of the element in the range considered to give an uncertainty in the ARHCO data in % or ppm. The range of variation for each element, shown on page 43 of reference 2 (Vol. I), from the flow with the second highest to the second lowest abundances was divided by this uncertainty and results in the figure of merit shown in Table XXII. The Ba uncertainty was calculated by combining the 42 ppm calibration variation with 11% of the average abundance in the range considered.

As can be seen in Table XXII Cr is found to be the most useful element. Fe is the second most useful although better measurements on Eu, Mg, Ti, and K and possibly Sc and Ba might make them comparable. Si is the least useful element in the existing data but more reliable values might improve its usefulness considerably.

Table XXIII shows the mean abundances and root-mean-square deviations of 13 elements for 19 type locality groups of ARHCO basalts

Table XXI
Summary of evaluation of ARHCO chemical data

	Precision of measurement	Calibration Variation	ARHCO/others
<u>AA</u>			
K ₂ O	≤ 4%	≤ 6%	1.02
Na ₂ O	< 3%	≤ 2.2%	1.01
SiO ₂	≤ 2.2%	2.7%	1.03
TiO ₂	≤ 3.8% (≤ 0.081)	8%	0.97
FeO	≤ 2%	< 2%	1.00
Al ₂ O ₃	< 3%	< 2.2%	0.96
CaO	< 3.3%	5%	0.97
MgO	5.6%	< 2.7%	1.11
Ba	< 11%	~ 42 ppm	~ 180 ppm
<u>NAA</u>			
Na	< 3%	≤ 2.2%	.98
Fe	~ 4%	< 2%	.96
Sc	< 3.7%	< 1.4%	.88
Co	< 4.9%	< 1.2%	.92
Eu	< 8.4% or <.19 ppm	< 3.6%	.90
Cr	< 5.4% or <3.4 ppm	-	~ 1.06
La	< 4.1%	10%	1.15 → .95
Sm	< 2.8%	7.1%	.91 → 1.05
Th	- - - - -	Very Poor-	- - - - -

^aStandard deviation expressed as percent of the mean except for TiO₂ which is also expressed in absolute percent.

^bStandard deviation expressed as percent of the mean except for Ba which is expressed in absolute amounts (parts-per-million).

Table XXII

Usefulness of various elements as measured by ARHCO for basalt chacterization

Oxide or element measured by ARHCO	Method	Figure of merit for Characterization
SiO ₂	AA	2.7
Na ₂ O	AA	3.9
Al ₂ O ₃	AA	4.4
Co	NAA	5.2
CaO	AA	5.6
Ba	AA	6.5
TiO ₂	AA	7.7
MgO	AA	8.4
K ₂ O	AA	8.9
Eu	NAA	10.1
Sc	NAA	10.5
FeO	AA	12.8
Cr	NAA	34

shown on page 43 of ARH-ST-137, Vol. I. In addition, a group composed of samples from Spukshowki Canyon, Blair Point, Yellepit Pond and Selah Butte is also shown. The parent rocks occurred under the Umatilla flow except at Selah Butte where the Umatilla flow did not appear. The groups are in the same order as shown in reference 2 except for the Umatilla and Wahluke groups. Table XXIV shows the concordance of groups and ARHCO samples

For nearly all groups the root-mean-square deviation was calculated with the equation

$$(RMSD)_{ik} = \sqrt{\frac{\sum_{j=1}^n (x_{ij} - \bar{x}_{ik})^2}{n - 1}}$$

where x_{ij} is the abundance of element i in rock j , $\bar{x}_{ik}$ is the mean value of the abundance of element i for the group k and n is the number of group members. In each calculation the resulting $(RMSD)_{ik}$ were compared with minimum values deduced from Part I, and the larger was tabulated. The minimum RMSD values used for Table XXIII were the following: SiO_2 3.5%, Al_2O_3 3.6%, FeO 2.8%, MgO 7.2%, CaO 5.4%, Na_2O 3.9%, K_2O 8.1%, TiO_2 8.9%, Sc 4.0%, Eu 9.1%, Co 3.0%, Ba 9%, Cr 10%. The Ba and Cr values are estimates determined from Part I.

The $SiO_2 +$ values are the abundances of $SiO_2 + MnO + P_2O_5 + SrO + BaO +$ trace elements. These values were found in Part I to be somewhat more reliable than the SiO_2 data and could be determined from the other major element and volatility measurements.

TABLE XXIII

	ICE HARBOR II	ICE HARBOR I	WARD GAP	ELEPHANT MOUNTAIN
Major elements (in percent)				
$\text{SiO}_2^+ \text{ a}$	49.1 ± 1.7	48.4 ± 1.7	51.1 ± 1.8	50.0 ± 1.8
Al_2O_3	$11.3 \pm .4$	$12.7 \pm .5$	$12.8 \pm .5$	$12.5 \pm .4$
FeO	$16.3 \pm .5$	$13.6 \pm .4$	$14.6 \pm .6$	$13.8 \pm .4$
MgO	$4.6 \pm .3$	$6.9 \pm .5$	$4.6 \pm .3$	$4.3 \pm .3$
CaO	$9.0 \pm .5$	$10.5 \pm .6$	$8.2 \pm .4$	9.5 ± 1.4
Na_2O	$2.53 \pm .15$	$2.30 \pm .14$	$2.50 \pm .10$	$2.54 \pm .22$
K_2O	$1.12 \pm .09$	$.75 \pm .07$	$1.13 \pm .09$	$1.26 \pm .10$
TiO_2	$3.4 \pm .3$	$3.1 \pm .3$	$2.80 \pm .25$	$3.6 \pm .3$
Trace and minor elements (ppm)				
Sc	39.0 ± 1.6	42.0 ± 1.7	30.0 ± 1.7	33.0 ± 1.3
Eu	$5.4 \pm .5$	$3.3 \pm .3$	$2.83 \pm .26$	$2.90 \pm .26$
Co	39.0 ± 2.0	45.0 ± 2.2	41.7 ± 2.1	48.0 ± 2.4
Ba	2145 ± 112	837 ± 75	614 ± 55	771 ± 69
Cr	40 ± 4	62 ± 6	23.0 ± 2.3	27.0 ± 2.7
Ave. 13 elements	6.4%	6.5%	6.4%	7.2%
RMSD Best 12 elements	6.0%	6.2%	6.1%	6.6%

TABLE XXIII (cont.)

		Pomona	Rosa	Sentinel Gap	Sand Hollow
Major elements (in percent)					
SiO ₂ ⁺		50.7 ± 1.8	51.8 ± 1.8	52.9 ± 1.9	52.8 ± 1.8
Al ₂ O ₃		14.4 ± .5	13.1 ± .5	12.8 ± .5	12.6 ± .5
FeO		10.8 ± .3	14.3 ± .4	14.4 ± .4	13.7 ± .4
MgO		7.8 ± .6	4.9 ± .4	4.5 ± .3	4.8 ± .3
CaO		10.0 ± .5	8.0 ± .4	7.5 ± .4	8.0 ± .4
Na ₂ O		2.42 ± .09	2.77 ± .11	2.78 ± .11	2.85 ± .11
K ₂ O		.68 ± .11	1.20 ± .10	1.26 ± .10	.97 ± .08
TiO ₂		1.58 ± .14	2.53 ± .23	2.62 ± .23	2.57 ± .23
Trace and minor elements (ppm)					
Sc		33.0 ± 1.3	34.3 ± 1.4	34.8 ± 1.4	36.0 ± 1.4
Eu		1.54 ± .22	2.40 ± .22	2.18 ± .20	2.18 ± .20
Co		41.6 ± 2.1	37.7 ± 2.3	38.6 ± 1.9	39.3 ± 2.0
Ba		489 ± 101	678 ± 61	727 ± 65	688 ± 110
Cr		103 ± 10	43 ± 15	25.2 ± 4.3	50 ± 6
Ave.	13 elements	8.1%	8.2%	6.7%	6.9%
	Best				
RMSD	12 elements	7.0%	6.0%	5.9%	6.2%

TABLE XXIII (cont.)

