

AN ABSTRACT OF THE THESIS OF

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Dr. Roman A. Schmitt

Basalts of both Eocene and Miocene age from several groups along the Oregon and Washington coasts have been analyzed for some major, minor, and trace elements using instrumental neutron activation analysis (INAA). The rare earth element (REE) patterns observed in these samples are used for comparisons within the groups studied and for comparisons with other types of basalts. The three groups of Miocene basalts from the coast have been shown to be nearly identical chemically to three chemical types defined in the Columbia River Plateau basalts as follows: Depoe Bay Basalt \equiv Lower Yakima Basalt (high and low Mg types), Cape Foulweather Basalt \equiv Frenchman Springs Basalt, and the Basalt of Pack Sack Lookout \equiv Pomona Basalt. Possible models for the origin of these basalts erupted from vents over 500 km apart are also discussed. The Eocene basalts from the Oregon coast are found to be most similar to the basalts from the Hawaiian Islands, whereas the Metchosin Formation basalts on southern Vancouver

Island are found to be more similar to ocean ridge tholeiites. The basalts from the Crescent Formation on the Olympic Peninsula show a variety of chemical compositions and REE patterns which do not allow for simple classification of this formation.

Chemical Composition Studies of Oregon
and Washington Coastal Basalts

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Professor of Chemistry
in charge of major

Redacted for Privacy

Head of Department of Chemistry

Redacted for Privacy

Dean of Graduate School

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CHEMICAL COMPOSITION STUDIES OF OREGON AND WASHINGTON COASTAL BASALTS

I. INTRODUCTION

The Oregon and Washington coasts have undergone at least two distinct magmatic episodes during the Tertiary Period. The earlier of these two episodes occurred during the Eocene Epoch and consisted mostly of vast outpourings of submarine tholeiitic basalt. Later, probably more violent eruptions spread a thin blanket of alkalic basalts over the lower basalts along the Oregon coast. The basalts of this area and time are given the following names from North to South: Metchosin Formation, Crescent Formation, Roseburg Volcanics, Siletz River Volcanics, and the Umpqua Volcanics. Very little information is available on the minor and trace element compositions of these basalts. Thus one part of this research effort was to analyze these Eocene basalts for the minor and trace elements, especially the REE, using the INAA technique. The results of these analyses are used for comparisons within these basalt groups and with the various types of tholeiitic basalts in the whole Pacific and circum-Pacific Ocean area. The few Eocene alkalic basalts from the Oregon coast which were analyzed in this work have been grouped together and called the Eocene Alkalics for the purpose of this paper.

One sample from the Karmutsen Formation on Vancouver Island in British Columbia, which was erupted during the Triassic Period, was also analyzed and compared with the Eocene basalts.

The most recent magmatic episode occurred during the middle to late Miocene Epoch and consisted entirely of both submarine and sub-aerial tholeiitic basalts. Three groups of basalts were erupted separately in three different periods of time and given the following names from older to younger: the Depoe Bay Basalts, the Cape Foulweather Basalts, and the Basalt of Pack Sack Lookout by Snavely, MacLeod and Wagner (1973). These authors suggested that these basalts were related to three groups of basalt flows from the Columbia River Plateau based on major element compositions and also proposed a pair of models for the origin of co-magmatic basalts from such widely separated vent areas as these. Thus the second part of this research was to analyze these Miocene basalts for minor and trace element abundances (especially the REE) by INAA and to use these results for a much more accurate comparison with the plateau basalts. The models proposed for the origin of the basalts are also discussed with respect to this new data.

Since these Miocene and Eocene coastal basalts were extruded as separate events in time and apparently in environment, it seems logical to discuss them separately as well. The bulk of this paper has been divided into two parts for this purpose. The approximate location

of each of these samples has been indicated on a map of the area in
Figure 1.

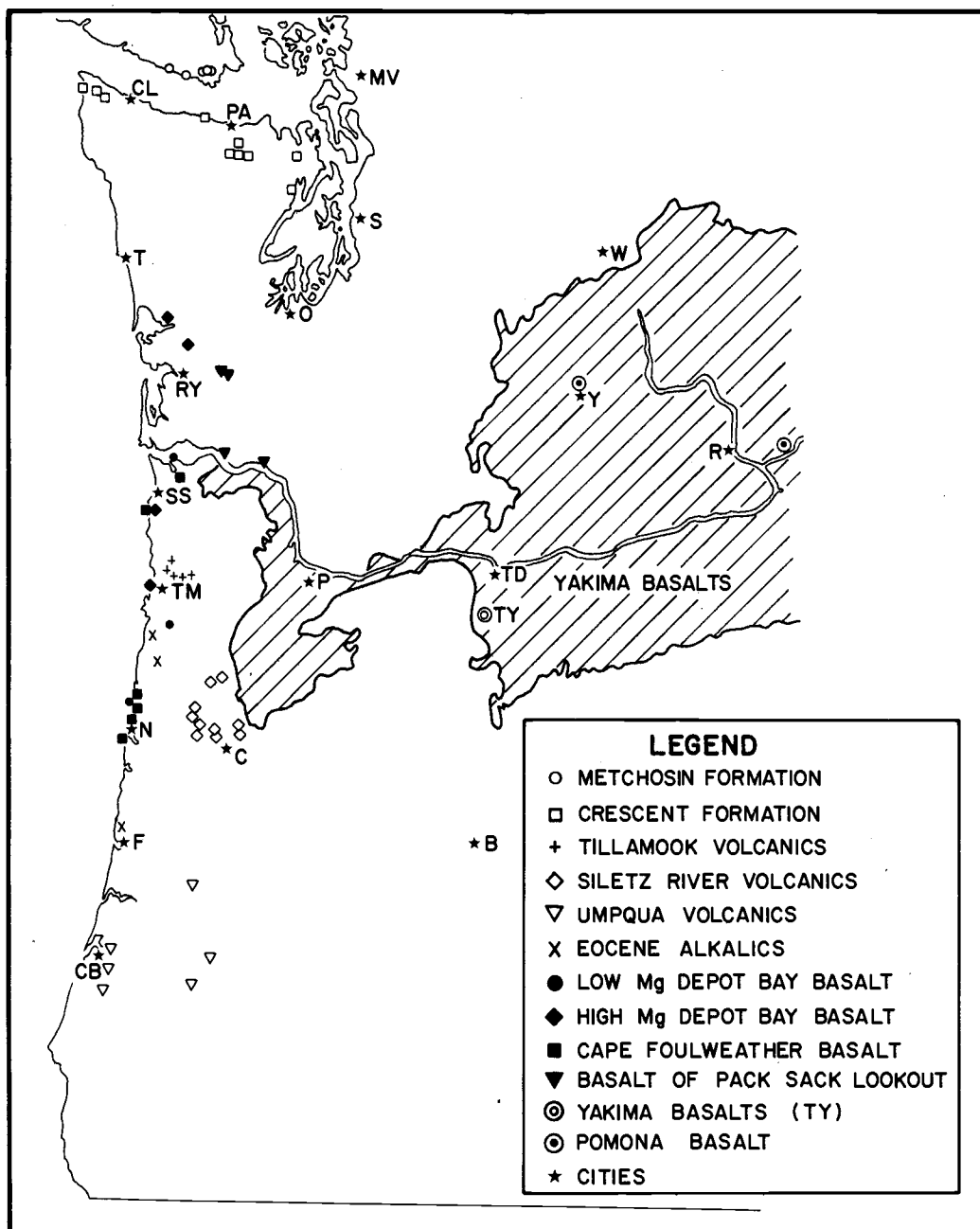


Figure 1. Map of the study area shows the approximate locations of the analyzed samples. Cities shown on the map are designated by the following letters: CL, Clallam Bay; PA, Port Angeles; MV, Mount Vernon; S, Seattle; T, Taholah; W, Wenatche; O, Olympia; RY, Raymond; Y, Yakima; R, Richland; SS, Seaside; TM, Tillamook; P, Portland; TD, The Dalles; N, Newport; C, Corvallis; F, Florence; B, Bend; CB, Coos Bay.

II. EXPERIMENTAL

The samples from the Karmutsen, Metchosin, and Crescent formations; the Depoe Bay and Cape Foulweather basalts; and the basalt of Pack Sack Lookout were obtained from Dr. Parke D. Snavely of the United States Geological Survey. These samples were small basalt chips or small sawn blocks contained in separate white cloth bags.

Since most of the samples had been sawn, it was decided to wash the samples to remove possible exterior contamination using the following scheme:

1. The sample was rinsed with plain water.
2. The sample was placed in 1N HNO₃ (distilled water) in an ultrasonic cleaner for 2-3 minutes.
3. The sample was scrubbed with a small brush and distilled water.
4. The sample was dried with acetone.

Weight loss in the samples due to this process was of the order of 0.1% and was apparently mostly due to the ultrasonic cleaner and the scrubbing process.

At this point the samples were given the following simple designations for easier handling and greater distinction between formations (See Appendix tables for USGS designations):

1. Karmutsen and Metchosin Formation basalts were designated K1 through K6,
2. Crescent Formation basalts were designated C1 through C10,
3. Depoe Bay basalts were designated D1 through D7,
4. Cape Foulweather basalts were designated CF1 through CF6,
5. Pack Sack Lookout basalts were designated P1 through P4.

In order to get a representative aliquant from these samples the basalt pieces were crushed to cinder size pieces with a jaw crusher and then further crushed to a very fine powder with a semi-micro pulverizer (99.9% alumina plates). The crusher and pulverizer were thoroughly cleaned between samples. A small amount of the next sample was run through both to precondition the machines. The machines were recleaned before crushing the remainder of the sample. The samples were transferred to clean seven dram polyethylene vials and thoroughly mixed. Weighed aliquants of approximately one gram from each of the samples were placed in sealed half dram polyethylene vials and these vials placed in sealed two dram vials along with a second half dram vial to insure that the sample vial remains in the same position at all times.

The various samples from the Columbia River Basalt were obtained from Dr. Jon S. Fruchter of the University of Oregon Center for Volcanology. These samples were coarsely ground basalt contained

in half dram vials. The samples were recrushed and treated the same as the previous samples.

The samples of Cove Palisades volcanic ash were obtained from Dr. R. A. Schmitt of Oregon State University. These samples were in the form of large chunks. Small pieces were chipped from these chunks and treated the same as the previous samples.

Several pieces of basalt from the same quarry, from which the U. S. G. S. standard basalt BCR-1 was obtained, were crushed in the same manner and the powder passed through 100 mesh netting. This powder was split in half after thorough mixing and the splits labelled CRB-I and CRB-II (CRB \equiv Columbia River Basalt). This powder is designated for use as an "in house" standard because of the dwindling supply of BCR-1. Four aliquants of CRB-I were partially analyzed during the course of this work. The compositional agreement between aliquants and with BCR-1 was generally very good.

Elemental abundances in all of these samples were determined by sequential instrumental neutron activation analysis (INAA). This method of analysis has been discussed in detail in previous papers (Coles, 1973; Miller, 1974) and the general outline of the procedure used in this work is given in Table 1. Each sample was activated twice. The first activation called a "rabbit run" used the pneumatic transfer system of the Oregon State University TRIGA reactor.

Table 1. INAA Scheme.

Counting Sets				
Activation	Isotope	Half-Life*	E γ (keV)*	Counting Set
		1. 15 min decay, 200 sec count Ge (Li)		
		2. 3 hr decay, 800 sec count Ge (Li)		
		3. 1 day decay, 400 sec count Ge (Li)		
		4. 3 day decay, 10K sec count Ge (Li)		
		5. 1 week decay, 4K-20K sec count Ge (Li)		
		6. 2 week decay, 10K-20K sec count Ge (Li)		
		7. 6 week decay, 20K-40K sec count Ge (Li)		
25 kW for 2 min,	Ti - 51	5.79 min	320	1
"Rabbit Run"	Mg - 27	9.46 min	1014	1
(7.5×10^{10} n/cm ² /sec)	V - 52	3.75 min	1434	1
	Al - 28	2.33 min	1779	1
	Ca - 49	8.80 min	3084	1
	Dy - 155	2.32 hr	95	2
	Mn - 56	2.38 hr	847	2
	Na - 24	15.0 hr	1369, 2754	3
1 MW for 3 hr,	K - 42	12.4 hr	1525	4
"Long Lived"	Sm - 153	46.8 hr	104	5, 6
(3×10^{12} n/cm ² /sec)	Lu - 177	6.74 day	208	5, 6
	Yb - 175	101 hr	396	5, 6
	Ba - 131	12.1 day	496	5, 6
	Nd - 147	11.1 day	91, 531	5, 6
	La - 140	40.2 hr	1596	5, 6
	Eu - 152	12.7 yr	122, 1408	6, 7
	Tb - 160	72.1 day	299	6, 7
	Th(Pa - 233)	27.0 day	312	6, 7
	Cr - 51	27.8 day	320	6, 7
	Fe - 59	45.6 day	1099	6, 7
	Sc - 46	83.9 day	1121	6, 7
	Ta - 182	115 day	1221	6, 7
	Co - 60	5.26 yr	1332	6, 7
	Ce - 141	32.5 day	145	7
	Hf - 181	42.5 day	482	7
	Cs - 134	2.05 yr	797	7
	Zr - 95	65.5 day	757	7

* Values obtained from: Gamma Ray Energy Tables for Neutron Activation Analysis. 1970. Compiled and edited by R. H. Filby, A. I. Davis, K. R. Shah, G. G. Wainscott, W. A. Haller, and W. A. Cassatt, Washington State University, Pullman.

Samples were activated for two minutes at a flux of 8×10^{10} neutrons/cm²/sec. For the "long lived" activation samples were placed in the rotating rack around the reactor core for approximately three hours at a flux of 3×10^{12} n/cm²/sec. Samples and standards were activated under the same conditions. A combination of the following properties of radionuclides was used to determine which nuclides were present: gamma ray energies, gamma ray intensities, and half-lives. A listing of the samples analyzed in each section of this work is given in Table 2.

The gamma energies associated with some of the nuclides used in this analysis are similar to minor gamma ray energies of other nuclides. These interfering gamma rays may cause a significant increase in activity at the useful gamma ray energy. This activity must be subtracted out by applying the ratio of the intensities of the interfering gamma ray and another gamma ray of the same nuclide in a pure elemental standard to the gamma ray activities in the sample. For all cases except ¹⁴¹Ce the interference correction amounts to less than 5% of the total activity in my samples. The Ce correction varies from 25-75%. A listing of these interferences is also given in Table 3.

The accuracies of the analysis of the above samples fall within the following ranges:

>40%--Cs;

10-40%--K₂O, Zr, Dy;

Table 2. Activation Sets.

Basalt Type	Sample	Rabbit Run*	Long Lived Run	
Crescent Formation	C1	1	1	
	C2	1	1	
	C3	1	1	
	C4	1	1	
	C5	1	1	
	C6	1	1	
	C7	2	1	
	C8	2	1	
	C9	2	1	
	C10	2	1	
Karmutsen Formation	K1	2	1	
Metchosin Formation	K2	1	1	
	K3	1	1	
	K4	1	1	
	K5	1	1	
	K6	1	1	
	Pack Sack Lookout	P1	3	2
P2		3	2	
P3		3	2	
P4		3	2	
Depoe Bay	D1	3	2	
	D2	3	2	
	D3	3	2	
	D4	3	2	
	D5	3	2	
	D6A	1	1	
	D6B	2	2	
	D7	3	2	
Cape Foulweather	CF1	3	2	
	CF2	3	2	
	CF3	3	2	
	CF4	3	2	
	CF5	3	2	
	CF6A	2	1	
	CF6B	3	2	
	TY15	2	2	
Columbia River	(High Mg Yakima)	TY18	2	
	(Low Mg Yakima)	TY6	1	
	(Prineville)	TY4	1	
	(Frenchman Springs)	TY20	2	
	(Pomona)	CR1	3	
		73-5	2	
	(USGS Standard)	BCR-1	1,2	1
		BCR-2	1,2	2
		BCR-3	3	1
		BCR-4	3	2
	(In House Standard)	CRB-IA	-	1
		CRB-IB	-	2
		CRB-IIA	-	1
CRB-IIB		-	2	
Cove Palisades (Volcanic Ash)	CPL	1	1	
	CPD	2	1	
	CPa	2	1	
	CPb	2	1	

*Samples activated in each of three separate "rabbit runs" and two separate "long lived runs" are designated by the numbers in these columns.

Table 3. Interfering Nuclides.

Nuclide Used	E γ (keV)	Interfering Nuclide
^{152}Eu	122	^{147}Nd , ^{131}Ba
^{141}Ce	145	^{59}Fe
^{177}Lu	209	^{175}Yb
^{160}Tb	299	^{233}Pa (Th)
^{233}Pa (Th)	312	^{141}Ce , ^{160}Tb
^{51}Cr	320	^{147}Nd , ^{177}Lu
^{175}Yb	396	^{147}Nd , ^{233}Pa (Th)
^{95}Zr	756	^{152}Eu
^{59}Fe	1099	^{160}Tb
^{46}Sc	1120	^{152}Eu , ^{160}Tb
^{140}La	1596	^{152}Eu

10-20%--TiO₂, Ba, Ce;

5-10%--MgO, CaO, Cr₂O₃, Tb, Yb, Lu, Hf, Ta, Th;

<5%--Al₂O₃, FeO, Na₂O, MnO, Sc, V, Co, La, Sm, Eu.

These estimated accuracies were determined by comparing the abundances in duplicate aliquants of the U. S. G. S. standard basalt BCR-1 and duplicate aliquants of two of the samples (D6 and CF6). Also duplicate counts were made for many of the elements, and the variation in these taken into account.

The results of the analyses of several samples of Tillamook, Roseburg and Siletz River Volcanics by Drs. M. J. Dudas and R. A. Schmitt are discussed in this paper. The abundances of Ca, Mg, Sr, K and Mn were obtained by atomic absorption spectroscopy. The other abundances were determined by INAA. Al abundances were determined via INAA in this work.

The data for the samples analyzed for this paper are tabulated in the Appendix.

III. MIOCENE BASALTS

1) Results

1.1) Comparison of Results with Other Work

The basalts from the Columbia Plateau were obtained from the University of Oregon and had been previously analyzed by the following people: Osawa and Goles, CR-1; Nathan and Uppuluri, TY 4, TY 6, TY 15, TY 18, TY 20; and Fruchter, 73-5 (Nathan and Fruchter, 1974; Fruchter, private communication). These analysts used an INAA method which was developed by Osawa and Goles and gradually improved by Nathan and Uppuluri and finally by Fruchter to obtain elemental abundances for Fe, Cr, Na, Sc, Co, Ba, La, Sm, Eu, Lu, and Th. The analysis of Osawa and Goles does not agree with this analysis within analytical error except for Fe and Ba. The analyses of Nathan and Uppuluri agree with the results of this analysis quite well except for Lu and Th, and Fruchter's analysis is in excellent agreement with this analysis. The agreement obviously becomes better with their later results. In almost all cases of disagreement, their values are higher than the values from this analysis, and the agreement becomes better with later analyses increasing the reliability of the values from this analysis. Nathan and Uppuluri also analyzed two of these samples for major elemental abundances by x-ray

fluorescence analysis. The agreement with this analysis is excellent with the exception of MnO where the values from this analysis are also low.

The coastal basalts had also been previously analyzed for major element composition (Snavely et al., 1973). Their analyses generally show about 5% higher Al_2O_3 , about 10% higher MnO and about 2 to 3% lower total Fe than this analysis. The other elements are in very good agreement. The abundances of Al_2O_3 in this analysis of the USGS standard rock BCR-1 averaged 5% lower than the accepted value, and the Al_2O_3 abundances in this work were thus raised 5%. The BCR-1 elemental abundance values from this analysis for the rest of the elements determined are in good agreement with the accepted values including the MnO abundance (Laul and Schmitt, 1973; and Flanagan, 1967). The INAA technique is very sensitive for Mn, and there is no reason to doubt the values obtained.

1.2) Stratigraphy and Variation of the Coastal Basalts

Further discussion of this data is placed in order by following the stratigraphy of Wright, Grolier and Swanson (1973) and Nathan and Fruchter (1974) for the Columbia River Basalt and that of Snavely et al. (1973) for the coastal basalts (Table 4). The oldest of these coastal basalts are the Depoe Bay basalts which are overlain by the Cape Foulweather basalts. The Depoe Bay basalts are similar to the Lower

Table 4. Miocene Basaltic Stratigraphy. (Not all plateau chemical types have Coast Range equivalents.)

K-Ar Dates	Coast Range Basalts	Yakima Basalts	K-Ar Dates
	---	UPPER YAKIMA (chemical types)	
	---	Ice Harbor	
	---	Elephant Mountain	
9.0 ± 1.4 m. y. ^a	Basalt of Pack Sack		
12.9 ± 2 m. y. ^b	Lookout	Pomona	
	---	MIDDLE YAKIMA (chemical types)	13.4 ± 0.4 m. y. ^c 16.5 ± 0.8 m. y. ^b
	---	Umatilla	
	---	Roza	
	Cape Foulweather Basalt	Frenchman Springs	
16 ± 0.65 m. y. ^d			15.3 ± 0.8 m. y. ^e
14.5 ± 1.0 m. y. ^e	DEPOE BAY BASALT (chemical types)	LOWER YAKIMA (chemical types)	15.2 ± 0.7 m. y. ^b 16.4 ± 0.6 m. y. ^b
15.2 ± 0.6 m. y. ^e		High Mg	
14 ± 2.7 m. y. ^e		Low Mg	

^aR. E. Denison (written communication to Snively *et al.*, 1973).

^bHolmgren (1970).

^cEvernden and James (1964).

^dJ. Obradovich (written communication to Snively *et al.*, 1973).

^eTurner (1970).

Yakima basalts which are overlain by the Frenchman Springs chemical type of the Middle Yakima basalts. The Frenchman Springs basalts are also similar to the Cape Foulweather basalts. The Pomona flows form the lower member of the Upper Yakima and are similar to the basalt of Pack Sack Lookout defined by Snavely et al. (1973). The possibility that the basalt of Pack Sack Lookout is a flow of Pomona basalt cannot be ruled out because of the paucity of intrusive features. However Pomona flows are generally limited to the central part of the Columbia Plateau and no Pomona flows have been found in areas between the plateau and the Cathlamet area. The basalt of Pack Sack Lookout overlies Yakima basalt in some places but has no contacts with the other coastal basalts. Dates obtained by the K-Ar method on basalts from Pack Sack Lookout show that they are the youngest of these coastal basalts (Snavely et al., 1973).

The variation in chemical composition from sample to sample in the basalt of Pack Sack Lookout is very small (Appendix, Table 13). The greatest variation is shown by K_2O content which ranges from 0.4% to 0.7%. For most elements the total variation is less than 10% from the mean. With the exception of one of the six samples, the variation in the Cape Foulweather basalts is also generally less than 10% (Appendix, Table 12). The exception shows high MgO and quite high Cr_2O_3 content and slightly lower values for the REE. The K_2O content is again more variable than the other elements ranging from 0.6% to

1.3%. At first glance the composition of the Depoe Bay basalts appears to show variability of up to 50% (Appendix, Table 11). However, if the samples are divided into two different groups on the basis of MgO content, a remarkable uniformity within each group becomes apparent. This fact is not entirely surprising since both Wright et al. (1973) and Nathan and Fruchter (1974) found a similar grouping of compositions around low and high Mg Lower Yakima basalts. Since the high Mg basalts overlie the low Mg basalts on the plateau, this similarity in variation with Mg content is a very strong argument in favor of a common magma source for the basalts from the coast and the basalts from the plateau. One of the higher Mg Depoe Bay basalts (D3) seems to be fairly intermediate between the low and high Mg end members for many of the elements studied. However it has been classified as a high Mg basalt in the rest of this paper for easier data reduction on the basis of its MgO and REE contents. The high and low Mg Depoe Bay basalts will be treated as separate chemical types in this paper although they are apparently only end members of a somewhat continuous variation.

2) Discussion

2.1) Fractional Crystallization

The chemical composition of magmas may be changed during

ascent by several factors including fractional crystallization, wall rock reactions, reaction with ground water, assimilation of crustal material, etc. Fractional crystallization is thought to be a major factor in the chemical composition of many magmas and has several fairly well defined effects. Early fractional crystallization of olivine and pyroxene at high temperature preferentially reduces Mg content of the magma compared with Fe thus increasing the Fe/Mg ratio. Plagioclase preferentially takes in Ca during early crystallization, and fractionation of these crystals should result in lower Ca and Al contents in the magma.

Clinopyroxene also takes in Ca during crystallization. However Al is included in clinopyroxene in only very small quantities, and thus a decrease in both Ca and Al contents of magma indicates fractional crystallization of plagioclase. At high pressures plagioclase is unstable and Ca and Al go into the garnet and spinel phases, but the plagioclase phenocrysts observed in these samples suggests that plagioclase was stable during fractional crystallization. Since the primary minerals involved in fractional crystallization of the samples are apparently olivine, plagioclase, and pyroxene, one would expect continuing fractional crystallization to increase the Fe/Mg ratio and lower the Ca and Al contents of the magma.

Trace and minor elements either enter the crystal lattices or remain in the magma depending in large part on their ionic radius and

charge. Green and Ringwood (1967) have defined the elements which tend to follow the crystals in basaltic magmas (Cr, Co, V, Sc, and Mn) as compatible and those which are left behind (K, Zr, Ti, Ba, Cs, light REE, Hf, Th, and Ta) as incompatible. Continuing fractional crystallization should decrease or have little effect on the content of compatible elements in a magma but should increase the content of incompatible elements. It is improbable that all of the basalts were derived from the same primary magma; however, it is possible that they were derived from very similar primary magmas which resulted from different periods of partial melting of the mantle. Thus in this section of the paper the basalt samples are compared with each other to determine possible relative amounts of fractional crystallization.

The average abundances of several representative elements in the low and high Mg Depoe Bay basalts and Cape Foulweather basalts have been normalized to the average abundances in the basalt of Pack Sack Lookout and plotted according to atomic number in Figure 2. The basalt of Pack Sack Lookout appears to have the most primitive composition, but it was the last of the series to be extruded. From the trends shown on this plot it is obvious that there was no one primary magma, and the choice of the basalt of Pack Sack Lookout as a normalizer is arbitrary.

In comparison with the other Miocene coastal basalts, the low Mg Depoe Bay basalts have large Fe/Mg ratios which suggest more

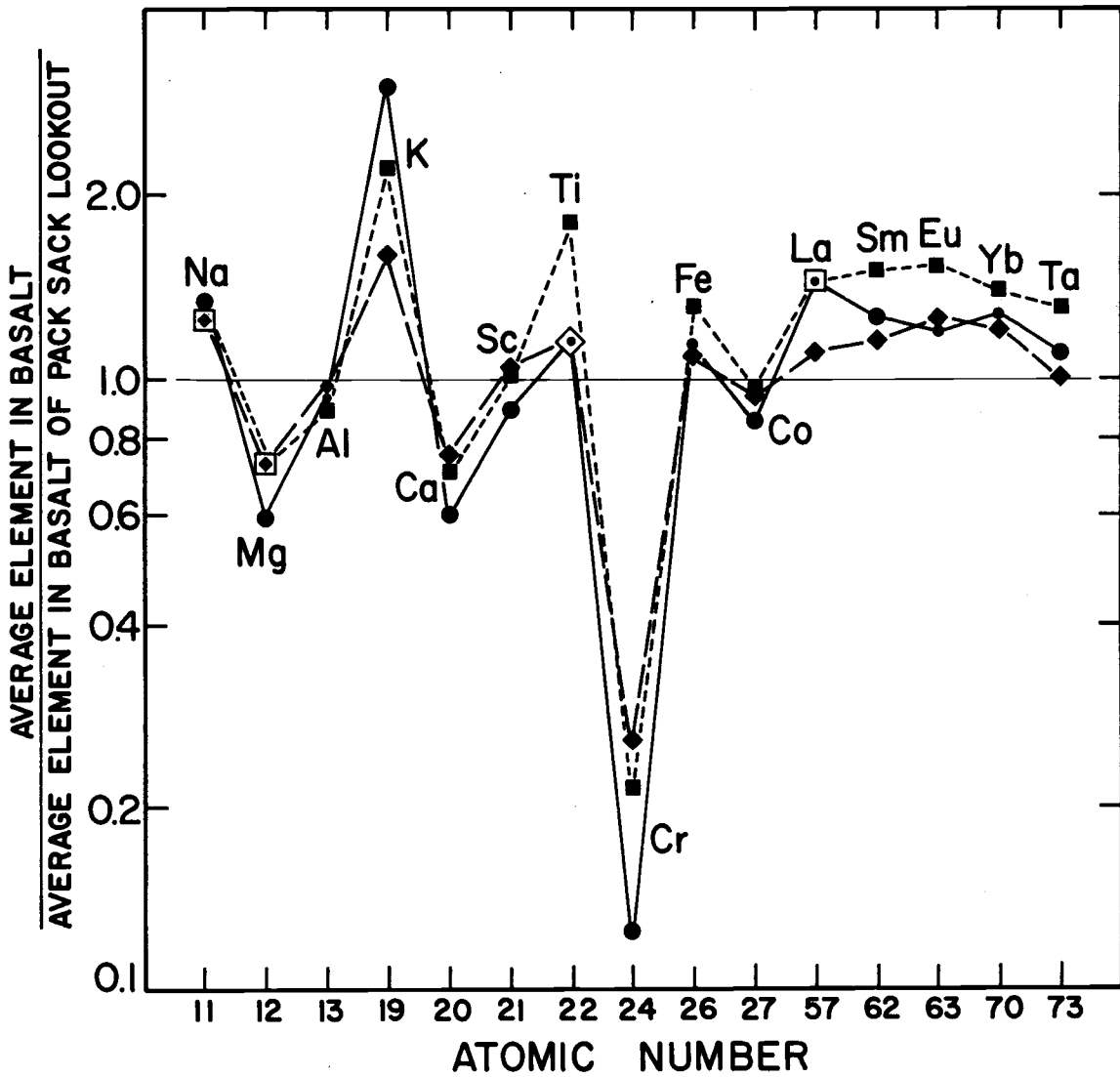


Figure 2. Average abundances of several representative elements in low (●) and high (◆) Mg Depoe Bay basalts and Cape Foulweather basalts (■) are normalized to the average abundances of the basalt of Pack Sack Lookout.

extensive fractional crystallization of olivine and pyroxene from their original magma. These basalts also have the lowest CaO and low Al_2O_3 contents suggesting more fractional crystallization of plagioclase. The incompatible element content is high and suggests a large degree of fractional crystallization for these basalts. The apparently younger high Mg Depoe Bay basalts have lower Fe/Mg ratios, somewhat higher CaO and Al_2O_3 contents, and lower content of incompatibles than the low Mg Depoe Bay basalts suggesting less extensive fractional crystallization of olivine, pyroxene, and plagioclase and generally less fractional crystallization than the older basalts.

The intermediate aged Cape Foulweather basalts have the largest Fe/Mg ratios suggesting the greatest fractional crystallization of olivine and pyroxene. These basalts show the lowest Al_2O_3 and fairly low CaO suggesting a fairly large extent of fractional crystallization of plagioclase. The incompatible element contents of these basalts are the highest in the Miocene group and indicate that fractional crystallization has had more effect on this magma than the others.

The basalt of Pack Sack Lookout has the highest CaO, Al_2O_3 , and MgO contents, the lowest Fe/Mg ratios, and the lowest amounts of the incompatible elements. These facts suggest that the basalt of Pack Sack Lookout has suffered the least fractional crystallization of olivine, pyroxene, and plagioclase.

Petrographic studies of the Miocene coastal basalts were performed by Snavely et al. (1973). Their results can be interpreted to agree with the above discussion, but may be interpreted in other ways just as easily. They show that the Depoe Bay basalts in general show no phenocrysts and no olivine along with higher plagioclase. The Cape Foulweather basalts contain sparse, large phenocrysts of calcic plagioclase and higher olivine than the others. Their plagioclase content is similar to the Pack Sack Lookout basalt, and the pyroxene content is similar to the Depoe Bay basalts. The Pack Sack Lookout basalt contains numerous small phenocrysts of plagioclase and microphenocrysts of olivine and pyroxene all of which grade serially to groundmass size. The plagioclase phenocrysts have calcic cores and sodic rims, and the olivine phenocrysts have pyroxene reaction rims. Many of the phenocrysts have glassy inclusions. These basalts have some olivine and the most pyroxene of the group in the groundmass.

The distinctive large plagioclase phenocrysts in the Cape Foulweather basalts are consistent with the suggested degree of fractional crystallization of this magma. However one might expect to see similar phenocrysts in the Depoe Bay basalts which underwent only somewhat less fractional crystallization. A possible explanation for this difference is that the Cape Foulweather basalts appear to have been erupted under more violent conditions which may have caused

some stirring in the magma chamber and brought some of the settled crystals into the erupting magma.

The high pyroxene content of the Pack Sack Lookout basalt is consistent with a much smaller degree of fractional crystallization. These basalts were erupted on dry land, and the small phenocrysts grading to groundmass size may be due to the somewhat slower cooling in the sometimes very thick flow. The reaction rims on the plagioclase and olivine phenocrysts indicate they remained in equilibrium with the liquid during cooling. The glass inclusions in these phenocrysts may also indicate a fairly rapid cooling such as would occur at the surface.

The various compositions observed for these basalts could also possibly be explained by varying degrees of assimilation of crustal material by the parent magma. The incompatible elements would be preferentially assimilated and would increase in concentration in the magma with increasing assimilation. The Sr isotope ratio should also increase during this process because the radiogenic ^{87}Sr is formed in crystals which normally accept Rb ions and is thus incompatible, whereas normal Sr acts as a compatible element. Thus in this process one would expect higher Sr ratios to correspond with higher K_2O and REE abundances. McDougall (1974) shows that the basalt of Pack Sack Lookout definitely has the largest Sr isotope ratio of the coastal basalts.

However the data presented here show that these basalts have the lowest K_2O and REE contents of the coastal basalts indicating that assimilation of crustal material was probably not the primary source of variation in these basalts. The plagioclase phenocrysts in the Cape Foulweather basalts also show that there must have been at least some fractional crystallization in the coastal basalts.

Variation in chemical composition may also be caused by differing depths of partial melting and magma separation within the mantle, and by differing degrees of partial melting. According to Green and Ringwood (1967) partial melting is the reverse of fractional crystallization provided the crystalline phases are similar. Thus the smaller the degree of partial melting, the higher the concentrations of the incompatible elements and the higher the Fe/Mg ratios. These authors also show that higher pressure (greater depth) of magma separation causes lower Al_2O_3 content in the melt and higher pyroxene/olivine ratio in the remaining crystals.

The relative degree of partial melting which would account for most of the variation in these basalts may be determined by examining the relationships of the incompatible elements and the Fe/Mg ratios in these basalts as shown in Figure 2. Using this method the coastal Miocene basalts have the following order with respect to increasing degree of partial melting: Cape Foulweather basalt, low Mg Depoe

Bay basalt, high Mg Depoe Bay basalt, and basalt of Pack Sack Look-out.

It is most likely that the actual variation observed in these basalts is due to a combination of varying degrees and depths of partial melting and varying amounts of fractional crystallization.

2.2) Chemical Comparison of Coastal and Plateau Basalts

The similarity of certain chemical types in the Columbia River basalts to the Miocene coastal basalts has been mentioned. In this section averages of the results of the present analysis on the coastal basalts are compared to average abundances for both coastal and plateau basalts taken from Snavely et al. (1973) and to average abundances for plateau basalts taken from Nathan and Fruchter (1974), this analysis, and the data obtained from the Center for Volcanology at the University of Oregon (Fruchter, private communication). Sample localities included in the University of Oregon (U. of O.) average abundances are given in the Appendix. The values from Snavely et al., were recalculated 100% water free and thus may differ somewhat from the whole rock analysis.

Snavely et al. (1973) did not differentiate between low and high Mg Yakima and Depoe Bay basalts so their results cannot be compared with others. Their averages do show very good agreement between

the Lower Yakima basalts and the Depoe Bay basalts on a major element basis.

The compositional averages for the low Mg Yakima and Depoe Bay basalts are given in Table 5. The results for the one low Mg Yakima basalt from this work show very good correlation with the U. of O. and Nathan and Fruchter averages except for MnO, Cr_2O_3 , MgO and Th. Discrepancies in MnO and Th abundances have been noted before on the samples analyzed by both groups. Thus these results are in very good agreement since the Cr_2O_3 content of these samples is quite variable. The average for low Mg Depoe Bay basalts follows the composition of the low Mg Yakima basalt sample from this analysis very closely and generally falls closer to the U. of O. or Nathan and Fruchter averages when it deviates from the sample from this work.

Table 6 shows the average compositions of the high Mg Yakima and Depoe Bay basalts. The average abundances for the high Mg Yakima basalts are again in very good agreement, and the average abundances from this work agree better with the U. of O. average abundances. The Al_2O_3 abundance from this analysis appears to be low but agrees with the Depoe Bay average. The high MgO value in this average seems to be anomalous but real. The average for the high Mg Depoe Bay basalts falls within the range of the high Mg Yakima basalt averages showing the high degree of similarity between these basalts.

Table 5. Low Mg Lower Yakima and Depoe Bay Basalts.

	Lower Yakima Ave. (Snavely)*	Depoe Bay Ave. (Snavely)*	LOWER YAKIMA		DEPOE BAY	
			Nathan & Fruchter ⁺ Ave.	U of O ^x Ave.	This Work	This Work Ave.
TiO ₂ (%)	2.0 - 2.0	2.0	2.20	2.04	2.0	1.9
Al ₂ O ₃	14.2 - 13.6	14.0	13.76	13.39	13.3	12.7
FeO ⁺⁺	11.5 - 12.1	12.1	12.30	11.8	11.6	12.0
MgO	4.2 - 4.2	3.6	3.38	3.13	3.8	3.6
CaO	7.9 - 7.9	7.1	7.11	6.76	6.8	6.3
Na ₂ O	3.0 - 3.0	3.3	3.27	3.03	3.0	3.2
K ₂ O	1.3 - 1.4	1.4	1.78	2.07	1.7	1.5
MnO	0.21 - 0.18	0.21	0.21	0.207	0.174	0.172
Cr ₂ O ₃ (ppm)			15	17	32	18
Sc			31	31	33	31
V					350	320
Co			34	35	37	35
Zr					110	160
Ba			~600	645	590	580
La			24	24.1	24.2	24.3
Ce					48	49
Nd					28	25
Sm			6.9	6.8	6.3	6.4
Eu				1.9	1.81	1.79
Tb					1.00	1.00
Dy					6	6
Yb				2.9	3.8	3.3
Lu			0.59	0.56	0.50	0.50
Hf					4.6	4.8
Ta					0.73	0.75
Th			5.8	6.2	4.5	5.3
Cs					1.4	1.6

* Snavely *et al.* (1973).

+ Nathan and Fruchter (1974).

^x Average of analyses obtained from Fruchter (private communication).⁺⁺ Total Fe was calculated as FeO for all data tables in this paper.

Table 6. High Mg Lower Yakima and Depoe Bay Basalts.

	YAKIMA			DEPOE BAY
	Nathan & Fruchter Ave. ⁺	U. of O. ^x Ave.	This Work Ave.	This Work Ave.
TiO ₂ (%)	1.78	1.76	1.9	1.9
Al ₂ O ₃	14.33	14.09	13.4	13.3
FeO	11.42	11.46	11.0	11.9
MgO	4.90	4.77	5.8	4.6
CaO	8.72	8.43	8.3	7.9
Na ₂ O	2.84	3.0	2.9	3.0
K ₂ O	1.17	1.22	1.2	0.8
MnO	0.20	0.188	0.185	0.196
Cr ₂ O ₃ (ppm)	36	55	66	37
Sc	33	35	38	37
V			320	320
Co	38	38	41	38
Zr			150	170
Ba	~500	488	440	420
La	19	18.4	18.5	19.1
Ce			38	41
Nd			22	24
Sm	5.3	5.76	5.6	5.9
Eu		1.71	1.71	1.74
Tb			0.90	0.90
Dy			6	5
Yb		2.7	3.1	3.1
Lu	0.40	0.49	0.47	0.47
Hf		3.8	3.9	4.2
Ta			0.60	0.69
Th	3.5	3.6	3.0	3.3
Cs			0.6	0.9

⁺ Nathan and Fruchter (1974).

^x Average of analyses obtained from Fruchter (private communication).

The Frenchman Springs and Cape Foulweather basalt average abundances are shown in Table 7. The agreement of all the average abundances in this table is very good except for the Al_2O_3 , Cr_2O_3 , and MnO contents which have been discussed previously.

The averages for the Pomona and Pack Sack Lookout basalts show a much larger variability. The reason for this is that data on the trace elements in Pomona basalts is scarce. Data has been obtained for only three samples, two of which have also been analyzed in this work. Two of these samples seem to be higher in trace elements than the Pack Sack Lookout basalt, but the third agrees very well. This may not be surprising since the Pomona basalt consists of several flows whereas the Pack Sack Lookout basalt appears to have been the result of a single flow. The major element averages for Pack Sack Lookout basalt agree quite well with Snavelly's average for Pomona basalts. Data for these basalts is shown in Table 8 (Nathan and Fruchter did not give an average for Pomona basalts).

Snavelly et al. (1973) plotted silica variation diagrams of the major elements for these coastal and plateau basalts which show the groupings of the three pairs. The SiO_2 content of these samples cannot be determined by INAA, so another element has been chosen as the base for variation diagrams of the trace elements. The total Fe content of basalts, which is easily and accurately obtained and is the only major element determined in all of the U. of O. samples, has

Table 7. Frenchman Springs and Cape Foulweather Basalts.