		Gingko	Museum	Rocky Coulee	Gable Mountain
Major elements (in percent)					
SiO ₂ ⁺		51.1 ± 1.8	54.0 ± 1.9	53.5 ± 1.9	52.6 ± 1.8
Al ₂ O ₃		12.9 ± .5	13.9 ± 1.5	13.4 ± .5	13.0 ± .5
FeO		14.7 ± .4	10.8 ± .8	10.8 ± .3	13.9 ± .8
MgO		4.4 ± .3	5.0 ± .5	4.9 ± .4	4.1 ± .3
CaO		7.6 ± .4	8.0 ± .4	8.0 ± .4	7.7 ± .5
Na ₂ O		2.74 ± .09	2.80 ± .11	2.82 ± .15	2.67 ± .10
K ₂ O		1.10 ± .16	.95 ± .08	.96 ± .09	1.68 ± .19
TiO ₂		2.62 ± .23	1.65 ± .15	1.70 ± .15	2.58 ± .23
Trace and minor elements (ppm)					
Sc		34.4 ± 1.4	34.0 ± 1.4	33.0 ± 1.3	28.7 ± 2.1
Eu		2.26 ± .21	2.6 ± .15	1.54 ± .14	2.37 ± .22
Co		37.4 ± 1.9	39.0 ± 2.0	34.6 ± 1.7	43.0 ± 2.2
Ba		712 ± 79	686 ± 62	671 ± 60	695 ± 63
Cr		25 ± 7	56 ± 22	48 ± 14	7.5 ± 2.1
Ave.	13 elements	8.5%	9.0%	7.8%	8.5%
RMSD	Best 12 elements	6.5%	6.5%	6.1%	6.8%

TABLE XXIII (cont.)

		Huntzinger	Priest Rapids					
			IV		III		II	
Major elements (in percent)		42.0 ± 1.8	58.9 ± 2.2	50.3 ± 1.8	50.3 ± 1.8			
	SiO ₂ ⁺	42.0 ± 1.8	58.9 ± 2.2	50.3 ± 1.8	50.3 ± 1.8			
	Al ₂ O ₃	15.2 ± .5	12.7 ± .5	12.3 ± .4	12.2 ± .4			
	FeO	10.6 ± .3	14.4 ± .8	15.3 ± .8	14.2 ± .4			
	MgO	6.9 ± .5	6.1 ± .4	4.5 ± .4	4.8 ± .3			
	CaO	8.9 ± .5	8.2 ± .4	7.6 ± .5	8.3 ± 1.0			
	Na ₂ O	2.44 ± .10	2.40 ± .09	2.52 ± .19	2.53 ± .10			
	K ₂ O	1.00 ± .08	.85 ± .07	.94 ± .15	.97 ± .08			
	TiO ₂	1.62 ± .14	2.72 ± .24	2.92 ± .26	2.97 ± .26			
Trace and minor elements (ppm)								
	Sc	27.6 ± 1.1	27.0 ± .15	38.0 ± 1.6	36.7 ± 1.5			
	Eu	1.76 ± .21	2.70 ± .25	2.82 ± .26	2.80 ± .27			
	Co	41.4 ± 2.1	40.0 ± 2.0	39.4 ± 2.0	38.0 ± 1.9			
	Ba	557 ± 50	688 ± 179	612 ± 55	611 ± 55			
	Cr	175 ± 17	86 ± 9	14 ± 4	16 ± 2			
Ave.	13 elements	6.4%	7.8%	8.9%	6.9%			
RMSD	Best 12 elements	6.0%	6.3%	7.3%	6.4%			

TABLE XXIII (cont.)

	Priest Rapids I	Umatilla	Spukshowki Canyon Group	Wahluke
Major elements (in percent)				
$\text{SiO}_2 + ^a$	51.4 ± 1.8	55.3 ± 1.9	51.0 ± 1.8	53.2 ± 1.9
Al_2O_3	12.2 ± .8	13.3 ± .5	13.1 ± .5	13.6 ± .5
FeO	15.0 ± .6	12.4 ± .7	14.3 ± .4	12.2 ± .3
MgO	4.6 ± .4	2.9 ± .4	4.5 ± .3	5.3 ± .4
CaO	7.7 ± .4	5.8 ± .3	7.8 ± .4	8.1 ± .4
Na_2O	2.57 ± .10	3.22 ± .18	2.76 ± .18	2.80 ± .11
K_2O	1.00 ± .17	2.67 ± .22	1.42 ± .21	1.90 ± .15
TiO_2	2.93 ± .26	2.41 ± .21	2.67 ± .24	1.80 ± .16
Trace and minor elements (ppm)				
Sc	38.0 ± 1.5	25.1 ± 1.6	34.0 ± 1.4	25.5 ± 1.0
Eu	2.75 ± .25	4.2 ± .4	2.19 ± .20	2.05 ± .19
Co	39.5 ± 2.0	25.9 ± 2.1	37.5 ± 2.1	37.5 ± 1.9
Ba	650 ± 58	3544 ± 319	690 ± 98	1115 ± 100
Cr	13.5 ± 1.4	8 ± 4	24 ± 4	36 ± 7
Ave. 13 elements	7.3%	9.9%	7.8%	6.9%
RMSD Best 12 elements	6.5%	7.2%	6.1%	5.9%

^a $\text{SiO}_2 + \text{P}_2\text{O}_5 + \text{MnO} + \text{BaO} + \text{SrO} + \text{trace elements}$

TABLE XXIV

ARHCO Basalt Samples Comprising groups
in Table XXIII and Figs. 1-4

1. ICE Harbor II	A-1424 No Sc, Eu, Co or Cr A-1426, A1427
2. ICE Harbor I	A-1425 No Sc, Eu, Co or Cr A-1423
3. Ward Gap	A-1275, A-1277, A-127
4. Elephant Mountain	A-1393 No Sc, Eu, Co or Cr A-1394, A-1395, A-1396, A-1397
5. Pomona	A-1266, A-1267, A-1268, A-1269, A-1270
6. Gable Mountain	A-2017, A-2018, A-2019 No Sc, Eu, Co or Cr A-1037, A-1038, A-1039
7. Huntzinger	A-1301, A-1032, A-1303, A-1304, A-1305
8. Priest Rapids IV	PR-01, PR-02, PR-21, PR-22
9. Priest Rapids III	PR-04, PR-05, PR-08, PR-23, PR-24
10. Priest Rapids II	PR-09, PR-10, PR-11
11. Priest Rapids I	PR-12, PR-13, PR-27A
12. Roza	A-1279, A-1280, A-1281
13. Sentinel Gap	K-5032, K-5033, K-5034, K-5035, K-5036
14. Sand Hollow	K-5001, K-5002, K-5003, K-5005, K-5007, K-5009
15. Gingko	K-5012, K-5014, K-5015, K-5017, K-5020 Na ₂ O value for K-5017 appears erroneous and abundance (2.80%) was derived from NAA measurements.

TABLE XXIV (cont)

16. Museum	K-5010, K-5011
17. Rocky Coulee	K-5025, K-5026, K-5026, K-5028, K-5029
18. Umatilla	A-1237, A-1238, A-1239, A-1283, A-1254 A-1255, A-1256, A-1175, A-1236, A-1235, A-1261, A-1262, A-1263, A-1264, A-1265 No Sc, Eu, Co or Cr A-1214, A-1215, A-1216, A-1217, A-1221, A-1220, A-1219, A-1348, A-1236
19. Group formed principally from Spukshowki Canyon rocks.	A-1177, A-1178, A-1179, A-1179, A-1181, A-1183, A-1253, A-1252, A-1251, A-1250, A-1249, A-1248, A-1204, A-1203, A-1202 A-1234 No Sc, Eu, Co or Cr A-1210, A-1209, A-1208, A-1207, A-1206 A-1205, A-1298, A-1297, A-1296
20. Wahluke	A-4016, A-4017

As seen in Table XXIII the average (by squares) of the root-mean-square deviations of all 13 elements range between 6.4 and 9.0%. If the worst element is discarded then the average RMSD ranges from 5.9 to 6.3%. As these values include measurement errors the flows in the localities sampled may be even more homogeneous. Thus, the first criterion mentioned in the Introduction to this section is satisfied; each flow has a definite chemical composition pattern with a small variation for a certain group of elements.

The next step is to determine if these groups are sufficiently different from each other to make unambiguous assignments of flow origin. One sample was selected from each group and it was usually the first sample in the chart on page 43 of reference 2 (Vol. I) which had measurements of trace elements. The elemental abundances of samples were compared with each group and a root-mean-square index of the agreement (IRMSD) was determined with the following equation.

$$IRMSD_{j,k} = \sqrt{\frac{\sum_{i=1}^m \left(\frac{V_{ij} - \bar{V}_{ik}}{RMSD_{ik}} \right)^2}{m - 1}}$$

where V_{ij} is the abundance of element i in the sample j , $\bar{V}_{ik}$ is the average abundance of element i in the group k , $RMSD_{i,k}$ is the root-mean-square deviation of element i in group k and m is the number of elements used in the calculation. This calculation was made for each value of j and each value of k . Before discussing the values which were obtained a brief discussion of their significance is worthwhile. If sample j is a member of group k , if group k is large enough that $RMSD_{i,k}$ have small errors, and if m is very large, then $IRMSD_{j,k}$ should equal 1. If j is not a member of group k , then $IRMSD_{j,k}$ should be larger than 1.

In a practical situation the number of rocks used in forming a type locality group may be quite small and the uncertainty in the $RMSD_{i,k}$ would be significant, $\sigma(RMSD_{i,k}) \sim RMSD_{i,k} / \sqrt{2(n-1)}$ where n is the number of rocks comprising group k . Erroneously small values of $RMSD_{i,k}$ (because of the small number of samples), could then inflate $IRMSD_{i,k}$ considerably. The use of minimum $RMSD_{i,k}$ to reduce this effect, tends to depress the values of $IRMSD_{j,k}$ even below 1. As an example, if the minimum $RMSD$ were chosen correctly, in groups comprising 26 rocks, $IRMSD$ for group members would be .87 and would be rather insensitive to the number of rocks in the group. The error is $IRMSD$, however, is very sensitive to the number of elements in sample j used in the calculation, and this uncertainty is $\sqrt{m/2} / ((IRMSD * (m - 1)))$.

This factor is pertinent to the number of elements used in the comparison between a sample and a group. In the example given above for 13 elements the uncertainty in IRMSD would be 0.24. As a test, the abundances of 24 samples of the Umatilla group were compared with their group elemental averages and RMSDs in the fashion described above. The average of the 24 values of the IRMSDs was 0.85 and the root-mean-square deviation in the values was .29 which is consistent with theoretical expectations. A cut off of 1.5 on the value of IRMSD will be used in Part III in the comparisons between borehole rocks and reference groups. Only ~1% of the group members would be expected to have an IRMSD as large as 1.5.

The comparisons (IRMSD values) between the individual type locality samples and the various type locality groups are shown in Figures 1-4. A dashed line is placed in each drawing to indicate IRMSD of 0.7. For groups 1 and 2 in Fig. 1 only one trace element analysis was available. Thus, there is zero deviation for each of the trace elements and only the major elements contribute to the IRMSD. These IRMSDs then are anomalously low for the group members. In general for the small number of samples comprising most groups, IRMSD are smaller than 0.85 mentioned earlier. This arises as the minimum RMSD (for each element) used in the calculation contains not only uncertainties due to rock inhomogeneity and instrumental precision errors, which would appear in the small groups, but

Fig. 1. Statistical comparisons of chemical abundances of individual rocks with ARHCO type locality groups.

<u>Rock Designation</u>	<u>Source</u>
A-1424	Ice Harbor II
A-1425	Ice Harbor I
A-1276	Ward Gap
A-1393	Elephant Mountain
A-1266	Pomona
A-2017	Gable Mountain

XBL769-4048

also calibration variations which generally would not appear in such groups. It was necessary to include these in the calculations because measurements on borehole samples discussed in Part III were made at a different time and possibly in different laboratories. There are no ambiguities in assignments in Fig. 1 as in each case the rock agrees well with one group, i.e., $\text{RMSD} < 1$, and all other groups have $\text{IRMSD} \geq 1.5$. It should be pointed out that this is an analysis of groups as measured by ARHCO and not of flows. In Part III the significance of these groups with respect to flows will be discussed.

Figure 2 shows two rocks whose origin is uncertain from the chemical data. PR-09 could belong to group 9 (Priest Rapids III) or 10 (Priest Rapids II). PR-12 could belong to groups 9, 10, or 11. More trace elements measured with high precision might well distinguish these ambiguities. Rock A-1279 may have an erroneous Cr measurement and would otherwise also agree with group 19 which will be discussed subsequently. This possible Cr error may be contributing an unnecessarily large RMSD to the Cr value for the Roza group and allow some rocks to agree in composition with Roza which otherwise would be eliminated.

In Fig. 3, rock K-5032 agrees with groups 12 (Roza), 13 (Sentinel Gap) and 15 (Gingko). It also agrees with 19, a group made up of rocks (from Spukshowki Canyon and other sites) which were found directly under the Umatilla flows. Group 19 may well represent the Roza, Sentinel Gap or Gingko groups. Rock K-5001 agrees with both Sand Hollow and Roza.

Fig. 2. Statistical comparisons of chemical abundances of individual rock with ARHCO type locality groups.