	FRENCHMAN SPRINGS				CAPE FOULWEATHER	
	Snavely* Ave.	Nathan & ⁺ Fruchter Ave.	U. of O. ^x Ave.	This Work	Snavely* Ave.	This Work Ave.
TiO ₂ (%)	3.0 - 3.4	3.00	2.93	2.8	3.0	3.0
Al ₂ O ₃	13.6 - 13.0	13.71	13.05	12.5	13.9	12.5
FeO	14.0 - 14.7	14.16	14.23	13.6	14.1	14.0
MgO	4.5 - 4.6	4.19	4.21	4.3	3.9	3.6
CaO	8.3 - 8.5	8.46	8.22	7.5	7.9	7.5
Na ₂ O	2.9 - 2.7	2.86	2.87	2.9	3.0	3.0
K ₂ O	1.2 - 1.3	1.33	1.29	1.0	1.0	1.1
MnO	0.24 - 0.24	0.24	0.21	0.180	0.22	0.181
Cr ₂ O ₃ (ppm)		30	49	74		31
Sc		34	35	38		36
V				430		380
Co		39	40	40		39
Zr				170		180
Ba		~ 550	566	470		480
La		24	24.0	23.5		24.3
Ce				50		52
Nd				31		30
Sm		7.4	7.78	7.3		7.7
Eu			2.18	2.18		2.28
Tb				1.14		1.17
Dy				6		7
Yb			3.3	3.4		3.6
Lu		0.47	0.55	0.53		0.53
Hf			5.2	5.0		4.8
Ta				0.87		0.89
Th		3.7	3.9	3.8		3.9
Cs				0.7		1.0

* Snavely *et al.* (1973).⁺ Nathan and Fruchter (1974).^x Average of analyses obtained from Fruchter (private communication).

Table 8. Pomona and Pack Sack Lookout Basalts.

	POMONA			PACK SACK LOOKOUT		
	Snavely* Ave.	U. of O. ^x Ave.	This Work Ave.	This Work & U. of O. ⁺ 73-5	Snavely* Ave.	This Work Ave.
TiO ₂ (%)	1.7		1.7	1.5	1.6	1.65
Al ₂ O ₃	15.1		13.4	13.6	15.1	13.8
FeO	10.8	11.4	11.5	10.9	10.3	10.6
MgO	7.0		6.7	7.8	6.9	6.5
CaO	10.9		10.0	9.9	10.6	10.5
Na ₂ O	2.3	2.29	2.5	2.4	2.3	2.4
K ₂ O	0.62		0.8	0.7	0.56	0.5
MnO	0.20		0.173	0.166	0.18	0.161
Cr ₂ O ₃ (ppm)		131	127	161		144
Sc		38	37	36		35
V			300	270		270
Co		48	42	43		41
Zr			140	130		100
Ba		280	220	200		220
La		20.0	19.1	17.2		17.0
Ce			40	37		35
Nd			24	24		21
Sm		5.38	5.6	5.1		5.1
Eu		1.8	1.68	1.57		1.49
Tb			0.87	0.75		0.82
Dy			5	5		5
Yb		3.55	3.0	2.9		2.6
Lu		0.61	0.43	0.40		0.40
Hf			3.9	3.5		3.4
Ta			0.80	0.73		0.68
Th		3.3	2.7	2.7		2.5
Cs			0.2	0.2		0.2

* Snavely *et al.* (1973).

^x Average of analyses obtained from Fruchter (private communication).

⁺ Average of duplicate analyses of sample 73-5.

been chosen as the base for this paper. The diagrams for two representative REE and the rest of the trace elements are shown in Figures 3 through 8. The data on the plateau basalts from the U. of O. has been plotted and outlines drawn around the different chemical types, when sufficient points are obtained, to show the comparison of the plateau and coastal basalts.

The points of two of the low Mg Depoe Bay basalts always fall within the outline of the low Mg Yakima basalts. The other low Mg Depoe Bay basalt has an anomalously high FeO content which keeps it from falling within the outlines. However the trace element contents of this sample fall within the trace element variations of the low Mg Yakima basalts for all but one element (Ba) which is only slightly low. Thus these diagrams provide excellent evidence for the correlation of the low Mg Yakima and low Mg Depoe Bay basalts.

The points for the three high Mg Depoe Bay basalts which have been definitely classed as high Mg basalts fall within or very near the outlines of the high Mg Yakima basalts in all cases except one Cr_2O_3 point. The one Depoe Bay basalt which appears to be intermediate in composition falls within the low Mg Yakima outlines for Cr_2O_3 , Sc, and Co and within the high Mg Yakima outlines for Co, Ba, and Lu. This basalt falls between the outlines for La and Th and thus does not really correlate with either chemical type. These diagrams thus show that the correlation between the end members of the low and high Mg

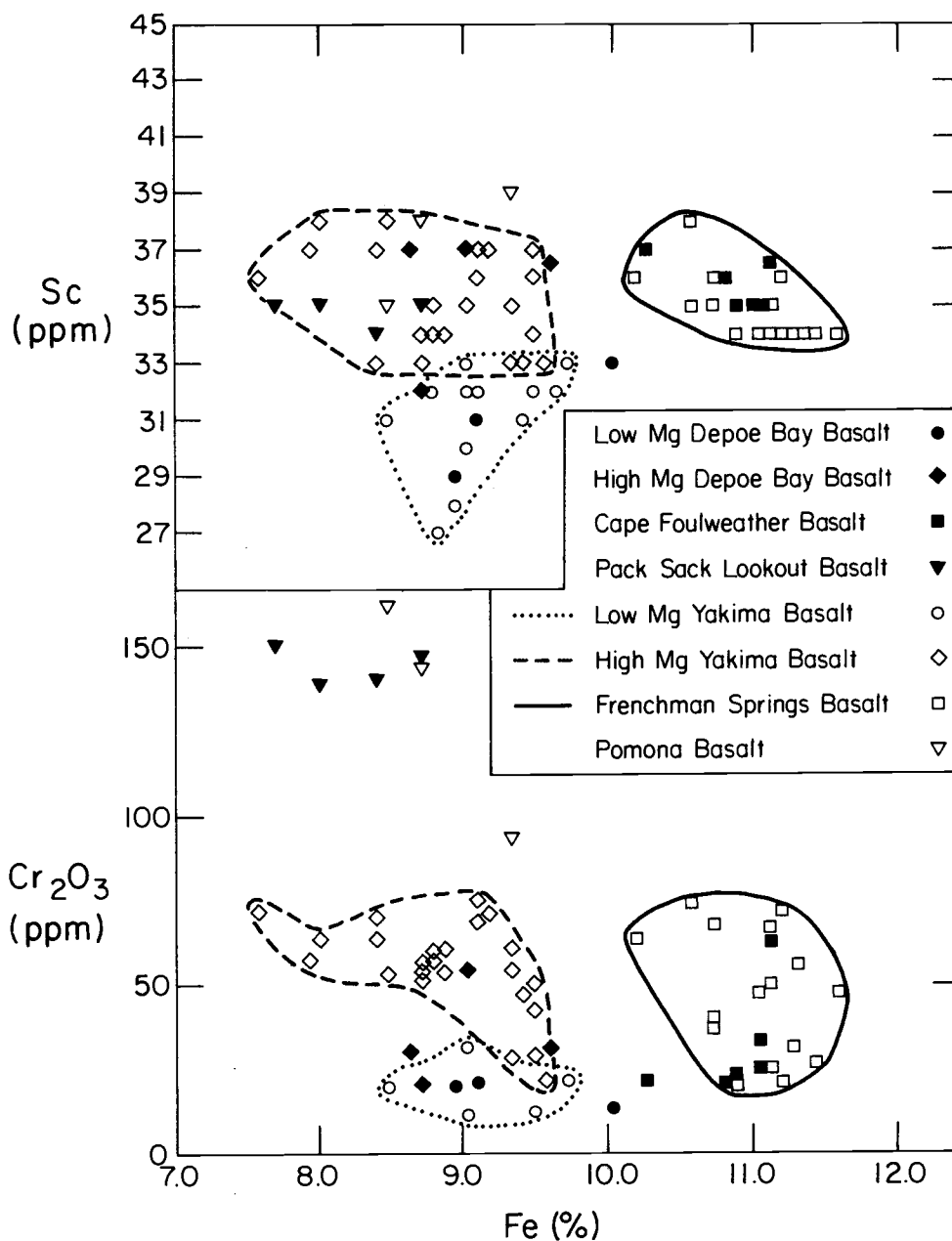


Figure 3. Variation diagram of Fe versus Sc and Cr₂O₃. Solid symbols are for the coastal basalts, and open symbols are for the plateau basalts. Sample representations are as follows: ○, ●, low Mg, ◇, ◆, high Mg Lower Yakima and Depoe Bay basalts; □, ■, Frenchman Springs and Cape Foulweather basalts; ▽, ▼, Pomona basalt and basalt of Pack Sack Lookout. The regions for low Mg and high Mg Lower Yakima and Frenchman Springs basalts are designated by dotted, dashed, and solid lines, respectively. No region for Pomona basalt is designated due to lack of sufficient data.

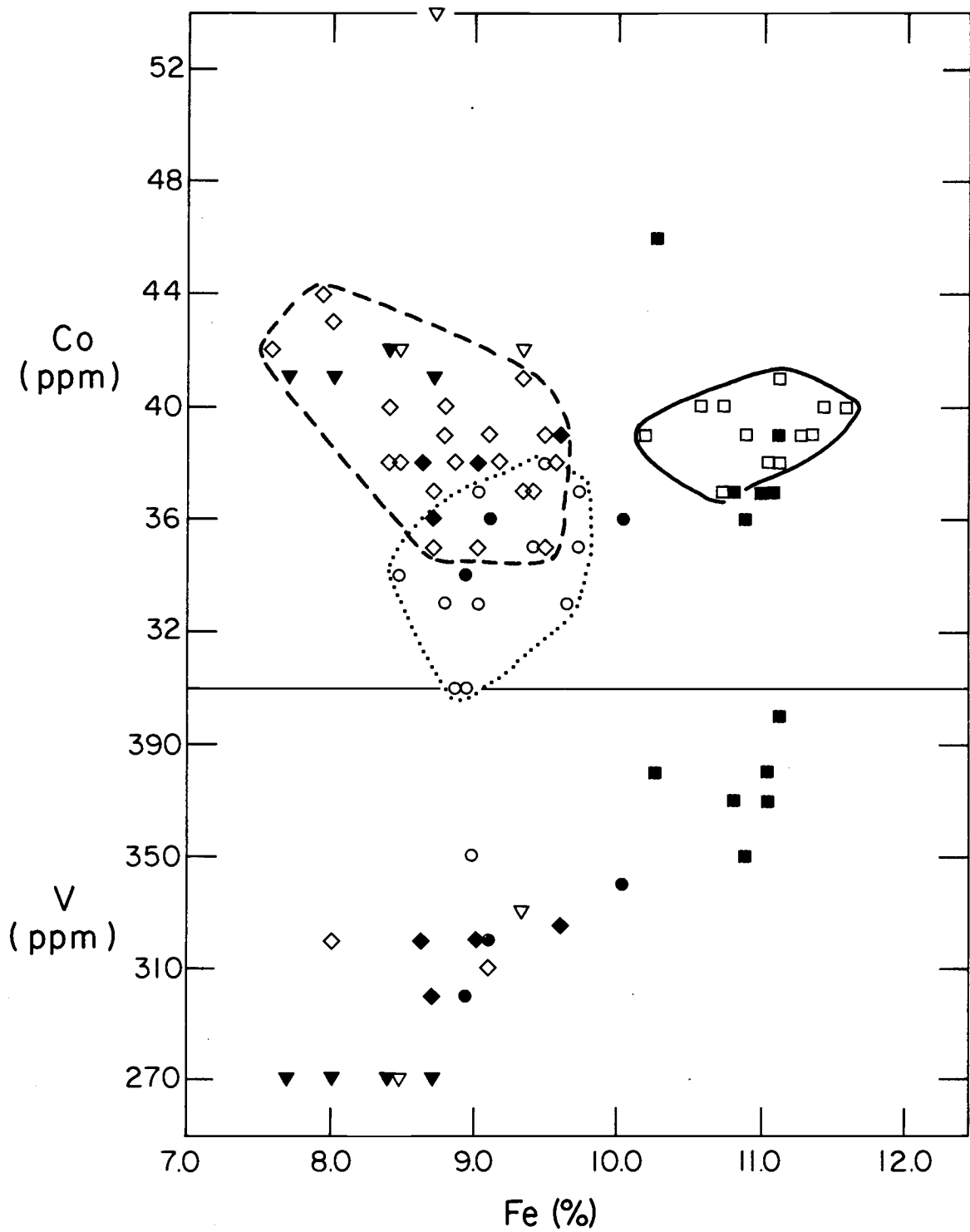


Figure 4. Variation diagram of Fe versus Co and V. Symbols are same as in Figure 3.

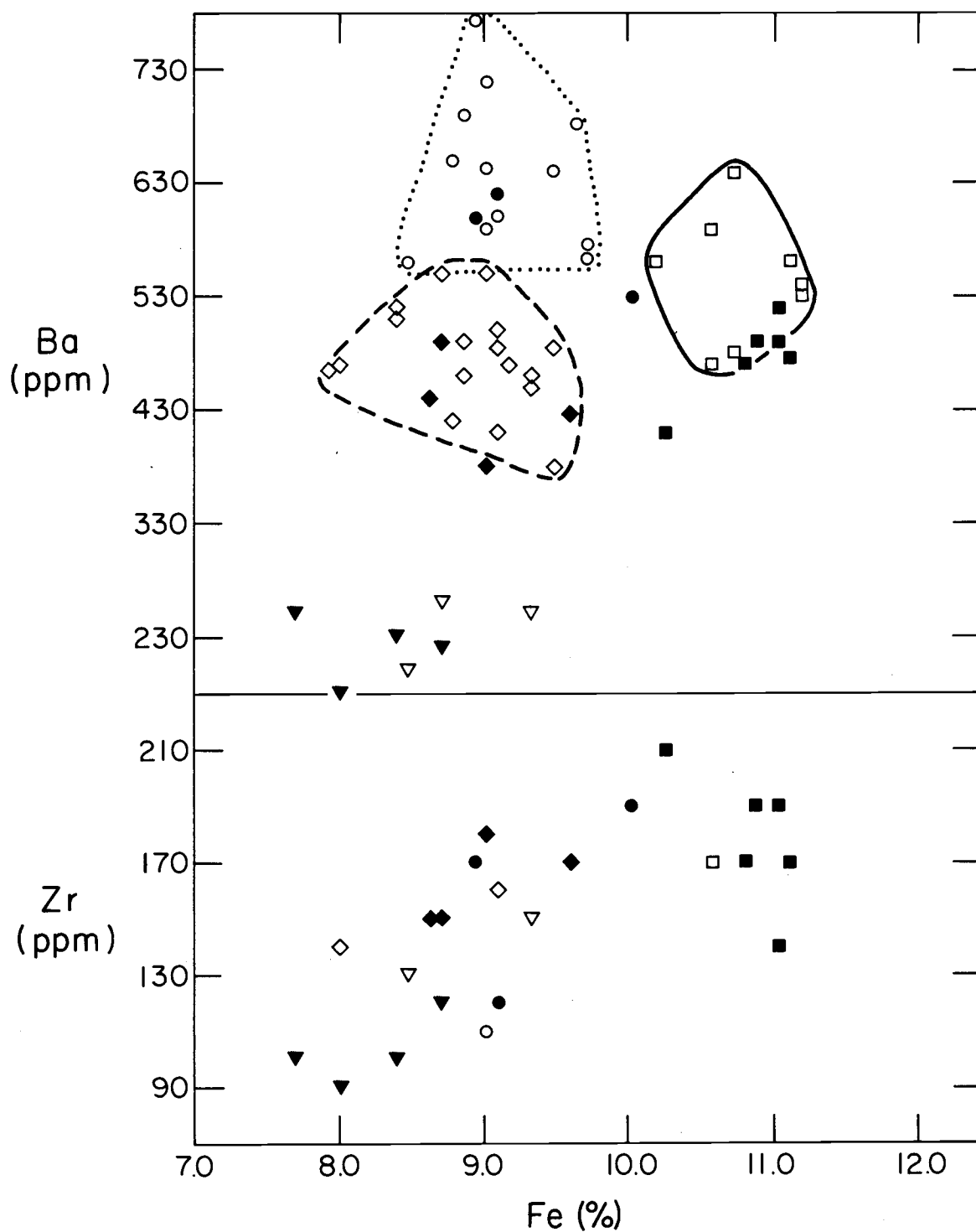


Figure 5. Variation diagram of Fe versus Ba and Zr. Symbols are same as in Figure 3.

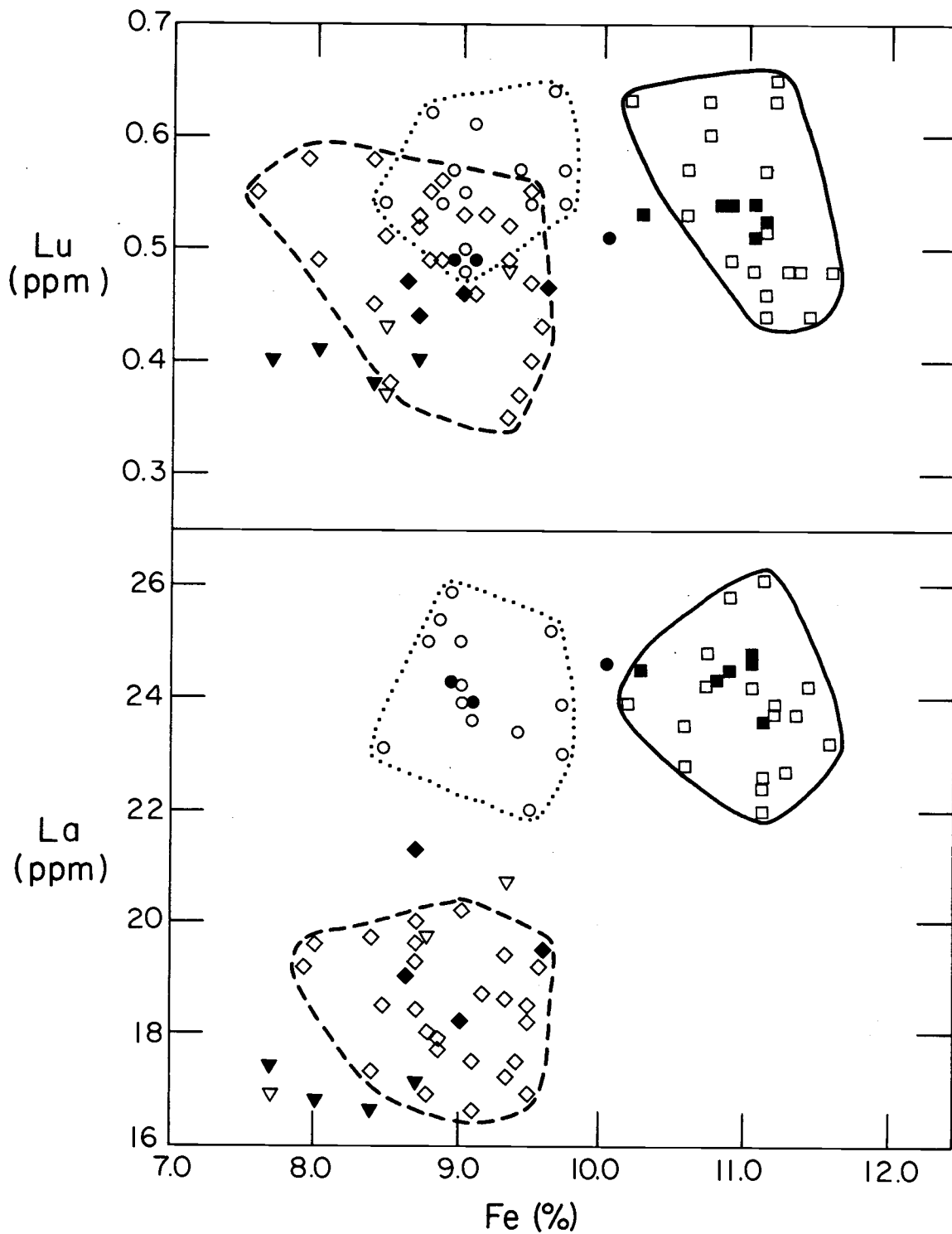


Figure 6. Variation diagram of Fe versus La and Lu. Symbols are same as in Figure 3.