<u>Rock Designation</u>	<u>Source</u>
A-1301	Huntzinger
PR-01	Priest Rapids IV
PR-04	Priest Rapids III
PR-09	Priest Rapids II
PR-12	Priest Rapids I
A-1279	Roza

XBL769 - 4046

Fig. 3. Statistical comparisons of chemical abundances of individual rock with ARHCO type locality groups.

<u>Rock Designation</u>	<u>Source</u>
K-5032	Sentinel Gap
K-5001	Sand Hollow
K-5012	Gingko
K-5010	Museum
K-5025	Rocky Coulee
A-1241	Sillusi Butte

XBL 769 - 4047

Better and more extensive Cr measurements of the Roza group should remove this ambiguity. Rock K-5012 agrees with Roza, Sentinel Gap, Gingko and group 19. This is a reiteration of the effects mentioned for rock K-5032. Rocks K-5010 and K-5025 belong to either the Museum or Rocky Coulee flows. More data is needed for the Museum flow, especially Cr values. Rock A-1241 from Sillusi Butte agrees with the Pomona group and should be a member of the Pomona flow. Rock A-1241 is representative of a group of rocks from Sillusi Butte, Rush Canyon, Spukshowki Canyon and possibly Selah Butte.

In Fig. 4 rock A-1237 obviously belongs to the Umatilla group. Rock A-1253 is a member of group 19 and the same comments apply as for Rock K-5032 discussed under Fig. 3. Rock A-1295 is from Selah Butte. It agrees with the Rocky Coulee and Museum groups, although only the major elements were measured. Trace element measurements can resolve ambiguities but do not contribute to them. It was found in this study that the major elements by themselves did not distinguish some rocks adequately. For example A-1038, A-1039 (Gable Mountain) and PR-27 A (Priest Rapids I) would appear to belong to group 19 if only the chemical data on major elements were used, whereas rocks from the same groups in which trace elements had been measured could readily be distinguished from group 19. In any event the group from Selah Butte of which A-1295 is a member occurs under the rocks of group 19 and this is also consistent with it being part of the Museum or Rocky Coulee flows. Rock A-1184 is representative of a group of rocks from Blair Point occurring under

Fig. 4. Statistical comparisons of chemical abundances of individual rocks with ARHCO type locality groups.

<u>Rock Designation</u>	<u>Source</u>
A-1237	Sillusi Butte
A-1253	Spukshowki Canyon
A-1295	Selah Butte (only major elements)
A-1184	Blair Point
A-4016	DH-4

Average deviation from group means (expressed in RMSD)

Group Number	Group
1	Ice Harbor II
2	Ice Harbor I
3	Ward Gap
4	Elephant Mountain
5	Pomona
6	Gable Mountain
7	Huntzinger
8	Priest Rapids IV
9	Priest Rapids III
10	Priest Rapids II
11	Priest Rapids I
12	Roza
13	Sentinel Gap
14	Sand Hollow
15	Gingko
16	Museum
17	Rocky Coulee
18	Umatilla
19	Spukshowki Canyon

XBL 769-4049

group 19. Rock A-1184 does not agree well with any of the 18 groups in the figures, although the IRMSD from the Roza group is 1.27. Because of significant errors in the Blair Point measurements as indicated in the earlier report, the assignment is uncertain. Rock A-4016 does not agree with any of the listed groups. It forms a group of its own, Wahluke, along with Rock A-4017 on the chart on page 43 of reference 2 (Vol. I).

PART III

Correlations Between Borehole Samples and Reference Samples

Introduction

In the preceding section it was shown that over half of the ARHCO type locality groups (reference 2, Vol. I, page 43) could be distinguished from each other from the existing chemical data. There was some ambiguities between the remaining groups but it was suggested that these could be reduced by better or more extensive measurements. If all such ambiguities were removed, however, there would still remain the question as to the extent that the rather limited selections of rocks in each type locality group can identify flows at different geographical locations. This problem is effected by two main factors, the general extent of chemical homogeneity of the basalt flows in the Pasco Basin and local effects which can change composition such as alteration.

Some of the previous measurements on the Pomona and Elephant Mountain flows bear on the first factor. The 18 samples of the Pomona flow analyzed at LBL⁵ were collected by H.U. Schmincke from an area in excess of 5000 square miles, and the 12 Elephant Mountain samples (also collected by H.U. Schmincke) were collected from an area in excess of 2000 square miles. The average root-mean-square deviation of the abundances of 21 trace, minor, and major elements was 5.2% for the Elephant Mountain samples and 4.9% for the Pomona samples. These values are slightly smaller than the ARHCO values shown in Table XXIII and suggest the latter may be consistent with general flow variations over an extended area.

As a method of checking this premise and the general applicability of chemical measurements for flow identification, the ARHCO chemical data on cores from 5 boreholes in the Columbia River Plateau region are utilized. A method of analysis is employed which exploits the usefulness of the main body of data without being greatly disturbed by occasional bad measurements. If the latter occur in only a few percent of the measurements, this can still cause frequent complications when 13 elements are being considered per sample. Each sample is compared with each type locality group, just as in Part II, except that one element is removed from the calculations. The rejected element is the one whose abundance deviates most from the group average when expressed in units of the root-mean-square deviation for that element in the group.

Some of the sensitivity for distinguishing between flows is lost particularly when one element is responsible for most of the distinctive chemical features of a flow. This is more than compensated by the increase in reliability of the assignments. If completely reliable data were used this rejection of an element would probably not be necessary.

PART III

Conclusions

The type locality groups given in reference 2 with one revision are adequate to assign 90% of the basalt core samples from boreholes DDH-3, DH-4 and DH-5 down to the level of the Priest Rapids IV flow. These correlations are very prominent and the flow assignments are nearly unambiguous when trace as well as major element abundances are available. The revision was the use of U.S.G.S. and L.B.L. data, normalized to the ARHCO calibrations, for the Elephant Mountain type locality group. The samples that correlated with the Elephant Mountain group also correlated to a smaller extent with the Ward Gap group. Additional measurements of trace and major elements on Ward Gap type locality samples could indicate if the Elephant Mountain-Ward Gap compositional differences are significant. The prominence of the correlations also indicates that the general character of the borehole chemical data for DDH-3, DH-4, and DH-5 down to the Priest Rapids IV level is comparable to that of the type locality data.

The correlations for boreholes DDH-1 and DH-2 were of the same type as for the other three boreholes, but the assignments were more ambiguous because useful trace element data was not available.

Below the Priest Rapids IV flow, there is considerably more ambiguity in assignments for flows above the Vantage Sandstone Formation. It is likely that better and more extensive trace element measurements would greatly reduce these ambiguities. The high Mg lower Yakima basalts

appear below the Vantage Sandstone Formation and correlate with the Museum and Rocky Coulee flows for DH-4 and DH-5 samples. The correlations of DDH-3 samples with these latter two groups, however, are much less prominent. Generally the other lower Yakima basalts do not correlate with any of the type locality groups.

The flow assignments and their respective depths in borehole DDH-3 were Ice Harbor I (210-290 ft), Elephant Mountain-Ward Gap (330-415 ft), Pomona (500-610 ft), Gable Mountain (690-755 ft), Umatilla (860-1060 ft), and Priest Rapids IV (1180-~1280 ft). The flows identified in DH-4 correlate well with the Elephant Mountain-Ward Gap (20-40 ft), Pomona (80-160 ft), Huntzinger, (?-310 ft), Wahluke (360-390 ft), Priest Rapids IV (460-500 ft), and possibly Priest Rapids III, II, or I (520-620 ft) groups. The flows similarly identified in DH-5 correlated with the Elephant Mountain-Ward Gap (~205-285 ft), Pomona (340-460 ft), Huntzinger (540-600 ft), and probably Priest Rapids IV (690-710 ft) groups. For DDH-1 samples correlations were found with the Elephant Mountain-Ward Gap, Pomona, Gable Mountain, Huntzinger and probably Priest Rapids IV reference groups. For DH-2 samples correlations were found with the Elephant Mountain-Ward Gap, Pomona, Umatilla and Priest Rapids III, II, or I groups. The DH-1 and DH-2 assignments are more ambiguous than those in which trace elements were used. The DH-2 Umatilla group is very poorly defined either because the measurements are unusually bad or the type of locality group is not representative of the flow in the DH-2 area. For all boreholes there was an ambiguity between Ward Gap and Elephant Mountain assignments and between Priest Rapids I, II, and III assignments.

The probability that an assignment can be erroneous was calculated for a favorable case, the four samples from DDH-3 assigned to the Pomona flow. Such a calibration is much simplified when the assignment can be limited to one of a few groups of known composition. Further simplifications can be made with the assumptions that all abundance distributions for the type locality samples are distributed in a Gaussian fashion, all measurement errors of the borehole samples are similarly distributed, and the measured abundances for difference elements considered in this report are not correlated with each other. Such assumptions would be valid if all variations are due to Gaussian measurement errors. With these assumptions the probability of an error in the assignment of any of the four samples to the Pomona group is less than 1 part in 10^{10} .

Two samples from between the Pomona and Huntzinger flows in DH-4 had a chemical abundance pattern consistent with a basalt character but distinctly different from any of the reference groups. These samples, which may represent a flow of restricted lateral extent, and several other from close to the same depth in DH-4 may be of geological and geochemical interest.

PART III

Recommendations

If better and more extensive trace element analyses are made on middle Yakima type locality groups, the flows in DDH-3, DH-4, DH-5, should be systematically resampled from the Priest Rapids III level down to the top of the (low Mg) lower Yakima flows. The measurements should include the trace and major elements suggested in the Recommendations for Part II. Such measurements could determine the extent to which the new chemical abundance patterns for the middle Yakima type locality groups could represent those flows in the Pasco Basin.

The existing borehole data on lower Yakima basalts should be further examined to determine if chemical reference groups can be set up to distinguish between the different flows. Further measurements of trace elements by neutron activation analysis and hard X-ray fluorescence as well as major element analysis may be necessary to adequately resolve the flows chemically.

In selection of the ARHCO type locality and field section samples great care was taken to obtain fresh unaltered rock (reference 2 Vol I, page 38). Thus, for a given flow the chemical composition of rock from a borehole may deviate substantially from the type locality profile.

This should be particularly true near the top or bottom of the flow or near areas traversed by water. Certain elements might be more

susceptible to alteration than others and may serve as indicators as to the type of process causing the change. A comprehensive study of the major, minor, and trace elements abundances as a function of depth for specific flows could shed light on the migration of groundwater through the basalts in past geologic times. This might be of particular interest for rock in the "Umtanum" interval, (reference 2, Vol I, page 83), a very light dense glassy basalt flow near 60 m thick and about 915 m deep.

PART III

Discussion

The ARHCO boreholes are roughly located at the center and corner of a square of about 500 square miles area in the Pasco Basin and the locations are shown on page 57 of reference 2 (Vol. I). Two boreholes which are called DDH-1 and DH-2 in this work were referred to as ARH-DC-1 and RSH-1 is the reference mentioned above. The other three have the designations DDH-3, DH-4, and DH-5. Cores from the boreholes were sampled by ARHCO to depths of 1165 feet (DDH-1), 600 feet (DH-2), 3540 feet (DDH-3), 4765 feet (DH-4), and 4990 feet (DH-5). Only major element and Ba data was generally available for cores from DDH-1 and DH-2 although there were a few trace element results which were not used. The core from DDH-1 was sampled about every 20 feet and that from DH-2 about every 30 feet. The core from DDH-3 was sampled for major element analysis about every 30 feet and trace elements were measured on most of the samples. The core from DH-4 was sampled about every 24 feet on the average for major element analysis and trace element were measured on most of the samples. The core from DH-5 was sampled about every 25 feet for major element analysis and about half of the samples from depths above 3600 feet had trace element measurements.

The chemical abundance data for each core sample (from the 5 boreholes) were treated in the same fashion as the data on the individual type locality rocks in Part II. The value of IRMSD was calculated for each of

617 borehole rocks for each of 23 groups. IRMSD, as discussed in Part II, is an index of the deviation of the abundances of a rock from a given chemical group. It will normally average $\sim .85$ for a group member, but there will be about a 1 percent probability that it will be as large as 1.50, and the latter value was chosen as a cut-off point for most of the data. The data are presented in graphic form in Figs. 5-14. To facilitate reading the graphs a variable x is plotted which is equal to 1.50 minus IRMSD. Thus $x = 0$ for values of IRMSD which are equal to 1.50 or larger, and increasing values of x show increasing correlations between samples and groups. The data from DDH-1 and DDH-3 will be discussed in detail to indicate the type of information which can be obtained from major elements alone (including Ba) and with trace elements in addition.

DDH-1 Comparisons

Fig. 5 shows comparisons of samples from DDH-1 with eight type locality groups representing upper and middle Yakima flows. There are eight major elements included in the analysis (SiO_2 , Al_2O_3 , FeO , MgO , CaO , TiO_2 , Na_2O , K_2O) and Ba. There is no observed correlation between the samples and Ice Harbor II and I flows. Ward Gap shows several correlations but crude Cr data suggests that nearly all correlations except the upper-most two would be eliminated if good Cr data were available. The Elephant Mountain type locality group was not included in this analysis as the major element data available for this work appeared more questionable than that for the other type locality sites. A composite Elephant Mountain group

Fig. 5

Correlations of samples from borehole DDH-1 with upper and some middle Yakima reference groups. The plotted variable, x , is equal to 1.5-IRMSD . Data which include trace element measurements are plotted as $\bullet$. Data which do not include such measurements are plotted as X .

Fig. 5

DRILL HOLE 1
CIVE ELEMENT REJECTED

Fig. 6

Correlations of samples from borehole DDH-1 with some middle and lower Yakima reference groups. The plotted variable, x , is equal to 1.5-IRMSD . Data which include trace element measurements are plotted as $\bullet$. Data which do not include such measurements are plotted as X .