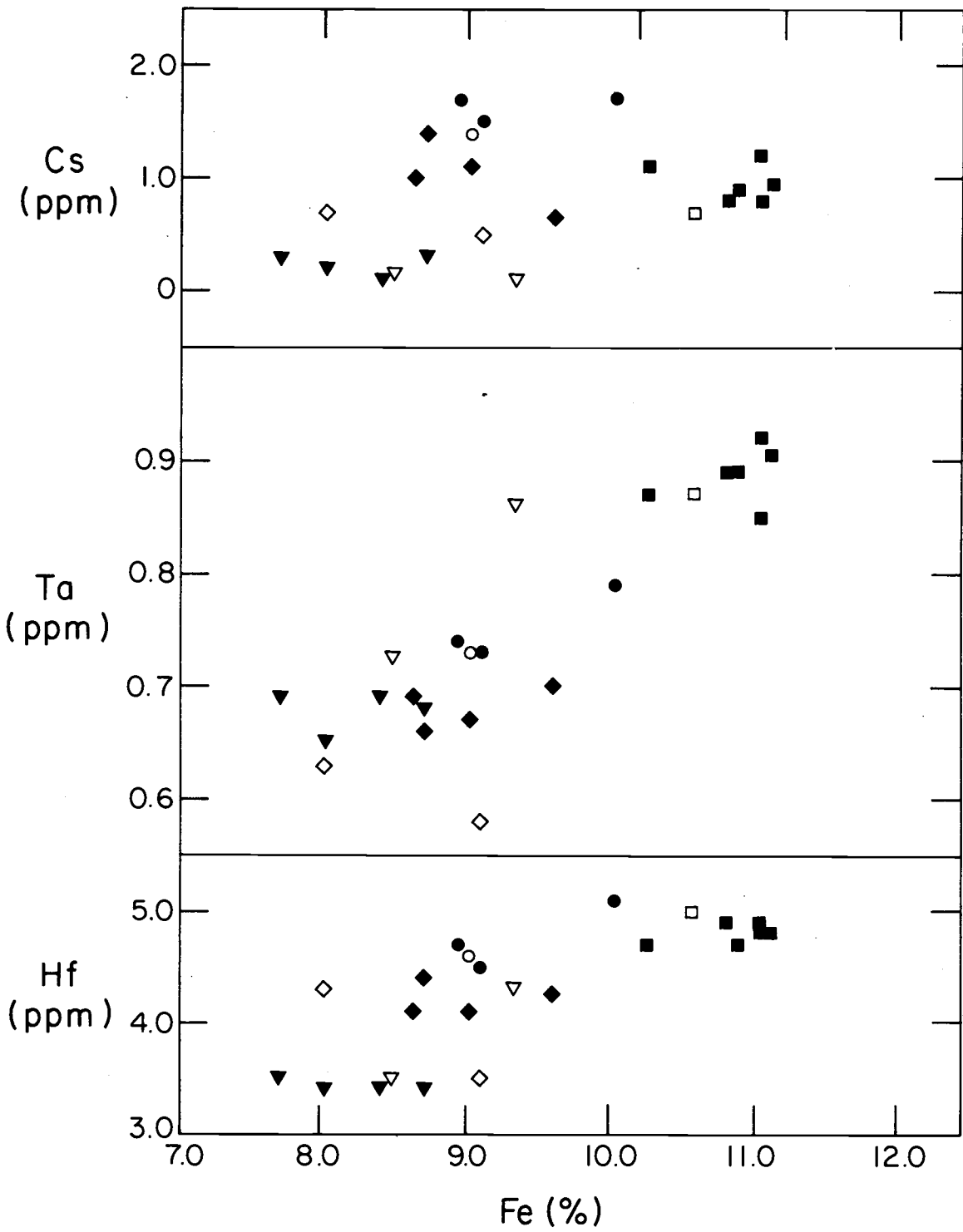


Figure 7. Variation diagram of Fe versus Cs, Ta and Hf. Symbols are same as in Figure 3.

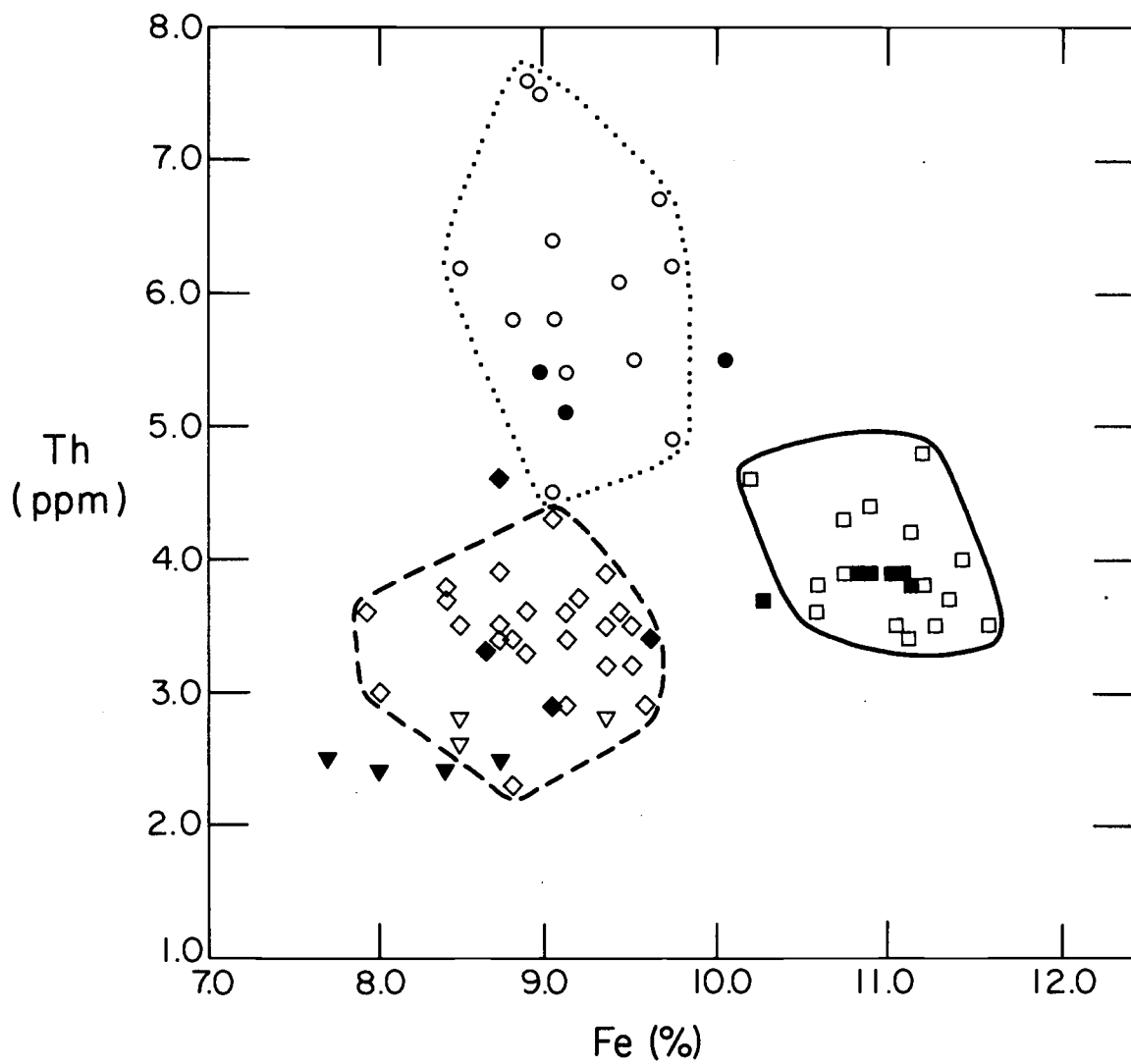


Figure 8. Variation diagram of Fe versus Th. Symbols are same as in Figure 3.

Yakima and Depoe Bay basalts is very good, but that the chemical types are transitional rather than distinct.

In the Cape Foulweather basalts there is again a maverick sample as has been noted earlier in the paper. Points from the other five samples all plot within or very near the outlines for the Frenchman Springs basalts showing the very good correlation between these two groups of basalts. The maverick sample has low FeO and Ba and high Co values when compared with the Frenchman Springs basalts. There were not enough points from the Pomona basalts to draw outlines and no definite correlations were found.

The REE compositions of these basalts normalized to the REE composition in chondrites also show good correlation. The ranges in the normalized patterns for each pair of basalts have been plotted against the ionic radii of the elements in Figures 9, 10, 11, and 12. The U. of O. values for the plateau basalts were combined with the values from this analysis in computing the ranges for these basalts. The Dy points are used sparingly since in many cases only one point is available and the error in the Dy numbers is quite high. The range of the low Mg Depoe Bay basalts falls entirely within the range of the low Mg Yakima basalts again showing excellent correlation for this chemical type. The intermediate Depoe Bay basalt has been plotted with the high Mg basalts, and the plot shows that the La and Ce points are slightly higher than high Mg Yakima range. However, the other

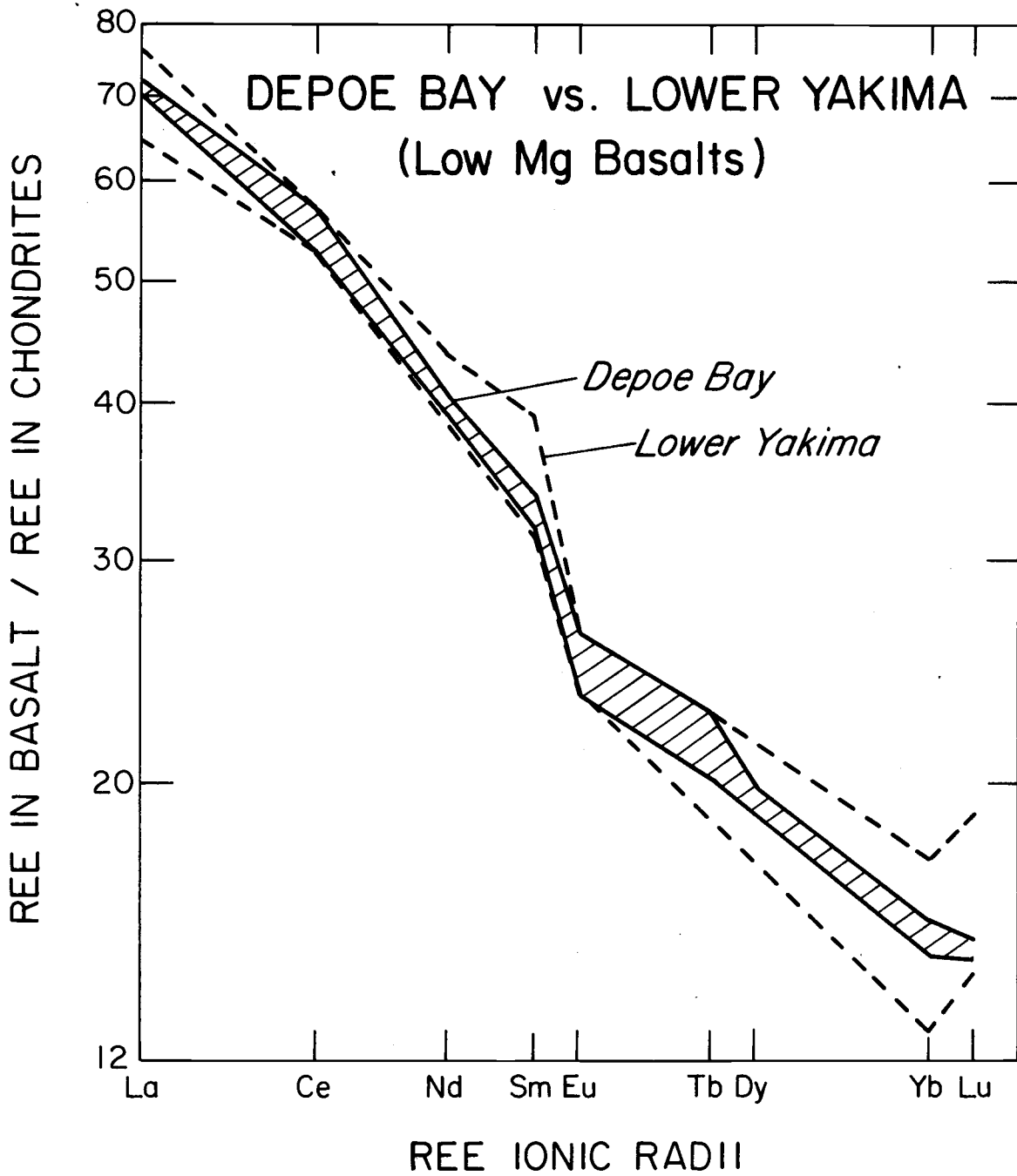


Figure 9. Abundance ranges of REE in low Mg Lower Yakima and Depoe Bay basalts are normalized to the average abundances in ordinary chondrites.

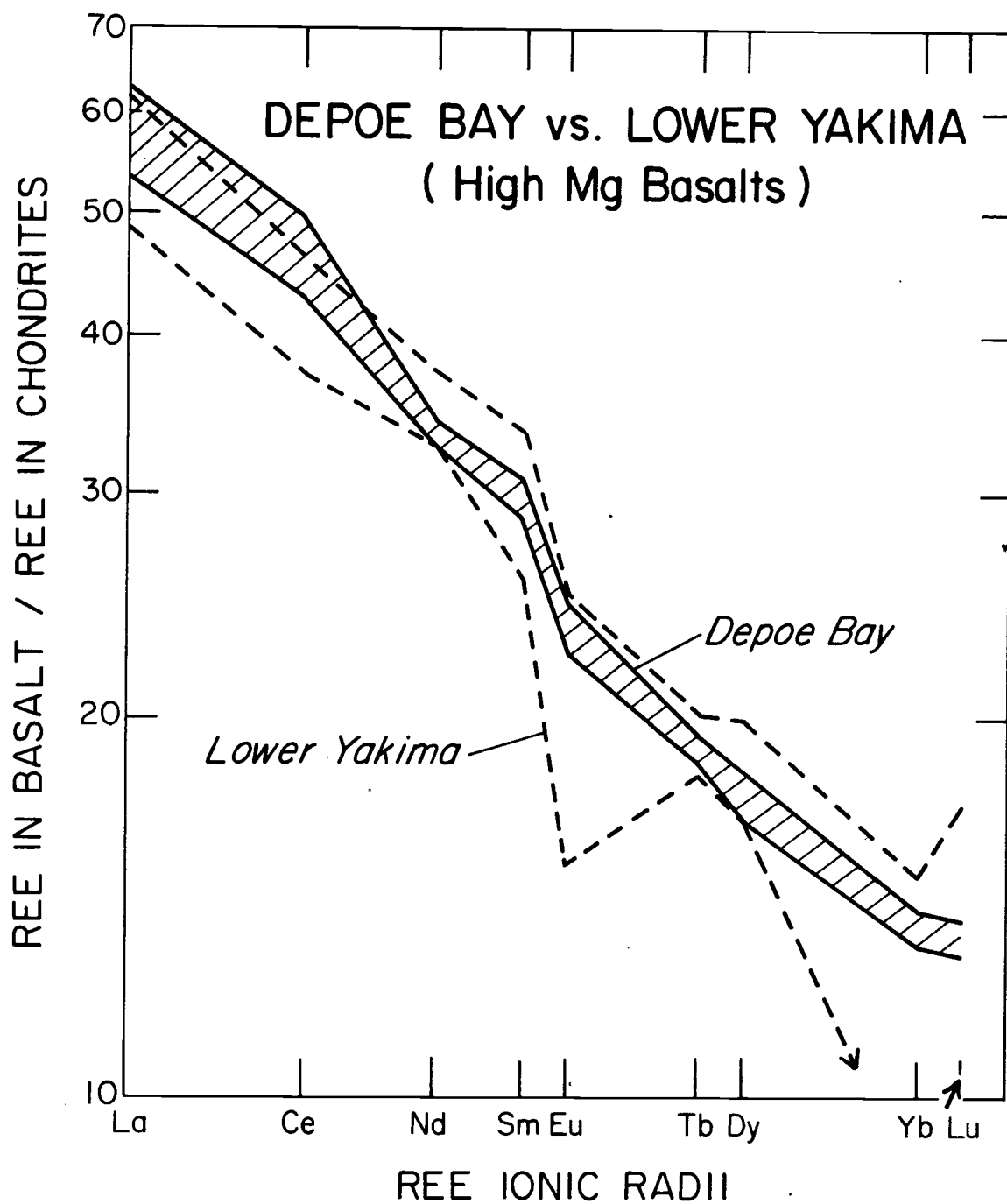


Figure 10. Abundance ranges of REE in high Mg Lower Yakima and Depoe Bay basalts are normalized to chondrites.

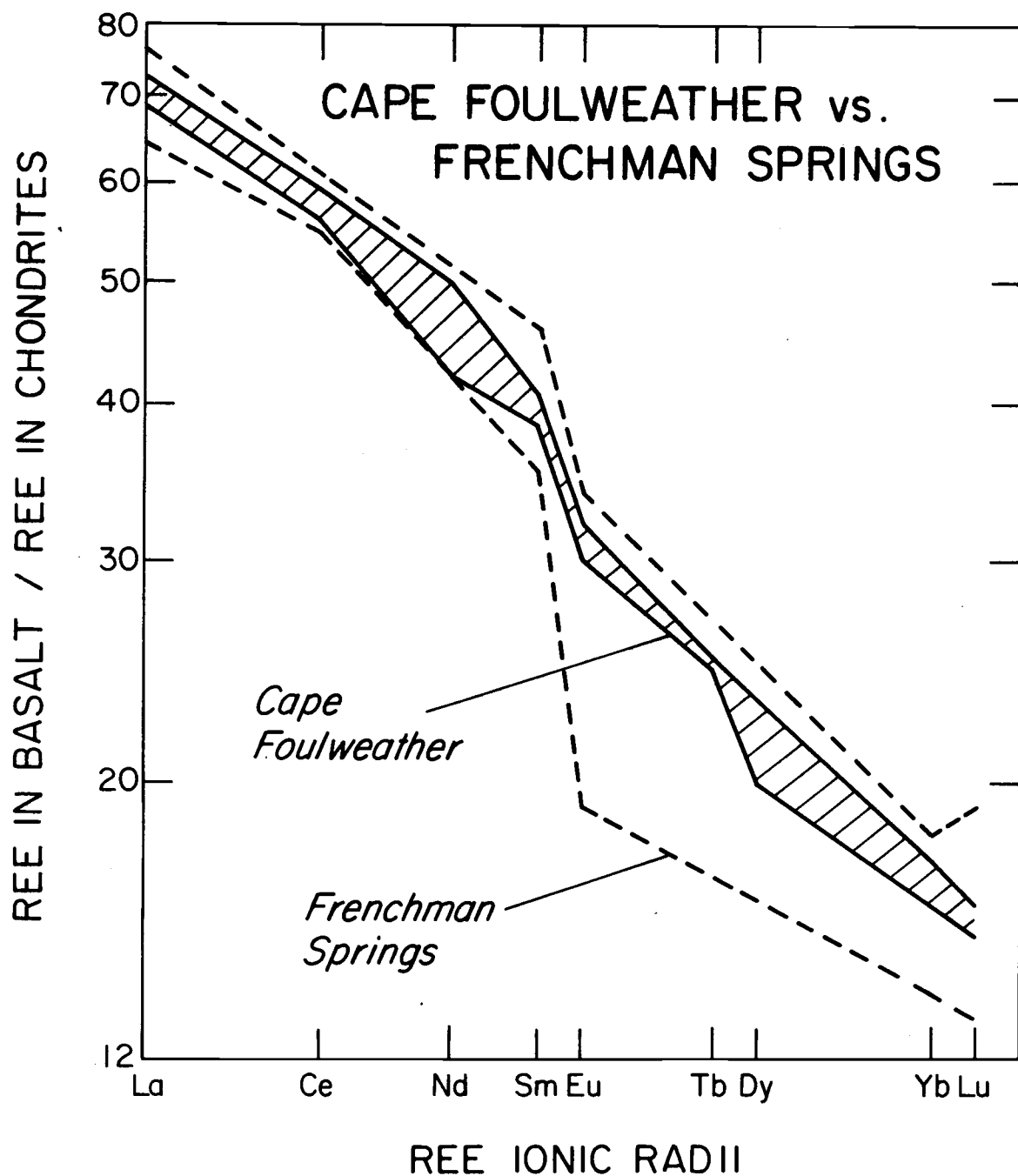


Figure 11. Abundance ranges of REE in Frenchman Springs and Cape Foulweather basalts are normalized to chondrites.

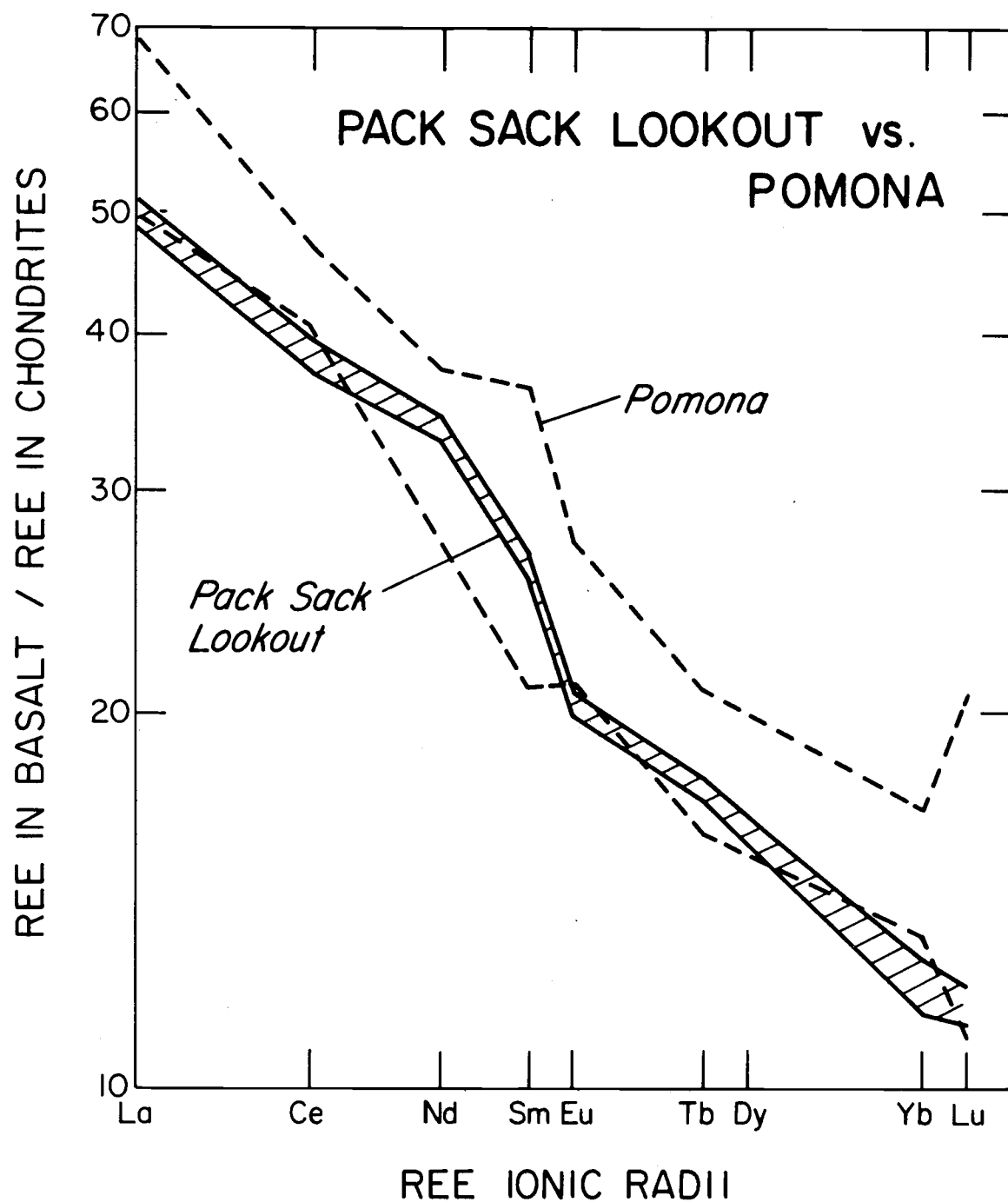


Figure 12. Abundance ranges of REE in Pomona basalt and basalt of Pack Sack Lookout are normalized to chondrites.

points fall within the high Mg Yakima range as do all the points for the other high Mg Depoe Bay basalts. The Cape Foulweather range also fits entirely within the Frenchman Springs range showing the very good correlation of these two groups.