Fig. 6

ROCKY
LOULEE

MUSEUM

GRAND

SAND HOLLOW

SENTINEL GAP

ROZA

PRVEST RAPIDS III

PRVEST RAPIDS IV

500

1000

Depth (feet)

DRILL HOLE 1
ONE ELEMENT REJECTED

however, was formed with U.S.G.S. and LBL data discussed in Part I. The abundance of each element was normalized to the calibration of the main body of ARHCO samples with the ratios of ARHCO/others also given in Part I. As can be seen in Fig. 5 the correlation of the uppermost two samples in DDH-1 with this composite group is very high. Again good Cr data would probably eliminate most of the other correlations. The next four samples from increasing depths in DDH-1 all show no correlation with any groups. The top pair (Ca-3 from 205 feet and CA-4 from 225 feet below the surface) are much different than the lower two in that they have almost no overlap with any of the reference groups. This would be expected as they are not basalts. For the next two samples, Ca-6 (225 ft) and CA-7 (265 ft), the closest agreement is with the Pomona flow although the overlap is too small for a convincing assignment. Such variations from the chemical pattern of the type locality groups may reflect alteration near the flow boundaries. The next group of 8 rocks correlate with the Pomona flow. The rock from the 300 foot level has IRMSD = 1.5 and is probably a flow member. There is a correlation with rocks at 640 feet but this is probably the Huntzinger flow. Trace element analyses would remove this ambiguity. The rocks from 475 to 600 feet correlate well with the Gable Mountain flow. There are two small correlations at 200 feet and ~1100 feet and trace element analysis would likely also remove these ambiguities. The next two samples at 610 and 615 feet do not agree with any of type locality groups, although they are consistent with basalt. Two of the next three rocks from 630 to 660 feet correlate

with the Huntzinger flow. The rock which disagrees, A-1041, is very similar chemically to the others except for Ba and K_2O . This may represent a difference in flow composition or more likely two bad measurements in one sample for which the procedures used in the analysis cannot compensate. Two correlations observed at 270 feet and 355 feet would probably disappear if trace elements measurements were available for those rocks. No correlations were observed with the Wahluke flow. At least 9 of the next 13 rocks correlate well with the Umatilla group. The other 4 all have very high barium content which is indicative of the Umatilla flow, and they also agree better with that group than any of the others. The next two rocks from 825 and 870 feet have nearly zero overlap with any of the type locality groups, and thus may not be basalts.

In Fig. 6 comparisons are shown between the rocks from DDH-1 and eight middle and lower Yakima groups. The rocks from 920 feet to 1115 feet show varying degrees of correlation with middle Yakima groups. Careful trace element measurements would likely distinguish between PR IV and the other groups and possibly distinguish amongst the other groups. There did not appear to be any significant correlation between the Museum and Rocky Coulee flows and the rocks from DDH-1.

DH-2 comparisons

The data from DH-2 are suspect because the material balance, which varies between 100.2 and 106.7%, is unusually high. Thus measurements of some elements or components are wrong. At least part of the

errors should be in one or more of these elements whose abundances are larger than the material balance discrepancy i.e., SiO_2 , Al_2O_3 , FeO , and CaO .

Elephant Mountain-Ward Gap and Pomona flows are clearly defined in Fig. 7 but the Umatilla is not. The high Ba values, characteristic of the Umatilla flow occur in all core samples between 180 and 360 feet, but only two samples give a positive indication in Fig. 7. This is due principally to differences in FeO and CaO (and TiO_2 in one sample) between the core data and the reference Umatilla group. These differences may be related to the errors of measurement of DH-2 samples reflected by the material balance and therefore cannot be ascribed to source variations at this time. The comparisons of DH-2 samples with other reference groups is shown in Fig. 8. The Priest Rapids III-II-I groups are well defined but cannot be distinguished from each other. There are other ambiguities in assignments, but crude Cr measurements indicate these would be greatly reduced if good Cr data were available.

DDH-3 Comparisons

Trace elements as well as major elements were measured in most of the samples from DDH-3. The improvement due to the inclusion of trace elements is obvious as shown in Fig. 9 where the Ice Harbor I, Pomona, Gable Mountain, and Umatilla flows are unambiguously defined. There were no correlations between any rock from DDH-3 and the Ice Harbor II, Huntzinger or Wahluke flows.

Fig. 7

Correlations of samples from borehole DH-2 with upper and some middle Yakima reference groups. The plotted variable, x , is equal to 1.5-IRMSD. Data which include trace element measurements are plotted as • . Data which do not include such measurements are plotted as χ .

DRILL HOLE 2
ONE ELEMENT REJECTED

FIG. 7

Fig. 8

Correlations of samples from borehole DH-2 with some middle and lower Yakima reference groups. The plotted variable, x , is equal to 1.5-IRMSD . Data which include trace element measurements are plotted as $\bullet$. Data which do not include such measurements are plotted as X .

Fig. 8

It is possible to calculate the possibility of an erroneous assignment if certain limitations or assumptions can be placed on the calculation. These are first, the unknown rock, if it is a basalt, must conform to one of the type locality groups; second, uncertainties in the type locality values and in all measurements can be considered as Gaussian; and third, there are no coherences of significance (larger than measuring errors) between the abundances of the different elements used in the calculation. A failure of the third assumption will not change the sense of the calculations but will make low-correlation events appear less improbable than they are. In this procedure the probability is first calculated for each group and each rock that a group member will have abundances deviating from the group averages as much as the unknown rock. This is the degree to which the chemical profile of a given rock overlaps a given group. Thus for each rock the sum of all of the probabilities for the different groups are normalized to 1, and the resulting value for each group represents the respective probability that the rock belongs to that group.

The overlap between a rock and its parent flow can be lower than expected if chemical alterations have affected the composition or if the type locality comparison group is not representative of the flow. Usually this will not affect the sense of the calculation unless the overlap becomes so small that it is comparable with accidental overlaps with other groups. In this work only overlaps of 10^{-10} or larger for 13 elements are considered significant.

Fig. 9

Correlations of samples from borehole DDH-3 with upper and some middle Yakima reference groups. The plotted variable, x , is equal to $1.5 \cdot \text{IRMSD}$. Data which include trace element measurements are plotted as $\bullet$. Data which do not include such measurements are plotted as $\times$.

FIG. 9

Fig. 10

Correlations of samples from borehole DDH-3 with some middle and lower Yakima reference groups. The plotted variable, x , is equal to 1.5-IRMSD . Data which include trace element measurements are plotted as $\bullet$. Data which do not include such measurements are plotted as X .

FIG. 10

As shown in Fig. 9 core samples taken from depths of 490 to 615 feet in borehole DDH-3 correlate well with the Pomona flow. In Table XXV are shown the relative probabilities of these samples belonging to the different type locality groups when 13 elements are used in the classification. It is seen that the possibility of an erroneous assignment is less than 1 in 10^{13} if the restrictions set on the calculation are valid. The uncertainty, however, in the value is probably at least three orders of magnitude. This type of treatment was also applied to samples which showed no correlation with any of the groups in Fig. 9. The probability overlaps are tabulated in Table XXVI and are of the form:

$$\prod_i^{m-1} \left(\left(1 - 2 \int_0^{t_i} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} dy \right) / \left(2 \int_0^{t_i} \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi}} dy \right) \right)$$

where m is the number of elements and t_i is the deviation of element i from the group average expressed in units of the group RMSD for element i . The product is taken over $m-1$ elements with the smallest factor. The maximum value for any factor is cut off at 1. Values for the factors were taken from tables of the odds against the occurrence of deviations.⁹ Revised values for the Elephant Mountain group as discussed in the DDH-1 section are included in Table XXVI. Samples A-2005, A-2010, A-2015, A-2020, and A-2030 have nearly zero overlap with any any reference

Table XXV

Probability of selected samples from
DDH-3 belonging to different flows^a

Sample No. Depth. (ft.)	A-2011 500	A-2012 525	A-2013 575	A-2014 615
<u>Group</u>				
Ice Harbor II	10 ⁻¹¹³	10 ⁻¹¹⁶	10 ⁻¹¹⁷	10 ⁻¹¹⁷
Ice Harbor I	10 ⁻⁴¹	10 ⁻⁴³	10 ⁻⁴⁶	10 ⁻⁴⁵
Ward Gap	10 ⁻¹¹³	10 ⁻¹¹⁶	10 ⁻¹¹⁷	10 ⁻¹¹⁷
Elephant Mtn.	10 ⁻¹¹³	10 ⁻¹¹⁶	10 ⁻¹¹⁷	10 ⁻¹¹⁷
Pomona	1	1	1	1
Gable Mtn.	10 ⁻¹¹³	10 ⁻¹¹⁶	10 ⁻¹¹⁷	10 ⁻¹¹⁷
Huntzinger	10 ^{-24 b}	10 ^{-13 b}	10 ^{-14 b}	10 ^{-16 b}
Umatilla	10 ⁻¹¹³	10 ⁻¹¹⁶	10 ⁻¹¹⁷	10 ⁻¹¹⁷
Wahluke	10 ⁻¹¹³	10 ⁻¹¹¹	10 ⁻¹¹⁷	10 ⁻¹⁰⁵
PR IV	10 ⁻²⁷	10 ⁻¹⁷	10 ⁻²⁴	10 ⁻¹⁶
PR I,II, III	10 ⁻¹¹³	10 ⁻¹¹⁶	10 ⁻¹¹⁷	10 ⁻¹¹⁷
Roza	10 ⁻¹¹³	10 ⁻¹¹⁶	10 ⁻¹¹⁷	10 ⁻¹¹⁷
Sentinel Gap	10 ⁻¹¹³	10 ⁻¹¹⁶	10 ⁻¹¹⁷	10 ⁻¹¹⁷
Gingko	10 ⁻¹¹³	10 ⁻¹¹⁶	10 ⁻¹¹⁷	10 ⁻¹¹⁷
Sand Hollow	10 ⁻⁷⁹	10 ⁻⁶⁰	10 ⁻⁷⁵	10 ⁻⁵⁸
Rocky Coulee Museum	10 ⁻⁴⁶	10 ⁻²⁶	10 ⁻³⁵	10 ⁻²⁶

^aCalculation assumes all distributions are Gaussian and basalt samples must belong to one of the listed flows. Thirteen elements were used in the calculation. The probability the Pomona type locality samples would have elements deviating from the group average as much as the unknown were 2×10^{-9} , 7×10^{-5} , 6×10^{-3} , and 10^{-2} for samples A-2011, A-2012, A-2013, and A-2014, respectively.

^bSecond most probable assignment.

TABLE XXVI

Probabilities^a that group members would deviate in abundances from group means as much as unknown samples from DDH-3 (Probability = 10^{-2})

Sample No. Depth from Surface (ft).	A-2550	A-2006	A-2008	A-2009	A-2010	A-2015	A-2016	A-2020	A-2030
	300	330	375	420	470	670	690	780	1135
<hr/>									
Group	Values of z								
Ice Harbor II	b	41	49	35	b	b	36	b	b
Ice Harbor I		42	43	43			46		
Ward Gap		12	16	10			19		
Elephant Mtn. Revised (LBL & U.S.G.S.)		9 ^c 7 ^c	16 ^c 10 ^c	13 ^d 5 ^d			12 ^d -		
Pomona		89	76	102			68		
Gable Mtn.		16	21	20			9 ^d		
Huntzinger		89	81	98			59		
Umatilla		82	85	89			81		
Wahluke		60	62	74			40		
Priest Rapids IV		30	31	24			29		
Priest Rapids III		13	18	8 ^d			15		
Priest Rapids II		17	25	14			19		
Priest Rapids I		12	24	13			15		
Roza		17	27	22			12 ^d		
Sentinel Gap		21	28	23			10		
Sand Hollow		31	29	31			19		
Gingko		22	29	19			12 ^d		
Museum		50	48	46			24	60	
Rocky Coulee		68	67	76			33		

^aCalculations assume Guassian distribution for all abundance and no coherences between elements.

^bBlanks indicate $z > 81$, the maximum cut off when trace elements are not included.

^cThis is the highest probability for this sample and all others are over 3 orders of magnitude smaller.

^dThese values are the highest probabilities within a 3 order of magnitude uncertainty.

group and may not be basalts. Samples A-2006, A-2008, and A-2009 agree best with the revised Elephant Mountain group. As this calculation may be uncertain to three orders of magnitude the assignment of A-2009 from the chemical evidence alone is ambiguous with Priest Rapids III also being a possibility. Sample A-2016 agrees best with Gable Mountain although Elephant Mountain, Priest Rapids I, Roza and Ginkgo are also possibilities from the chemical data alone. Thus, there are only two rocks from DDH-3 whose assignments to flows indicated in Fig. 9 are ambiguous. The cover of this report shows the various curves in Fig. 9 superimposed on each other. The squares are samples with nearly zero overlap with any group.

In Fig. 10 are shown the correlations with 8 groups of middle and lower Yakima basalts. The Priest Rapids IV assignment is unambiguous. For rocks taken from depths of 1290 to 2150 feet assignments to other middle Yakima flows are not clear cut. The correlation with Sand Hollow for rocks below 2150 feet would be eliminated if it were not necessary to reject one element. In this case Cr, which is a characteristic element for Sand Hollow, is the element rejected.

DH-4 Comparisons

In Fig. 11 and 12 are shown the correlations between the DH-4 samples taken from depths of 2400 feet or less and upper, middle, and some lower Yakima groups. The revised Elephant Mountain abundances discussed in the section on DH-1 were included.

The trace element data in reference 2 (Vol. II, C-55) for sample A-4003 are different from those given by Tatman¹ and appear to have typographical errors. The Tatman data were used in Fig. 11. The top flow sampled in

Fig. 11

Correlations of samples from borehole DH-4 with upper and some middle Yakima reference groups as a function of depth. The plotted variable, x , is equal to 1.5-IRMSD . Data which includes trace element measurements are plotted as $\bullet$. Data which do not include such measurements are plotted as X .

FIG. 11

DRILL HOLE A
ONE ELEMENT REJECTED

Fig. 12

Correlations of samples from borehole DH-4 with upper and some middle Yakima reference groups as a function of depth. The plotted variable, x , is equal to 1.5-IRMSD . Data which includes trace element measurements are plotted as $\bullet$. Data which do not include such measurements are plotted as X .