The range in the basalt of Pack Sack Lookout tends to follow the base of the range in the Pomona basalts. This is not surprising, since only one of the three Pomona samples studied has trace elements in the same range as the basalt of Pack Sack Lookout. The values for this Pomona sample fall very near the range in the basalt of Pack Sack Lookout with the worst disagreement being less than 10% at Nd which is less than the error in the Nd value.

The Sr ratios determined by McDougall (1974) also show excellent agreement between members of each pair of coastal and plateau basalts as do the Pb ratios cited by Snaveley et al. (1973).

2.3) Comparison of Average Trace Element Compositions

The average values in the coastal basalts for the abundances of the REE, K_2O , Ba, Hf, Ta, and Th have been normalized to the values of these elemental abundances in ordinary chondrites as given in the article by Schmitt and Laul (1973) and plotted versus the REE ionic radii in Figure 13. The REE patterns for these basalts are typical for tholeiitic plateau basalts although the absolute values may be somewhat low. This similarity to the plateau pattern is predictable

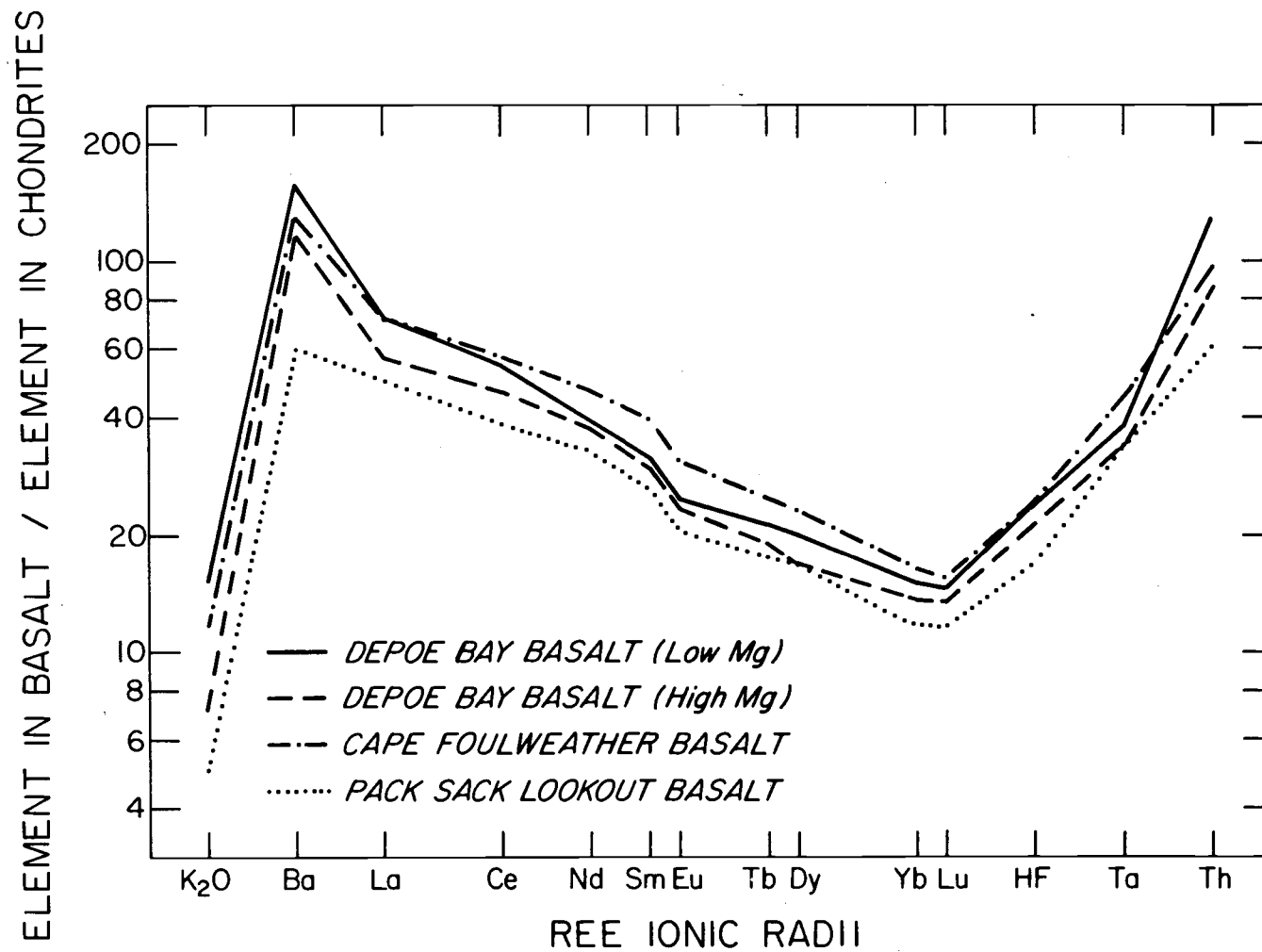


Figure 13. Average abundances of REE, K₂O, Ba, Hf, Ta and Th in the low and high Mg Depoe Bay and the Cape Foulweather basalts and the basalt of Pack Sack Lookout are normalized to the average abundances in ordinary chondrites.

since these basalts were probably derived from the magma which gave rise to the tholeiitic basalts of the Columbia River Plateau. The pattern for these basalts is also somewhat similar to the proposed pattern for the crustal average of the REE. The REE patterns show a hint of a slight negative Eu anomaly which might indicate a fairly large loss of plagioclase from these basalts.

The Cape Foulweather basalts show the highest REE content and are followed by the low and high Mg Depoe Bay basalts. The basalt of Pack Sack Lookout is the lowest in REE content as well as the other incompatible elements in the plot. With the exception of the K_2O , Ba, and Th points in the Cape Foulweather pattern, which are slightly lower than the low Mg Depoe Bay points, the incompatible elements follow the same order as the REE. These patterns show that the incompatible elements tend to act as a group in magmatic process, however the Th and K_2O values seem to be slightly enriched in the Depoe Bay basalts as compared to the other coastal basalts.

Further evidence that the incompatibles are enriched as a group is found in the Fe variation diagrams. All of the incompatible elements show definite positive correlation with increasing Fe content with the possible exception of Cs and Th. This correlation is probably due to the fact that both Fe and the incompatibles tend to be concentrated in a magma by fractional crystallization. The compatible

element V correlates with Fe also, but this is probably due to the similar ionic radii of these elements.

An attempt was made to correlate K_2O content with La content in order to see if the REE tend to follow K in magmatic events (Figure 14). For the Depoe Bay and Pack Sack Lookout basalts the correlation is fairly good, but in the Cape Foulweather basalts there is a fairly large variation in K_2O content and practically no variation in La content. From these results it is obvious that the REE may follow K in some cases, but they do not necessarily always follow this element.

3) Conclusion

As discussed earlier in this paper the average chemical compositions of the coastal and plateau basalts are very similar as are the Fe variation diagrams and REE patterns. No other basalts could be found in the literature with chemical compositions as similar to these Miocene plateau basalts as were the coastal basalts; even the mid-ocean ridge tholeiites show greater variation from ridge to ridge (Kay, Hubbard and Gast, 1970). The following observations are derived from this data.

- 1) Discussion of the probable fractional crystallization histories of these basalts has shown that the basalt of Pack Sack Lookout and the Cape Foulweather basalts are not simply fractional crystallization derivatives of the Depoe Bay basalts nor do they appear to

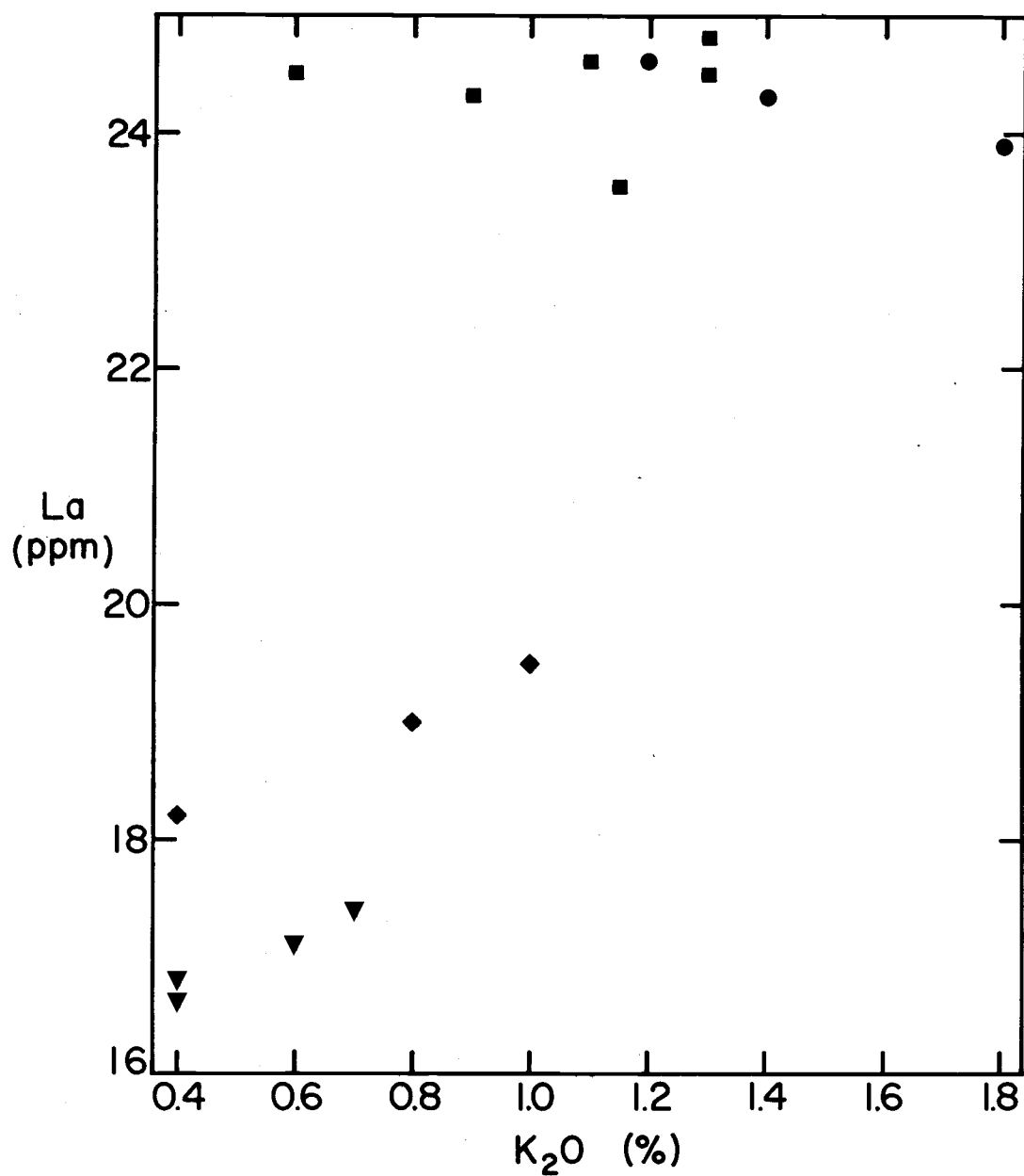


Figure 14. Correlation plot of K₂O versus La abundances in Depoe Bay and Cape Foulweather basalts and basalt of Pack Sack Lookout. Symbols have same meaning as in Figure 3.

grade from one to the other by any other means. These facts require that the basalts were formed from different episodes of partial melting.

2) A plausible explanation for the great similarity of these basalts is that they were derived from a common partial melting event in the mantle. The equivalent chemical compositions of basalts from the two areas might possibly be coincidental, but this seems highly unlikely since there are at least three equivalent pairs of coastal and plateau basalts which erupted at apparently completely different times from different partial melting episodes in apparently different tectonic environments (Snively et al., 1968; Atwater, 1970).

3) The equivalence of the chemical compositions of the pairs requires that very little contamination or fractional crystallization can have occurred between separation of the magma and eruption at the very widely separated dike swarms.

The following observations are taken from Snively et al. (1973).

4) The total volume of basalt, including both the plateau and the coastal basalts, demands a very large magma source.

5) During the same approximate time of extrusion of these plateau and coastal basalts, rocks of predominantly andesitic and dacitic composition were being erupted along the present site of the intervening western Cascade Range. . . .

6) Local vent areas and intrusive bodies of Miocene basalt are restricted to that part of coastal Oregon and Washington south of the Olympic Peninsula and north of the Klamath Mountains, an area that is considered to be underlain by oceanic crust (Snively and others, 1968).

The enrichment of the light REE relative to the heavy REE in these basalts also must be explained. According to Schilling (1971) the only major mineral which could cause an enrichment of the light REE by fractional crystallization at intermediate to low pressures is Ca-rich clinopyroxene. Using his data the degree of fractional crystallization of this mineral necessary to cause the observed REE pattern from a primary magma consisting of a flat or tholeiitic pattern is greater than 75%. Both Green and Ringwood (1967) and O'Hara (1968) show that olivine and possibly orthopyroxene are most involved in the fractional crystallization of a tholeiitic magma. Thus it seems rather unlikely that fractional crystallization is entirely responsible for the observed REE pattern. Green and Ringwood also noted this problem and postulated the existence of inhomogeneities of the incompatible elements in the upper mantle caused by various periods of partial melting. The incompatible elements would be easily transported in the mantle by fluids developed from minor amounts of partial melting, and areas of more concentrated incompatible elements developed. Such a process would tend to fractionate the REE, and concentration of Rb in one area over a long time would cause an increase in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, thereby explaining the variation observed in these ratios in different regions. These authors also suggest that wall rock reactions with the magma in the lower crust or upper mantle could also cause enrichment in the incompatible elements and the light REE, but that

Sr would act as a compatible element and would not be enriched in the magma.

A few models for the origin of the coastal and plateau basalts have been proposed recently. McDougall (1974) proposed that the partial melting episode in the mantle was caused by extensional tectonics in the Columbia Plateau region analogous to the process which has produced the marginal seas in oceanic regions. The magmas produced underwent olivine fractionation and wall rock contamination in a crustal magma chamber. He suggests that the Sr isotope data show that Yakima basalts could be the result of continuing wall rock contamination in this magma chamber. He also says the increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratio might be caused by isotopic equilibration with crustal material. The REE data presented here shows that these basalts are not likely to be due to continuous crustal contamination but are most likely caused by variations in depth of partial melting and/or inhomogeneities in the incompatible element content of upper mantle. The fact that the largest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are not coincident with the greatest REE contents in these basalts also favors the latter hypothesis. It is also hard to imagine isotopic equilibration on so grand a scale as the volume of the Yakima basalts.

Snively et al. (1973) have proposed two models for origin of these basalts. Their shear model suggests a continuous horizontal shear zone in the upper mantle under Oregon and Washington. Partial

melting would have occurred at approximately the same time under the coastal and plateau vent areas and under similar pressure-temperature conditions in this shear zone. On the basis of this data this model would require a very homogeneous mantle, comparable pressure and temperature conditions in two apparently different tectonic environments, and somewhat equivalent fractionation and contamination histories for three different periods of eruption. For these reasons this model appears highly unlikely.

Their other model envisages that these basalts were derived by partial melting of eclogite in the subducted Juan de Fuca plate. This magma could have risen rapidly along major fractures near the plateau and along the underthrust zone to a major fracture zone underneath the present coast. Different source depths or degrees of partial melting are cited as causing the different magmas. This model does not explain the observed enrichment of the incompatible elements over oceanic tholeiite composition. This enrichment would have to occur at the area of partial melting which does not seem likely, but the real problem is trying to explain the high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios compared to oceanic tholeiites using this model. It also seems unlikely that the Juan de Fuca plate would have migrated so far inland under the continent.

Following the argument of Green and Ringwood (1967), tholeiites which have erupted on continents appear to be derived from

magmas which have fractionated and possibly reacted with wall rock in magma chambers in the uppermost mantle or lower crust. These magmas have been derived from partial melting deeper in the mantle. In the case of the Yakima basalts such a chamber must have been very large to account for the volume of lava extruded in individual events. It is possible that this chamber was thin similar to sills and extended far enough laterally to intersect the underthrust zone described by Snavely et al. (1973), and thus be tapped occasionally to produce the coastal basalt flows. The composition of these basalts could thus be explained by varying degrees of partial melting, inhomogeneous mantle compositions, fractional crystallization, and/or wall rock reactions. This model is also similar to the proposed models for other plateau flood basalts which is not true for the models proposed by Snavely et al. (1973). This model does have two problems in common with their second model however. The magma is still required to migrate up the underthrust zone without contamination, and it does not explain the andesitic and dacitic basalts in the Cascade Range.

This model is not proposed as the final answer but as another possible explanation for the observed basalt distribution.

IV. EOCENE BASALTS

1) Results

The samples from the Karmutsen, Metchosin, and Crescent Formations were obtained from Dr. Parke Snavely of the U. S. G. S. Chemical analysis for the major element contents of these samples has apparently been done by the U. S. G. S. , however these results are presently unavailable as is the petrographic and stratigraphic information for these samples.

One section of the Crescent Formation has been studied recently by Glassley (1973). He classified his samples as upper or lower member basalts according to the stratigraphy of his section. He also claimed that these two members could be distinguished chemically using a plot of the FeO/MgO ratio versus TiO₂ content and the chondritic normalized REE patterns. This distinction was not clear in several of the present samples, and one sample shows an REE pattern which agrees well with Glassley's upper member tholeiites, but definitely plots with the lower member tholeiites in the FeO/MgO versus TiO₂ figure. Thus his distinction does not appear to hold for the whole Crescent Formation and no lower or upper member classification can be made for the present samples.

The range in chemical composition of the present samples (Table 9) compares well with the range in composition of Glassley's

Table 9. Chemical Composition Ranges in Metchosin and Crescent Formation and Umpqua Volcanics.

	Metchosin	Crescent	Umpqua*
TiO ₂ (%)	1.0 - 2.5	0.8 - 2.9	---
Al ₂ O ₃	12.0 - 14.0	13.0 - 17.4	13.9 - 15.4
FeO	10.7 - 15.5	8.5 - 14.4	9.9 - 13.1
MgO	5.2 - 8.6	3.5 - 8.6	5.1 - 8.2
CaO	7.6 - 11.9	6.9 - 11.2	9.6 - 13.1
Na ₂ O	1.9 - 2.8	2.2 - 4.6	2.0 - 3.8
K ₂ O	< 0.1 - 0.3	< 0.1 - 0.3	0.053 - 0.39
MnO	0.167 - 0.272	0.147 - 0.219	0.146 - 0.241
Cr ₂ O ₃ (ppm)	36 - 290	7 - 480	190 - 690
Sc	42 - 49	31 - 47	40 - 50
V	310 - 430	240 - 380	---
Co	39 - 49	31 - 49	46 - 53
Zr	< 60 - 190	< 60 - 230	---
Ba	< 30 - 60	< 30 - 220	70 - 140
La	2.9 - 11.3	2.5 - 20.6	8.0 - 13
Ce	7 - 27	7 - 39	21 - 34
Nd	< 8 - 26	< 10 - 26	---
Sm	2.5 - 8.0	1.8 - 7.6	3.2 - 5.1
Eu	0.89 - 2.6	0.67 - 2.3	1.3 - 1.9
Tb	0.58 - 1.8	0.39 - 1.5	0.62 - 1.0
Dy	4 - 11	3 - 10	---
Yb	2.4 - 7.4	1.6 - 7.5	2.1 - 3.0
Lu	0.36 - 1.12	0.24 - 1.14	0.34 - 0.52
Hf	1.8 - 6.1	1.8 - 7.3	2.4 - 4.2
Ta	0.17 - 0.67	0.17 - 1.45	0.20 - 1.3
Th	< 0.3 - 0.7	< 0.3 - 1.5	0.55 - 1.7
Sr	---	---	65 - 380

* These samples were analyzed by M. J. Dudas for all elements except Al₂O₃.

samples. Both sets of samples show a large degree of compositional variation from sample to sample. He has classified his samples as alkalic or tholeiitic on the basis of a silica versus total alkali diagram, using the line drawn between the Hawaiian alkalic and tholeiitic basalts on a similar diagram by MacDonald and Katsura (1964). This choice seems highly arbitrary since his calculated norms do not agree with this classification, and the dividing line between alkalic and tholeiitic Hawaiian basalts was based on norms.

The SiO_2 content of basalts cannot be determined by our INAA technique and is unknown for the present samples. Thus the norms cannot be calculated for these samples. However an upper limit for SiO_2 content may be determined by obtaining the difference between the total oxide content of the other major elements and 100%. The H_2O , CO_2 , and P_2O_5 contents must also be subtracted from this upper limit. A range of between 1 and 4.5% was allowed for these constituents, and the resulting ranges in SiO_2 were plotted on a silica versus total alkali diagram. The results of this plot are highly speculative and as mentioned above would not be completely trustworthy even if the SiO_2 contents were well known. However, it does show that the basalts from the Karmutsen and Metchosin Formations are all apparently tholeiitic. Most of the basalts from the Crescent Formation appear to be tholeiitic with the exception of three basalts from the same area which are on the border line. Classification of these

basalts on the basis of the $\text{Al}_2\text{O}_3 - \text{Na}_2\text{O} + \text{K}_2\text{O} - \text{SiO}_2$ relation introduced by Kuno (1960) is in agreement with the above results.

Previous chemical composition data for the Metchosin and Karmutsen Formation basalts could not be found in the literature. The composition of the present samples from these formations are generally in the same range as the Crescent Formation basalt (Table 9). They are in the lower part of the range for silica, alkalis, and REE and in the higher range for FeO and CaO.

The Eocene basalts from the Oregon Coast were collected and analyzed by Drs. M. J. Dudas and R. A. Schmitt. Several of the samples from the Siletz River Volcanics were collected from the same sites as the samples which were analyzed by Snively et al. (1968). The agreement between the analyses of corresponding samples is not good. Assuming the analyses are accurate, the variability in the compositions of these basalts from sample location to sample location appears to be related to the variability within each sample location. The compositions of the tholeiites from the Oregon coast (Tables 9 and 10) fall in the same general range as the basalts from Washington and Vancouver Island. However the three samples which are alkalic have much higher Na_2O , K_2O , and REE contents than do the other basalts.

Table 10. Chemical Composition Ranges* in the Tillamook and Siletz River Volcanics and the Eocene Alkalics.

	Tillamook	Eocene Alkalic	Siletz River	
			Older Unit	Younger Unit
Al ₂ O ₃ (%)	11.3 - 15.4	15.0 - 18.2	14.8 - 15.2	12.2 - 15.2
FeO	10.8 - 13.8	8.0 - 12.8	10.7 - 11.7	12.9 - 15.1
MgO	4.9 - 7.7	0.95 - 6.5	7.6 - 7.9	4.6 - 6.3
CaO	10.4 - 11.9	3.4 - 6.6	10.0 - 11.5	9.4 - 11.7
Na ₂ O	2.4 - 3.9	2.9 - 4.5	1.8 - 2.2	2.6 - 2.8
K ₂ O	0.14 - 0.28	1.3 - 1.7	0.095 - 0.10	0.13 - 0.72
MnO	0.156 - 0.272	0.137 - 0.174	0.170 - 0.198	0.181 - 0.239
Cr ₂ O ₃ (ppm)	59 - 480	9 - 140	420 - 480	73 - 290
Sc	32 - 42	8.7 - 18	38 - 42	37 - 41
Co	44 - 64	11 - 42	46 - 50	43 - 52
Ba	70 - 140	420 - 600	<50 - 70	<60 - 200
La	7.2 - 35	46 - 98	5.8 - 6.7	10.2 - 32.8
Ce	22 - 84	101 - 216	15 - 18	26 - 81
Sm	3.8 - 7.7	10 - 14	3.2 - 3.9	4.9 - 11.5
Eu	1.3 - 2.2	2.6 - 3.9	1.03 - 1.28	1.6 - 3.0
Tb	0.68 - 1.2	1.3 - 1.5	0.57 - 0.75	0.86 - 1.9
Yb	2.0 - 3.2	2.9 - 4.3	1.9 - 2.3	2.4 - 5.5
Lu	0.34 - 0.50	0.41 - 0.54	0.34 - 0.39	0.42 - 0.84
Hf	2.4 - 6.3	8.4 - 10.9	2.1 - 2.9	3.3 - 9.5
Ta	0.40 - 2.5	2.8 - 6.2	0.49 - 0.80	1.1 - 3.8
Th	0.67 - 6.8	5.3 - 13	0.50 - 0.60	0.8 - 3.5
Sr	140 - 330	440 - 840	200 - 206	150 - 190

*The samples in this table were analyzed by M. J. Dudas for all elements except Al₂O₃.

2) Discussion

2.1) Fractional Crystallization

The Karmutsen Formation is not included in the early tertiary eugeosyncline, and since there is only one sample from this formation, nothing can be said about fractional crystallization in this sample.

In Figure 15 the abundances of several representative elements in four of the Metchosin Formation samples have been normalized to the abundances in the other Metchosin sample and plotted against atomic number. For each element the four samples are either all enriched (or nonfractionated) or all depleted (or nonfractionated) compared to the fifth sample. Also the order of increasing enrichment or depletion is the same in almost all cases indicating that this formation has undergone some form of continuous fractionation. One would expect increasing REE concentrations with little if any enrichment in the light REE with respect to the heavy REE with increasing fractional crystallization, and the REE concentrations are in agreement with this trend (Figure 17). Thus the data obtained for this formation suggests that the variation in chemistry is the result of varying amounts of fractional crystallization on a single parent magma or similar parent magmas.

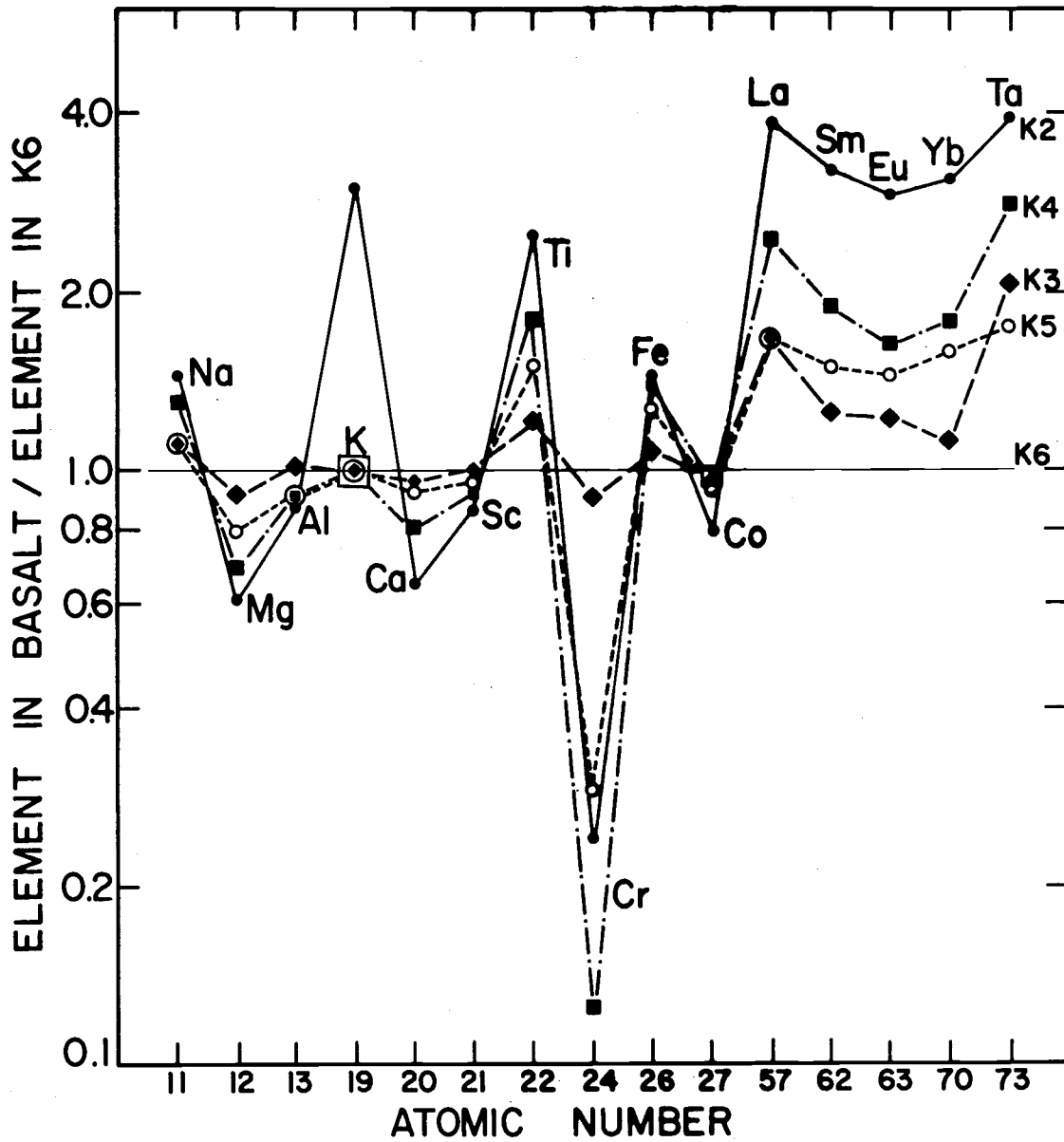


Figure 15. Abundances of several representative elements in four Metchosin Formation samples are normalized to the abundances of the fifth.

The REE compositions (Figure 19) of two of the samples from the Crescent Formation indicate that they have suffered a large amount of fractional crystallization. They both have highly enriched and relatively flat REE patterns, and one shows a definite negative Eu anomaly indicating a large loss of plagioclase. Another sample has low MgO content (Appendix, Table 16), but the FeO content is also low and the CaO and Al_2O_3 abundances are high which indicates that fractional crystallization is not the likely cause for the low value. Two other samples have low FeO content and Fe/Mg ratios as well as high concentrations of CaO and Al_2O_3 indicating possible primitive magmas. However judging by major and RE element trends, it is unlikely that all of the basalts in this formation were derived from these magmas by fractional crystallization.

The alkalic samples from the Eocene Oregon coast volcanics have much lower CaO contents than the others, but Eu anomalies are not apparent in the REE patterns. The two samples which appear more alkalic have very low MgO contents (Appendix, Table 21) and very high Fe/Mg ratios indicating large losses of olivine and pyroxene. These two samples have lower CaO than the third but higher Al_2O_3 which gives no indication of plagioclase fractional crystallization. The lower CaO could be due to pyroxene (augite) fractional crystallization.

The Tillamook Volcanics are quite uniform in major element chemistry (Appendix, Table 17). There is a fairly large and continuous variation in MgO content and Fe/Mg ratio, but this trend does not follow variation in REE concentration. The CaO contents are also very similar indicating fractional crystallization was not the primary cause of variation in these samples.

Snavely et al. (1968) divided the Siletz River Volcanics into an upper and lower unit. All of the samples for this report were obtained from the lower unit. On the basis of their stratigraphy and the observed chemical composition, these samples are again split into an older and younger unit. The samples within each unit are fairly uniform in composition (Appendix, Tables 19 and 20). However, samples from the younger unit have lower CaO, Al_2O_3 , and MgO abundances and higher Fe/Mg ratio, Na_2O , K_2O , and REE abundances as shown in Figure 16. This indicates that magma which formed the older unit probably underwent fractional crystallization to produce the magma for the younger unit.

One sample from the Umpqua Volcanics shows evidence of a much greater degree of fractional crystallization than the others (Appendix, Table 18); however, this sample appears to have also been much more weathered than the others and has a large, positive Eu anomaly indicating a concentrating of plagioclase. Thus the history of this sample is very obscure. The other samples are all quite

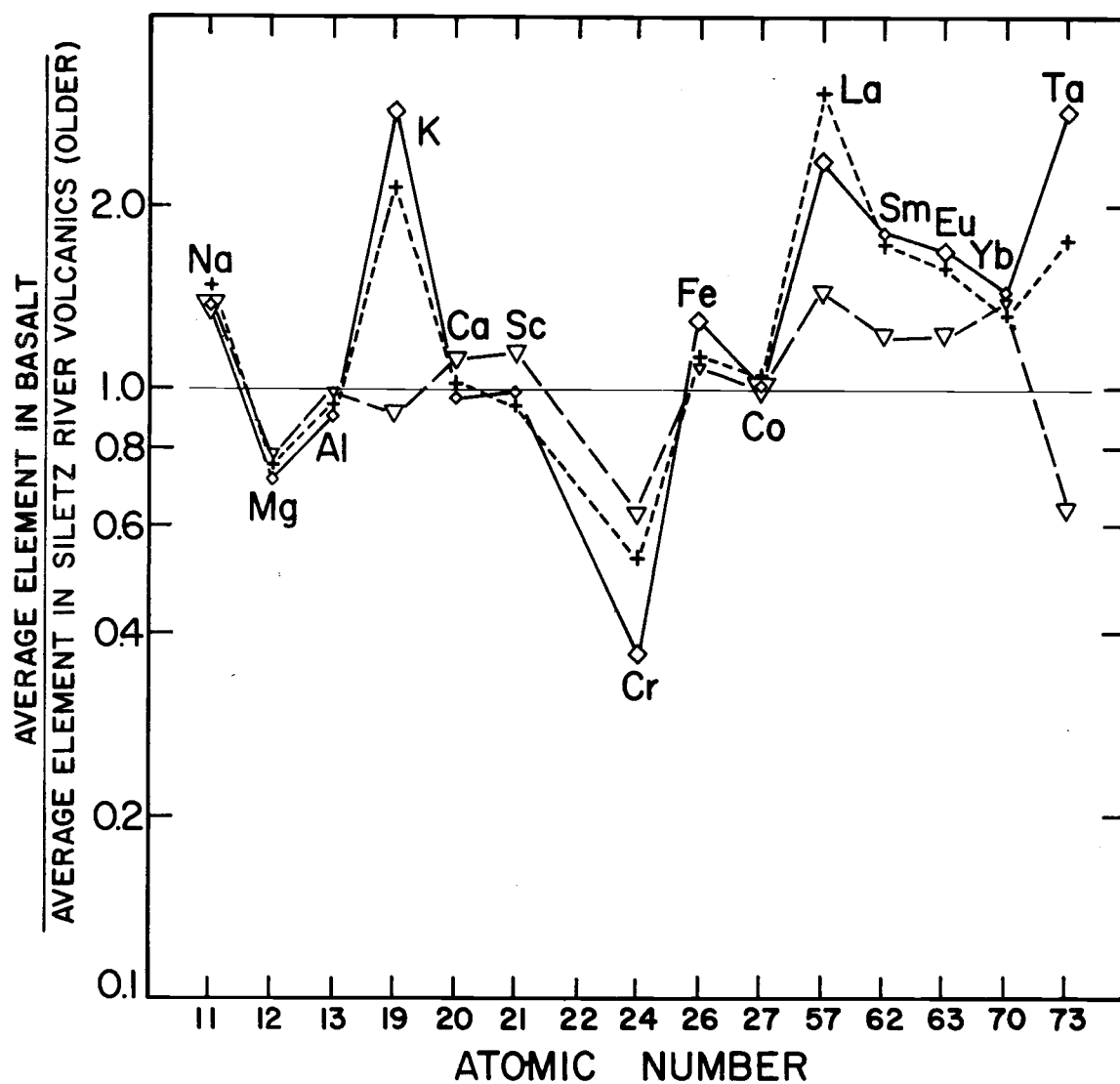


Figure 16. Average abundances of several representative elements in the Tillamook (+), Umpqua (▽), and Siletz River Volcanics (younger unit) (◇) are normalized to the average abundances of the Siletz River Volcanics (older unit).

uniform and are compositionally similar to the Tillamook Volcanics, except for low K_2O and Ta abundances.

2.2) Composition Comparisons with Other Basalts

The contents of most of the incompatible elements (K_2O , Ba, the REE, Hf, Ta, and Th) in all of the Karmutsen, Metchosin, and Crescent Formation samples have been normalized to the chondritic abundances and plotted against REE ionic radii. The ranges for Eocene basalts of the Oregon Coast were plotted in the same manner.

The REE pattern for the sample from the Karmutsen Formation (Figure 17) is similar to the patterns for the Hawaiian tholeiites (Figure 20). It is somewhat less enriched in the light REE than most of the Hawaiian basalts and also has low absolute abundances by comparison. The major element composition of the basalt is also similar to the composition of the Hawaiian basalts, and it plots with these basalts on an AFM diagram.

The REE patterns for the Metchosin Formation samples (Figure 17) are fairly flat with slight enrichment of the middle REE. As mentioned before the patterns appear to be transitional from a primary magma low in REE to a fractionated magma high in all the REE and more relatively depleted in Eu. The general pattern for these basalts is similar to the patterns for ocean ridge tholeiites (Kay, et al., 1970), island arc tholeiites (Jakes and Gill, 1970), and

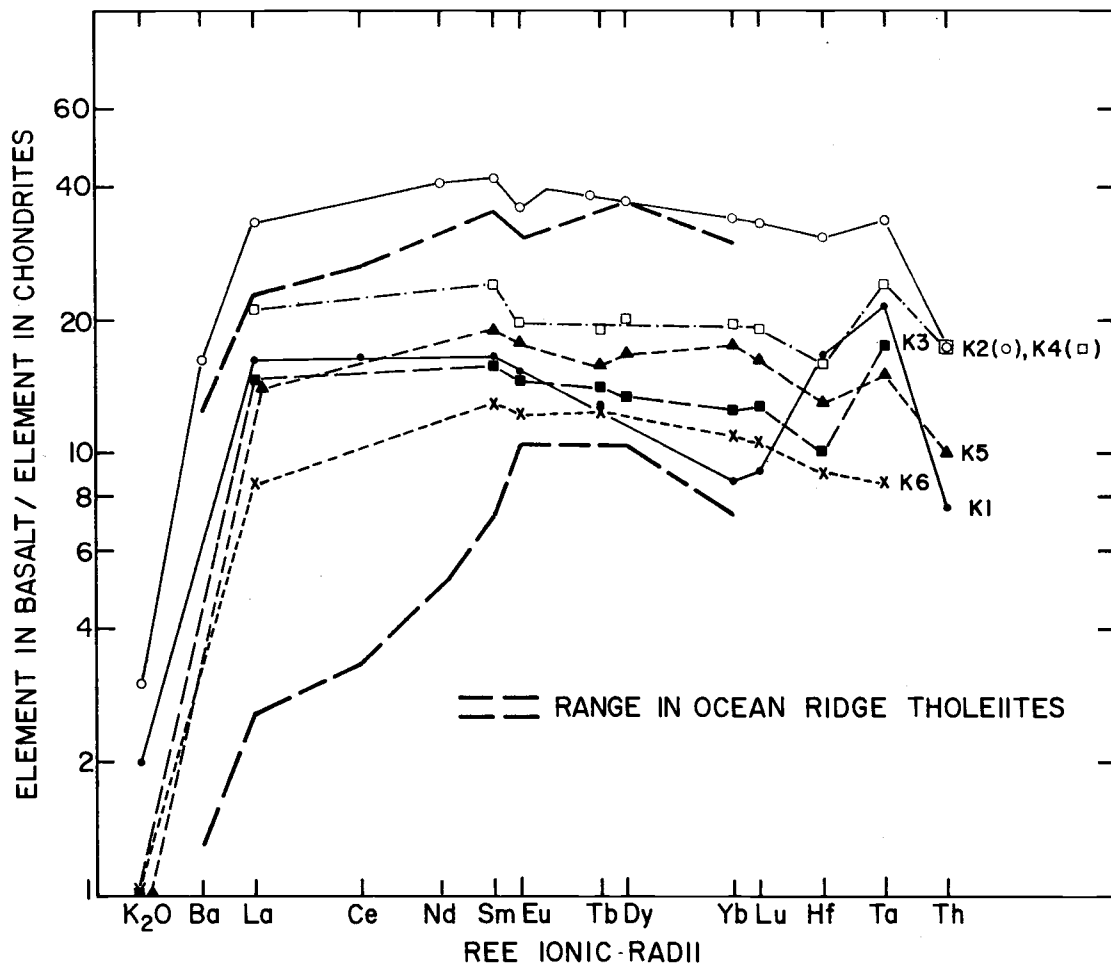


Figure 17. REE, K₂O, Ba, Hf, Ta and Th abundances in Karmutsen (K1) and Metchosin (K2-K6) Formation basalts are normalized to the average abundances in ordinary chondrites. The abundance range in ocean ridge tholeiites is plotted for comparison (Kay *et al.*, 1970).

tholeiites from behind the Mariana Island arc (Hart, Glassley and Karig, 1972). However the major and minor element contents of the Metchosin Formation samples are most similar to the ocean ridge tholeiites. On an AFM diagram (Figure 18) the Metchosin Formation basalts plot along the low alkali side of the ocean ridge tholeiite region. The more fractionated samples are relatively higher in iron, but the trend in these basalts generally follows the ocean ridge tholeiite trend.