Fig. 12

DRILL HOLE A
ONE ELEMENT REJECTED

DH-4 correlates very well with the Elephant Mountain group, although the Ward Gap group has a small correlation. Measurements of higher reliability including additional trace elements on Ward Gap type locality material and on the core samples might resolve this ambiguity. The next lower flow, Pomona, is very well defined. There appear to be intrusions and some evidence for fractionation or alteration in the Huntzinger flow which will be discussed at the end of the section. The correlation with the Wahluke group is larger than proper because the trace element measurements from the two DH-4 samples are the only ones available to form the reference group, and they are coincidentally nearly identical. The Umatilla flow is not detected and the next lower flow is Priest Rapids IV. The Priest Rapids III assignment looks moderately good although there are small correlations with other flows. More trace element data should remove that ambiguity. Nearly all of the other samples taken from the depths of 640 to 1470 feet correlate with either the Roza, Sentinel Gap, Sand Hollow or Gingko groups. More extensive trace element data should certainly reduce the possibly eliminate these ambiguities. Samples taken from depths of 1500 to 2180 ft correlate with the Museum and Rocky Coulee groups. More and better trace element data might also distinguish between them. The samples from 1790 to 2145 feet also correlate well with a group (not shown in the figures) of rocks from Selah Butte for which only major element abundances were useful. This latter group comprised samples A1288-A1295 (reference 2, Vol II, Table B-VI) and was described as

"flows of the high Mg chemical type" of the Lower Yakima Basalts (reference 2, Vol. II, Page B-27).

For 107 rocks below 2180 feet there were no correlations of significance for which both major and trace element data were useful although 11 rocks (eight without trace element abundances) exhibited values of x , ($x = 1.5\text{-IRMSD}$) ranging from .01 to .37.

The region in DH-4 between depths of 160 and 360 feet may be of geochemical interest. The abundances of all of the samples from this region are tabulated in Table XXVII. Two of the samples A-4012 and A-4013, which are called Group B in the Table, have a very similar chemical abundance pattern which is different from that of any of the reference groups. They are unusually abundant in MgO , Al_2O_3 , and Cr and unusually deficient in K_2O . There is no indication of this abundance pattern in data from any of the other 4 boreholes so Group B may represent a flow of restricted lateral extent. Three samples, A-4010, A-4011, A-4015, all have a similar pattern chemical abundance, and are called Group A in Table XXVII. The abundances of these samples can be mathematically related to the Huntzinger flow composition, Group B composition and the Wahluke flow-composition. For example, if magma of the Huntzinger composition fractionated to give a 30% component with the Group B composition, the residue would have the composition of Group A. On the other hand, the A composition pattern can also be obtained by mixing the Huntzinger (60%) and Wahluke (40%) patterns. A petrographic study might determine if either of these suppositions are viable.

Table XXVII

Abundances in Chemically Anomolous Regions of DH-4

Sample	A4009	A4010	A4011	A4012	A4013	A4014	A4015	A4016
Depth (ft)	160	185	200	235	275	305	340	365
Group or Pattern	Pomona	A	A	B	B	Huntzinger	A	Wahluke
<u>Abundances:</u>								
<u>In Percent</u>								
SiO ₂	51	52	50	49	50	51	51	53
Al ₂ O ₃	13.3	13.6	14.1	15.6	15.7	15.1	13.9	13.6
FeO	10.8	10.8	11.1	9.8	10.1	10.7	11.5	12.2
MgO	7.4	5.8	6.1	9.2	9.0	7.6	6.0	5.3
CaO	10.2	9.0	9.0	10.3	10.6	9.7	8.8	8.1
Na ₂ O	2.4	2.4	2.3	2.2	2.2	2.4	2.4	2.8
K ₂ O	0.3	0.9	0.9	0.1	0.3	0.8	1.4	1.9
TiO ₂	1.7	1.8	1.6	1.3	1.4	1.7	1.7	1.8
<u>In ppm</u>								
Sc	33	27	26	30	28	26	26	25
Eu	1.6	1.8	1.8	1.1	1.0	1.4	2.0	2.0
Co	42	38	40	42	45	39	37	37
Ba	500	830	690	490	390	560	830	1160
Cr	92	111	125	295	269	173	97	31

DH-5 Comparisons

The DH-5 correlations are shown in Figs. 13 and 14. The data used for Sc and Co in samples A5021, A5022, A5024, and A5026 were taken from Tatman¹ as there were apparently typographical errors in the Sc values and one Co value given in reference 2. The Elephant Mountain group was revised in the same manner as described for DDH-1 and part of its correlations are also shown in Fig. 13. The top flow sample correlates well with this revised Elephant Mountain group. There are smaller correlations with the Ward Gap, Priest Rapids (I,II,III) and Gingko groups. All but the first of these would likely be greatly reduced if no trace elements were rejected as the Sc abundance of these flow groups is quite different from that of Elephant Mountain. More extensive measurements of trace elements on the core samples and reference groups might distinguish much more completely between the Ward Gap and Elephant Mountain groups. There is a good correlation between the Pomona group and rocks from depths of 340 to 460 feet in DH-5. A small correlation of 3 of these rocks with the Huntzinger flow would be greatly reduced if their trace elements had also been measured. The next group of rocks correlates well with the Huntzinger group. A smaller correlation with the Pomona flow would be greatly reduced if no trace elements had been rejected as Cr differs by almost a factor of two between the two flows. There is no evidence of the Wahluke or Umatilla group in DH-5. Two rocks from a depth of ~700 feet correlate well with the PR IV flow. Smaller correlations with other flows would be much reduced if no trace elements

Fig. 13

Correlations of samples from borehole DH-5 with upper and some middle Yakima reference groups as a function of depth. The plotted variable, x , is equal to 1.5-IRMSD. Data which include trace element measurements are plotted as $\bullet$. Data which do not include trace elements are plotted as $\times$.

Fig. 13

Fig. 14

Correlations of samples from borehole DH-5 with some middle and lower Yakima reference groups as a function of depth. The plotted variable, x , is equal to 1.5-IRMSD . Data which include trace element measurements are plotted as $\bullet$. Data which do not include such measurements are plotted as $\times$.

FIG. 14

DRILL HOLE 5
ONE ELEMENT REJECTED

were rejected. From depths of 740 to 1680 feet there are correlations with Priest Rapids I, II, III, Roza, Sentinel Gap, Sand Hollow and Ginkgo groups. Better and more extensive trace element measurements might make conclusive distinctions between these groups possible. From 1840 to 2550 feet nearly all rock groups correlate to some degree with the Museum and Rocky Coulee groups. These rocks also correlate well with a group (not shown on graphs) of rocks from Selah Butte as discussed for DH-4 samples.

In DH-5 there were 14 minor correlations with those groups shown in Fig. 13 for 120 rocks from below 2190 feet. There were 2 correlations with the Wahluke group, 7 with the Gable Mountain group and 5 with the Umatilla group. For those groups shown in Fig. 14 there were two minor correlations between 2790 feet. Inclusions of trace element data would very likely have eliminated all of these.

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Average deviation from group means (expressed in RMSD)

Group Number	Group
1	Ice Harbor II
2	Ice Harbor I
3	Ward Gap
4	Elephant Mountain
5	Pomona
6	Gable Mountain
7	Huntzinger
8	Priest Rapids IV
9	Priest Rapids III
10	Priest Rapids II
11	Priest Rapids I
12	Roza
13	Sentinel Gap
14	Sand Hollow
15	Gingko
16	Museum
17	Rocky Coulee
18	Umatilla
19	Spukschowki Canyon

XBL 769-4049

XBL 769 - 4047

XBL769-4048