The Crescent Formation samples show a variety of REE patterns (Figure 19). Sample designations as shown on the plot are used here for clarity. Sample C8 is a diabasic sill which has a pattern similar to the Metchosin Formation patterns. However on a major element basis it is more similar to sample C7 which was obtained from the same area. The pattern for C7 is similar to the patterns for C10 and the Karmutsen Formation sample (similar to Hawaiian tholeiite). C10 has higher REE concentrations than C7. C9 is another diabase sill from the same area as C7 and C8. This sample is quite enriched in all of the REE but has a pattern similar to C7. Another sample (C1) is also high in all of the REE but has large, negative Eu anomaly. The pattern is quite flat and very similar to the pattern for the most fractionated Metchosin Formation sample. This Metchosin sample has less silica and alkali, but does appear to be fractionated to about the same extent.

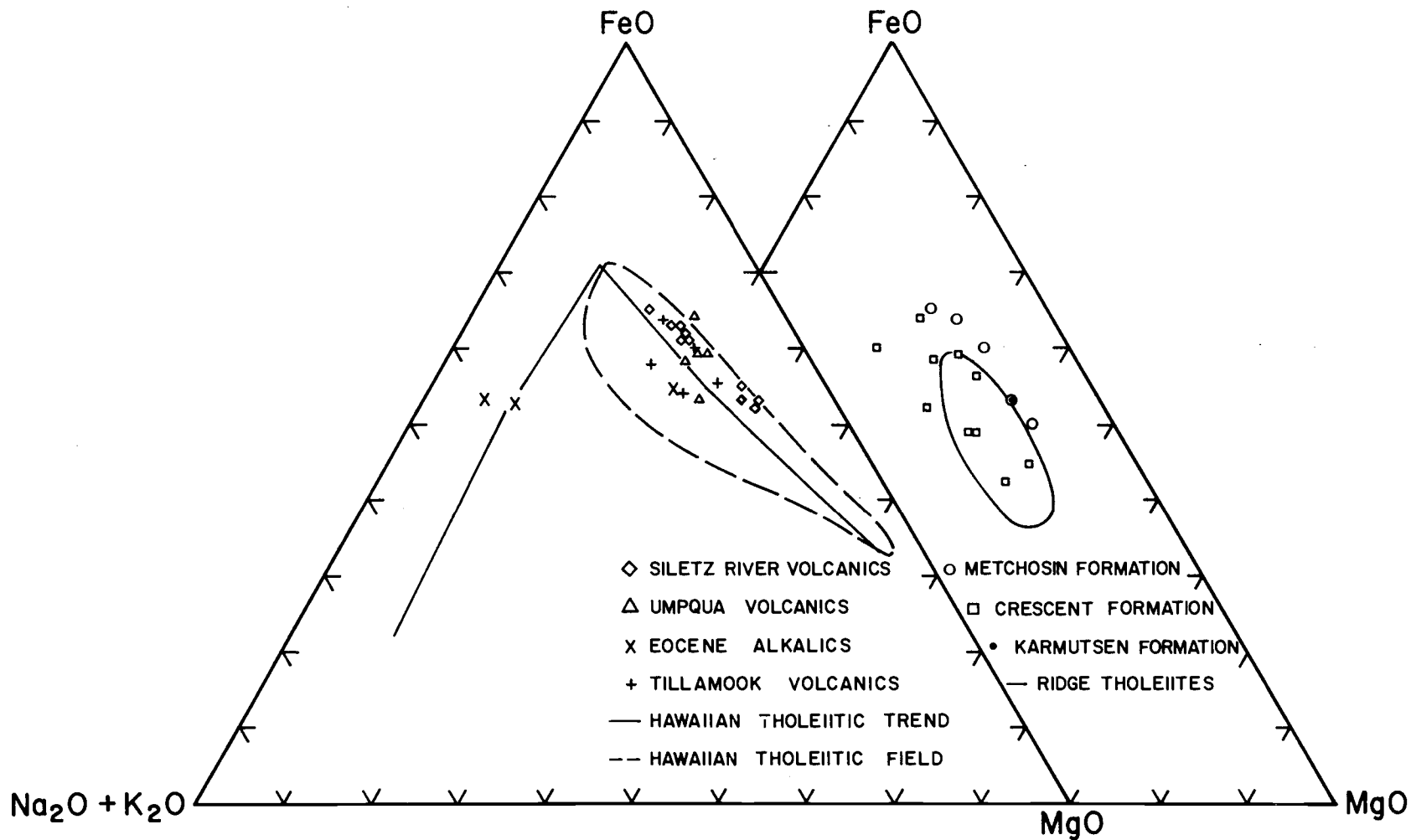


Figure 18. AFM (total alkalis vs. FeO (total Fe) vs. MgO) diagrams for the Eocene coastal basalts. Outlines of the fields in which the oceanic tholeiites (Glassley, 1973) and Hawaiian tholeiites (MacDonald and Katsura, 1964) are shown as well as the Hawaiian tholeiite trend line. The symbols are explained on the figure.

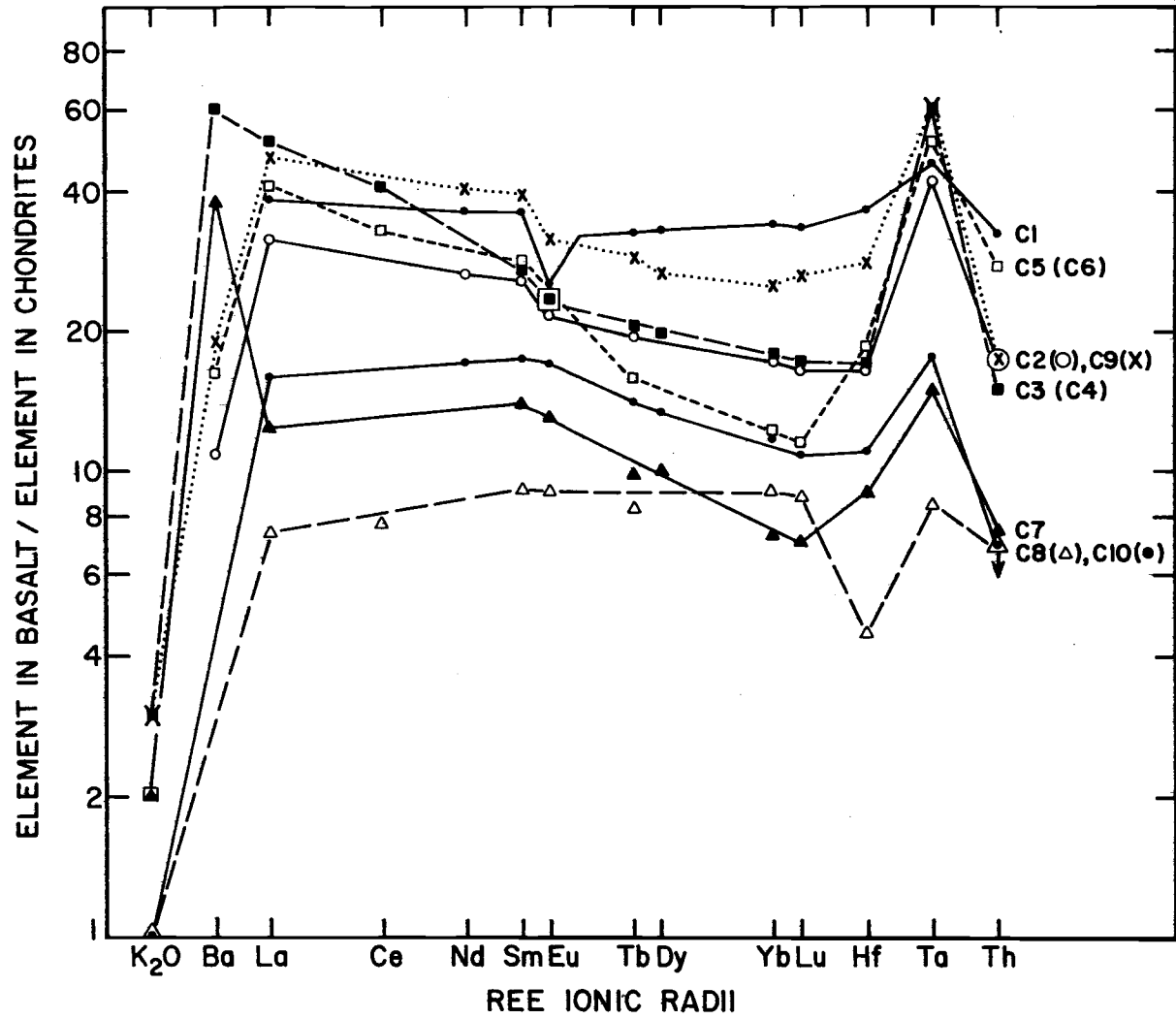


Figure 19. REE, K₂O, Ba, Hf, Ta, and Th abundances in Crescent Formation basalts are normalized to chondrites.

Two of the remaining samples (C5, C6) have very similar patterns and only one was plotted to prevent clutter. This pattern is quite similar to the Miocene tholeiite patterns (light REE enriched) discussed in part III of this paper. The major and minor element content of these samples is quite similar to that in the basalt of Pack Sack Lookout; except that the K_2O , Ba, Cs, and Th abundances are quite low following the general trend in the Crescent Formation samples.

The remaining three samples (C2, C3, and C4) are all apparently borderline between alkalic and tholeiitic basalts. The REE pattern for these samples is similar to the pattern for a transitional to alkaline basalt dredged from the Mariana trough, however the major elements do not match with those of the trough sample (Hart et al., 1972). There is no obvious fractional crystallization trend in the Crescent Formation samples, and it seems unlikely that they were derived from common or similar primary magmas. The Crescent formation samples plot near the ocean ridge and Hawaiian tholeiite fields on a AFM diagram (Figure 18) and show higher FeO and alkali contents with increased apparent fractionation.

The general REE pattern for the older unit of the Siletz River Volcanics is similar to the Hawaiian tholeiitic pattern (Figure 20), and the major element composition is quite similar to that of the Hawaiian tholeiites (MacDonald and Katsura, 1964). The younger unit

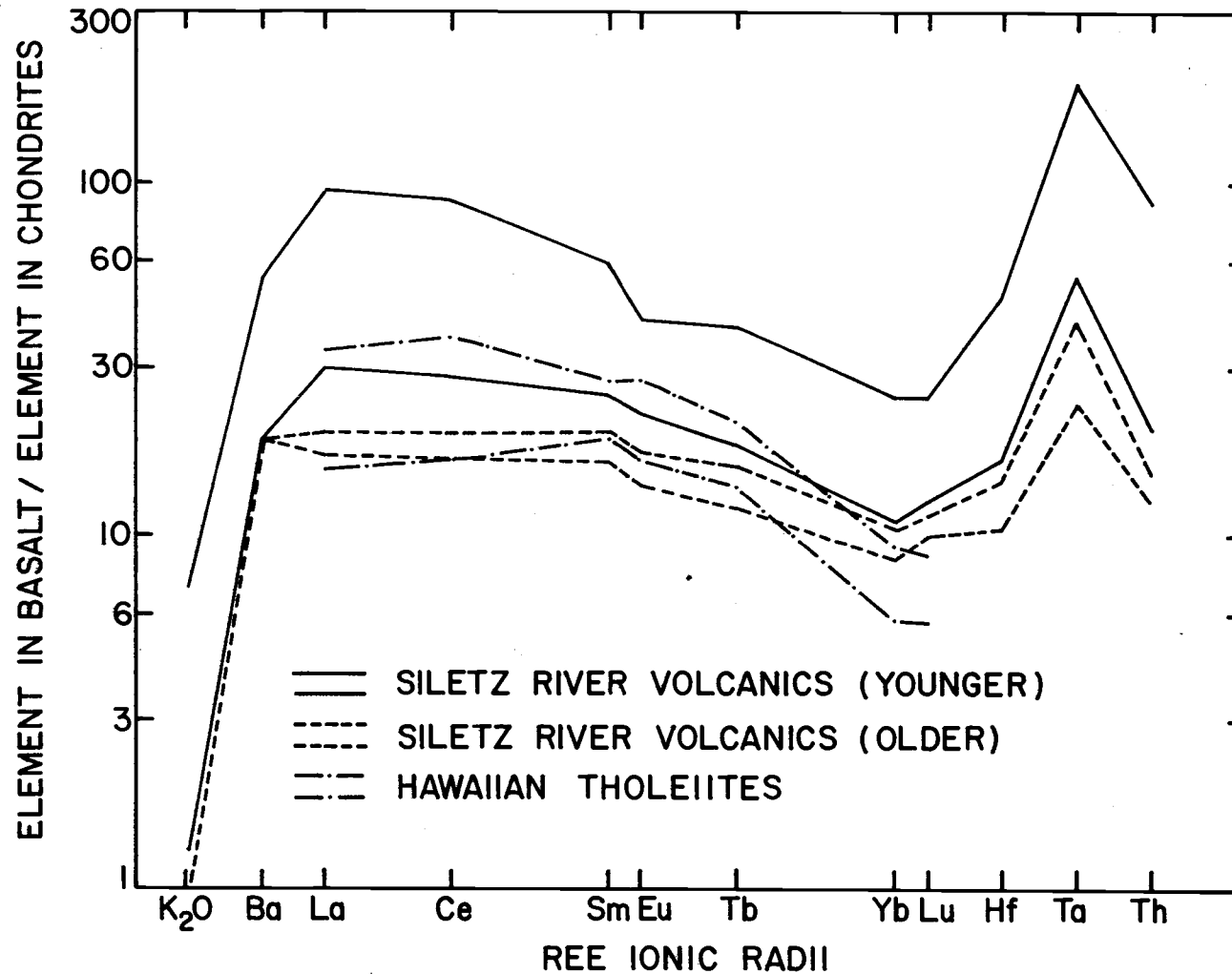


Figure 20. Ranges in abundances of the REE, K₂O, Ba, Hf, Ta and Th in the Siletz River Volcanics are normalized to chondrites. The abundance range in Hawaiian tholeiites is plotted for comparisons (Schilling and Winchester, 1969).

appears to be a fractional crystallization product of the older unit. The Tillamook and Umpqua Volcanics bear a greater resemblance to the younger unit of the Siletz River Volcanics with respect to major and minor element chemistry and REE patterns than to any other kind of tholeiite found (Figures 16 and 21). On an AFM diagram (Figure 18) all of these basalts fall in the same region very near the Hawaiian tholeiite field and following the Hawaiian trend line.

The REE patterns for the Eocene alkalis on the Oregon coast (Figure 21) are typical for alkaline basalts. The major element compositions bear some resemblance to the mugearites of the Hawaiian Islands (MacDonald and Katsura, 1964), but no definite correlation can be made. On an AFM diagram (Figure 18) these basalts plot near the Hawaiian alkalic field (MacDonald and Katsura, 1964), but not as close as the tholeiites.

The patterns for the elements Hf, Ta and Th in the Eocene and Miocene basalts pose a complex problem. Hafnium has the smaller ionic charge (+4) and a small hexacoordinated ionic radius (0.79\AA), and enrichment of this element with respect to chondrites falls within the enrichment range of the smaller REE for almost all of these basalts. Tantalum has the smallest ionic radius (0.72\AA) but the larger charge (+5), and generally falls in the range of the larger REE. The amount of Th enrichment does not follow any one particular trend.

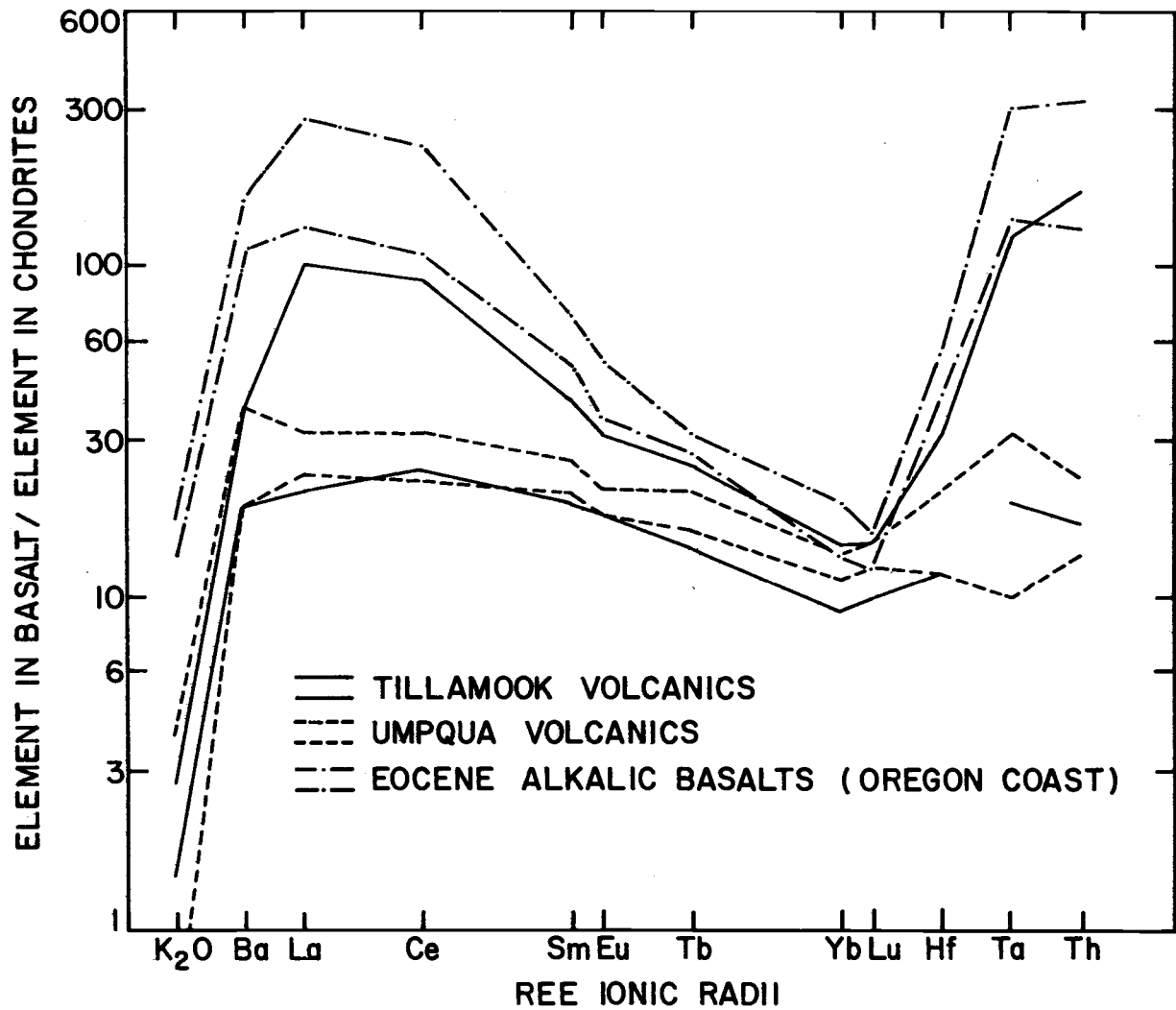


Figure 21. Ranges in abundances of the REE, K₂O, Ba, Hf, Ta and Th in the Eocene Alkalic basalts and the Tillamook and Umpqua Volcanics are normalized to chondrites.

This element has the largest ionic radius (1.08\AA) and a +4 charge, and it has enrichments varying from higher than La in the Miocene basalts to lower than Lu in some of the Eocene basalts. The Eocene basalts generally show depletion of Th compared to Ta, and this effect is probably a result of the difference in the origin of the Eocene and Miocene basalts. The partition coefficients of these elements for the major minerals are not known, and thus no explanation can be offered for the observed trends.

3) Conclusion

After study of current plate motions and the magnetic anomalies off the California coast, Atwater (1970) proposed two models for the Tertiary movements of the plates in the area of the western coast of North America. According to both models the Oregon and Washington coastal areas have been near a subduction zone throughout this period of time.

Snavely et al. (1968) propose that the crust under the Oregon coast is a fairly thin oceanic type crust and that the lower Siletz River Volcanics rose directly from mantle sources through north-trending fissures. This model is somewhat similar to the general theory for the origin of the Hawaiian lavas except that Hawaiian lavas apparently spend some time ponded in lava chambers under the crust.

The apparent fractional crystallization of magmas of the older unit of the Siletz River Volcanics to get magmas of the younger unit as shown in this work indicates that these lavas were probably ponded below the crust as well. Thus in general it is felt that the current evidence indicates that the Eocene volcanics on the Oregon Coast originated under pressure-temperature conditions in the mantle that were similar to the conditions for the Hawaiian basalts.

Based on the data from his study area, Glassley (1973) has proposed that Crescent Formation basalts are a piece of partially subducted oceanic crust which became separated from the Juan de Fuca plate and was uplifted during the Miocene age juxtaposing the upper and lower parts. The basalts of the Crescent Formation analyzed in this work show little correspondence to an upper or lower member or to oceanic crustal basalts. Some of the basalts show some resemblance to Hawaiian tholeiites, but correspondence is far from definite. There is also some resemblance to continental tholeiites in two of the samples, but in general the mixture of REE patterns and major element compositions of these samples remains a puzzle. According to Rau (1973) the sedimentary deposits in the Olympic Peninsula support the hypothesis of a subducting plate losing its sedimentary layers (and thus possibly a part of the plate) by a sort of scraping action of the overriding plate. The data in this paper do not appear to support this origin for the Crescent Formation; but since

the samples are from a different part of the formation, they do not necessarily detract from it either.

The data from the Metchosin Formation samples show that they are likely either from oceanic crust or originated in a similar manner to ocean ridge tholeiites. At least one of these samples shows greater fractionation than normally found in ocean ridge basalts. Since the stratigraphy of these samples is unknown, the relationship of the degree of fractionation to the time of eruption cannot be determined, and the possible relationship to oceanic crust remains unclear. Thus this data may or may not support the oceanic crust model for the Crescent Formation.

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APPENDIX

APPENDIX I

Discussion of Standards and Calculating Procedures

For most of the elemental abundances determined for this report liquid or solid standards containing only one element of interest were activated along with the samples. For some of the elements the USGS standard rock BCR-1 was used as the only standard, and for a few elements the USGS standard rock GSP-1 was used as the standard. Two BCR-1 aliquants were activated along with each group of samples and one GSP-1 aliquant with each long lived run. If both BCR-1 aliquants were in good agreement and did not agree with an elemental standard, the values for that element in the samples were reevaluated with respect to the accepted value for BCR-1 (Flanagan, 1967; Laul and Schmitt, 1973). This procedure was followed because the BCR-1 aliquants have the same matrix, configuration, and size as the samples thus reducing systematic errors.

In the rabbit runs solid standards were used for Ti (TiO_2), Mg (MgO), Al (Al foil), and Ca (CaCO_3). Solutions of compounds of the elements V, Dy, Mn, and Na in dilute acid were also used as standards. All of the MnO and Na_2O abundances were adjusted to the accepted BCR-1 values. The Al_2O_3 abundances were adjusted to agree with those of BCR-1 in rabbit runs number 2 and 3 and TiO_2

and Dy were adjusted to BCR-1 in Rabbit runs 1 and 2 respectively.

In the determination of the long lived activities liquid standards were used for Sm, Eu, Ce, Lu, Tb, Cr, Yb, Hf, Ba, and Nd in both runs and for La in run 1 and Cs in run 2. BCR-1 was used as the standard for K_2O , FeO, Sc, Co, and Ta in both runs and for Cs in run 1 and La in run 2. GSP-1 was used as the standard for Zr and Th in both runs. The values for Sm, Ba, and Nd abundances in both runs were adjusted to the accepted BCR-1 abundances, and the abundances for Hf and some of the Eu and La abundances in the first run were adjusted to agree with the BCR-1 abundances.

The calculation of the Ce abundances involved the subtraction of a 25 to 75% interference peak due to ^{59}Fe . This caused very few problems with large Ce concentrations; but when the Ce abundance was low and the Fe abundance high, the Fe contribution becomes greater than the Ce contribution to the peak and small percentage errors in the Fe amount subtracted can become large errors in the Ce result. This complication has been noted previously in this lab, and some Ce abundances were not added to the REE plots for this reason. The Nd and Dy abundances were also often left off at these plots because of the large errors involved in their determination.

Table 11. Depoe Bay Basalt.

	Low Mg			High Mg				
	D1	D2	D5	D3	D4	D6a	D6b	D7
TiO ₂ (%)	2.0	1.8	2.0	1.9	2.0	1.8	1.9	1.8
Al ₂ O ₃	12.7	13.4	13.8	13.1	13.5	13.8	13.2	14.0
FeO	12.9	11.5	11.7	11.2	11.6	12.2	12.5	11.1
MgO	3.9	3.3	3.5	4.4	5.0	4.8	5.0	4.2
CaO	6.3	6.5	6.1	7.1	7.7	7.7	7.8	8.3
Na ₂ O	3.2	3.2	3.2	3.2	3.2	3.0	3.0	3.0
K ₂ O	1.3	1.5	1.8	--	0.4	1.0	1.0	0.8
MnO	0.200	0.171	0.180	0.170	0.206	0.187	0.180	0.255
Cr ₂ O ₃ (ppm)	14	20	21	21	54	33	32	31
Sc	33	29	31	32	37	36	37	37
V	340	300	320	300	320	330	320	320
Co	36	34	36	36	38	38	40	38
Zr	190	170	120	150	180	170	170	150
Ba	530	600	620	490	380	420	430	440
La	24.6	24.3	23.9	21.3	18.2	19.5	19.5	19.0
Ce	52	48	48	45	40	43	42	39
Nd	25	26	25	24	24	24	24	23
Sm	6.6	6.2	6.4	5.6	5.7	6.0	6.0	5.9
Eu	1.92	1.72	1.74	1.65	1.68	1.76	1.80	1.72
Tb	1.07	0.97	0.95	0.87	0.89	0.91	0.91	0.89
Dy	6	6	6	5	5	5	5	5
Yb	3.4	3.4	3.2	2.9	3.0	3.1	3.1	3.1
Lu	0.51	0.49	0.49	0.44	0.46	0.46	0.47	0.47
Hf	5.1	4.7	4.5	4.4	4.1	4.2	4.3	4.1
Ta	0.79	0.74	0.73	0.66	0.67	0.69	0.71	0.69
Th	5.5	5.4	5.1	4.6	2.9	3.2	3.6	3.3
Cs	1.7	1.7	1.5	1.4	1.1	0.5	0.8	1.0

Sample #	USGS Designation	Sample #	USGS Designation
D1	WCF59-1	D5	SR59-6
D2	SR63-141	D6a	GM61-27
D3	MR69-145	D6b	GM61-27
D4	SR61-30	D7	SR63-79

Table 12. Cape Foulweather Basalt.

	CF1	CF2	CF3	CF4	CF5	CF6a	CF6b
TiO ₂ (%)	3.1	3.0	3.1	3.0	2.9	2.8	2.8
Al ₂ O ₃	13.1	12.9	12.9	13.1	13.1	13.1	12.7
FeO	13.2	14.2	13.9	14.0	14.2	14.0	14.6
MgO	3.2	3.6	3.8	3.1	3.3	4.2	4.1
CaO	7.7	6.7	7.6	7.2	6.8	8.1	8.1
Na ₂ O	3.0	3.0	3.1	2.9	2.9	3.0	2.8
K ₂ O	0.6	1.3	0.9	1.3	1.1	1.1	1.2
MnO	0.164	0.201	0.182	0.189	0.206	0.202	0.201
Cr ₂ O ₃ (ppm)	22	33	21	23	25	63	62
Sc	37	35	36	35	35	36	37
V	380	370	370	350	380	400	400
Co	46	37	37	36	37	39	39
Zr	210	190	170	190	140	160	180
Ba	410	490	470	490	520	480	470
La	24.5	24.8	24.3	24.5	24.6	23.5	23.6
Ce	53	54	52	53	52	51	51
Nd	29	32	28	27	32	33	30
Sm	7.8	7.8	7.8	7.9	7.7	7.5	7.5
Eu	2.31	2.34	2.31	2.31	2.28	2.19	2.20
Tb	1.18	1.17	1.17	1.17	1.17	1.20	1.16
Dy	7	7	7	7	7	6	6
Yb	3.8	3.6	3.6	3.5	3.6	3.7	3.7
Lu	0.53	0.51	0.54	0.54	0.54	0.52	0.53
Hf	4.7	4.9	4.9	4.7	4.8	4.7	4.9
Ta	0.87	0.92	0.89	0.89	0.85	0.90	0.91
Th	3.7	3.9	3.9	3.9	3.9	3.8	3.8
Cs	1.1	0.8	0.8	0.9	1.2	0.8	1.1

Sample #	USGS Designation
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CF1	SR64-23
CF2	SR61-123
CF3	YC-129
CF4	Mtil 68-37
CF5	SR59-32B
CF6a	SR66-12B
CF6b	SR66-12B

Table 13. Basalt of Pack Sack Lookout and Standard Basalts.

	P1	P2	P3	P4	BCR-1	CRB
TiO ₂ (%)	1.6	1.7	1.7	1.6	2.3	--
Al ₂ O ₃	14.3	14.6	14.4	14.3	--	14.0
FeO	10.8	9.9	10.3	11.2	--	12.3
MgO	6.7	6.2	6.8	6.1	3.6	--
CaO	10.3	10.4	11.1	10.1	6.7	--
Na ₂ O	2.5	2.5	2.2	2.3	--	--
K ₂ O	0.4	0.7	0.4	0.6	--	1.7
MnO	0.161	0.164	0.166	0.196	--	--
Cr ₂ O ₃ (ppm)	140	150	140	150	18	15
Sc	34	35	35	35	--	32
V	270	270	270	270	400	--
Co	42	41	41	41	--	35
Zr	100	100	90	120	170	180
Ba	230	250	180	220	--	580
La	16.6	17.4	16.8	17.1	25.5	25.3
Ce	35	36	35	34	55	53
Nd	21	21	21	22	--	30
Sm	5.1	5.2	5.0	5.1	--	6.7
Eu	1.47	1.52	1.46	1.49	1.91	1.91
Tb	0.82	0.83	0.80	0.82	1.00	0.97
Dy	5	5	5	5	6	--
Yb	2.6	2.8	2.5	2.6	3.4	3.4
Lu	0.38	0.40	0.41	0.40	0.51	0.49
Hf	3.4	3.5	3.4	3.4	5.1	5.0
Ta	0.69	0.69	0.65	0.68	--	0.73
Th	2.4	2.5	2.4	2.5	5.7	5.6
Cs	0.1	0.3	0.2	0.3	1.2	1.3

Sample #	USGS Designation	Sample #	USGS Designation
P1	SR65-130	BCR-1	USGS standard rock
P2	SR63-32	CRB	Research group standard rock
P3	GM61-109		
P4	SR59-8		

Table 14. Columbia River Plateau Basalts.

	TY4	TY6	* TY15	TY18	TY20	CR1	73-5	± Error *
TiO ₂ (%)	2.3	2.0	1.9	1.8	2.8	1.9	1.5	0.3
Al ₂ O ₃	13.4	13.3	14.0	13.6	12.9	13.8	14.0	0.6
FeO	12.5	11.6	10.3	11.7	13.6	12.0	10.9	0.4
MgO	4.7	3.8	5.5	6.2	3.9	5.7	7.7	0.6
CaO	7.7	6.8	7.9	8.7	7.5	10.2	9.9	0.7
Na ₂ O	3.3	3.0	2.9	2.9	2.9	2.6	2.4	0.1
K ₂ O	1.9	1.7	1.1	1.0	1.0	0.9	0.7	0.2
MnO	0.233	0.188	0.184	0.193	0.180	0.191	0.170	0.005
Cr ₂ O ₃ (ppm)	19	32	64	69	74	93	160	3
Sc	37	33	38	37	38	39	35	2
V	320	350	320	310	430	330	270	10
Co	28	37	43	39	40	42	42	2
Zr	120	110	140	160	170	150	130	50
Ba	2210	590	470	410	470	250	200	50
La	25.4	24.2	19.6	17.5	23.5	20.7	17.4	0.5
Ce	51	48	42	34	50	43	37	4
Nd	39	28	24	21	31	24	24	7
Sm	9.3	6.3	5.9	5.3	7.3	6.1	5.1	0.3
Eu	3.60	1.81	1.81	1.61	2.18	1.81	1.54	0.07
Tb	1.33	1.00	0.95	0.85	1.14	0.98	0.75	0.06
Dy	7	6	6	5	6	5	5	2
Yb	4.1	3.8	3.2	3.0	3.4	3.1	2.9	0.2
Lu	0.61	0.50	0.49	0.46	0.53	0.48	0.37	0.04
Hf	4.1	4.6	4.3	3.5	5.0	4.3	3.5	0.3
Ta	0.49	0.73	0.63	0.58	0.87	0.86	0.73	0.08
Th	3.6	4.5	3.0	2.9	3.8	2.8	2.6	0.3
Cs	2.0	1.4	0.7	0.5	0.7	0.1	0.2	0.4

TY: Tygh River (numbered from bottom up)

CR: Columbia River (Yakima Type)

73-5: 1973, #5

* Cited errors are the estimated maximum error in the abundances in Tables 10 through 15 and 21. See experimental section (II) for details on error determination.

Table 15. Karmutsen and Metchosin Formation Basalts.

	K1	K2	K3	K4	K5	K6
TiO ₂ (%)	1.4	2.5	1.2	1.8	1.5	1.0
Al ₂ O ₃	15.4	12.0	14.0	12.5	12.6	13.7
FeO	10.5	15.5	11.5	14.8	13.6	10.7
MgO	7.2	5.2	7.9	5.9	6.8	8.6
CaO	12.1	7.6	11.5	9.6	11.1	11.9
Na ₂ O	1.8	2.8	2.1	2.5	2.1	1.9
K ₂ O	0.2	0.3	0.1	<0.1	0.1	0.1
MnO	0.182	0.272	0.180	0.255	0.212	0.167
Cr ₂ O ₃ (ppm)	490	70	260	36	84	290
Sc	37	42	49	45	46	49
V	290	390	340	430	420	310
Co	45	39	48	48	46	49
Zr	<60	190	160	<70	<60	70
Ba	<40	60	<30	<50	<40	<30
La	5.5	11.3	4.9	7.1	4.9	2.9
Ce	15	27	12	16	12	7
Nd	13	26	<10	21	15	<8
Sm	3.2	8.0	3.1	4.7	3.7	2.5
Eu	1.10	2.61	1.09	1.45	1.29	0.89
Tb	0.59	1.78	0.65	0.90	0.74	0.58
Dy	4	11	4	6	5	4
Yb	1.9	7.4	2.7	4.3	3.8	2.4
Lu	0.31	1.12	0.43	0.64	0.55	0.36
Hf	3.3	6.1	2.0	3.4	2.6	1.8
Ta	0.43	0.67	0.35	0.48	0.30	0.17
Th	0.3	0.7	<0.3	0.7	0.4	<0.3
Cs	--	--	--	--	--	--

Sample #	USGS Designation	Sample #	USGS Designation
K1	MV71-29	K4	MV71-16
K2	MV71-13A	K5	MV71-17
K3	MV71-14	K6	MV71-25

Table 16. Crescent Formation Basalts.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
TiO ₂ (%)	1.6	1.9	1.8	2.0	2.1	1.3	1.2	0.8	2.9	1.4
Al ₂ O ₃	13.1	14.1	15.1	13.6	13.6	14.4	15.0	17.4	13.0	15.2
FeO	12.2	11.8	11.4	11.2	13.1	10.3	8.8	8.5	14.4	11.6
MgO	3.5	8.3	8.0	5.8	6.2	4.5	8.6	8.2	4.8	6.5
CaO	6.9	8.4	7.5	9.6	10.7	9.0	10.9	11.2	7.5	11.1
Na ₂ O	4.6	3.8	3.6	4.1	2.7	2.6	3.1	2.2	3.1	2.5
K ₂ O	<0.1	<0.1	0.3	0.2	0.2	0.2	0.2	0.1	0.3	0.1
MnO	0.187	0.150	0.161	0.172	0.219	0.275	0.147	0.152	0.217	0.168
Cr ₂ O ₃ (ppm)	35	310	310	223	44	120	440	480	7	150
Sc	31	47	38	42	40	36	40	38	38	44
V	310	370	300	380	360	280	240	240	290	320
Co	31	43	42	36	49	43	40	41	34	47
Zr	230	150	90	110	90	50	<60	<90	160	120
Ba	<30	40	220	<30	60	80	140	<30	70	<40
La	13.1	10.7	17.4	20.6	13.9	14.3	4.2	2.5	15.9	5.4
Ce	32	22	37	39	30	28	10	7	36	14
Nd	23	17	24	26	22	18	9	<10	26	11
Sm	7.0	5.0	5.2	5.9	5.4	4.3	2.7	1.8	7.6	3.4
Eu	1.83	1.58	1.70	1.85	1.69	1.37	0.95	0.67	2.30	1.24
Tb	1.53	0.92	0.96	1.03	0.74	0.72	0.46	0.39	1.35	0.66
Dy	10	6	6	7	4	4	3	3	8	4
Yb	7.5	3.8	3.9	4.5	2.7	2.9	1.6	2.0	5.5	2.6
Lu	1.14	0.56	0.58	0.66	0.39	0.43	0.24	0.30	0.89	0.37
Hf	7.3	3.3	3.4	3.8	3.7	2.7	1.8	0.9	5.6	2.2
Ta	0.92	0.84	1.21	1.45	1.02	0.99	0.30	0.17	1.24	0.35
Th	1.3	0.7	0.6	1.5	1.1	1.2	0.3	<0.3	0.7	<0.3
Cs	--	--	--	--	--	--	--	--	--	--

Sample #	USGS Designation	Sample #	USGS Designation
C1	HR-17	C6	SR61-163
C2	HR-25	C7	MR71-166
C3	HR-27	C8	MR71-187
C4	HR-28	C9	MR71-191
C5	SR60-4	C10	J101-104

Table 17. Tillamook Volcanics.*

	80	81	82	83	84
Al_2O_3 (%)	13.4	14.0	15.1	11.3	15.4
FeO	12.5	12.8	10.8	13.1	13.8
MgO	5.1	5.9	5.8	7.7	4.49
CaO	10.4	11.2	11.3	10.4	11.9
Na_2O	3.9	2.4	3.2	2.7	2.6
K_2O	0.16	0.27	0.19	0.15	0.28
MnO	0.272	0.261	0.199	0.156	0.232
Cr_2O_3 (ppm)	110	170	350	480	59
Sc	38	42	41	33	32
Co	44	51	46	64	47
Ba	140	70	70	70	135
La	13	12	7.2	35	26
Ce	33	32	22	84	60
Sm	5.4	5.4	3.8	7.7	7.5
Eu	1.6	1.6	1.3	2.2	2.2
Tb	1.0	1.0	0.68	0.69	1.2
Yb	2.7	3.2	2.5	2.0	2.9
Lu	0.50	0.47	0.46	0.34	0.49
Hf	3.8	3.7	2.4	6.1	6.3
Ta	0.51	0.54	0.40	2.5	1.4
Th	1.2	1.5	0.67	6.8	3.1
Sr	230	190	160	140	330

Sample Locations:

#80 - SE 1/4 sec. 8, T1S, R8W, Blaine, Ore.

#81 - NE 1/4 sec. 24, T1N, R8W, Enright, Ore.

#82 - SE 1/4 sec. 26, T2N, R5W, Timber, Ore.

#83 - SE 1/4 sec. 28, T1N, R9W, Nehalem, Ore.

#84 - SW 1/4 sec. 29, T2N, R9W, Nehalem, Ore.

* These samples were analyzed by M. J. Dudas via INAA and atomic absorption analysis. Al_2O_3 was determined via INAA in this work.

Table 18. Umpqua Volcanics.*

	89	90	91	92	93	94a
Al ₂ O ₃ (%)	15.4	13.9	14.7	14.1	14.6	14.6
FeO	13.1	12.5	12.3	13.0	10.9	9.9
MgO	5.1	6.1	5.9	6.0	6.5	8.2
CaO	12.0	10.9	13.1	11.0	12.8	9.6
Na ₂ O	2.1	3.2	2.4	2.8	3.0	3.8
K ₂ O	0.053	0.10	0.075	0.061	0.16	0.39
MnO	0.146	0.225	0.241	0.192	0.239	0.152
Cr ₂ O ₃ (ppm)	240	190	270	210	430	690
Sc	40	45	46	44	50	42
Co	48	46	50	49	53	51
Ba	70	120	70	70	140	70
La	10.8	8.0	8.4	8.4	8.6	13
Ce	29	23	21	21	23	34
Sm	5.1	4.2	3.9	4.0	4.0	3.2
Eu	1.6	1.3	1.3	1.3	1.4	1.9
Tb	0.97	0.76	0.76	1.0	0.91	0.62
Yb	2.5	2.7	2.6	3.0	2.6	2.1
Lu	0.43	0.50	0.47	0.52	0.47	0.34
Hf	4.2	3.1	2.4	3.3	3.1	3.1
Ta	0.64	0.44	0.20	0.41	0.32	1.3
Th	0.94	0.55	0.74	0.71	0.74	1.7
Sr	65	270	300	120	180	380

Sample Locations:

#89 - SW 1/4 sec. 34, T22S, R4W, Anlauf, Ore.

#90 - NE 1/4 sec. 25, T27S, R6W, Roseburg, Ore.

#91 - SW 1/4 sec. 24, T28S, R8W, Camas Valley, Ore.

#92 - NW 1/4 sec. 26, T29S, R12W, Coquille, Ore.

#93 - NW 1/4-NE 1/4 sec. 30, T28S, R12W, Coquille, Ore.

#94a- NE 1/4 sec. 3, T25S, R12W, Coos Bay, Ore.

* These samples were analyzed by M. J. Dudas via INAA and atomic absorption analysis. Al₂O₃ was determined via INAA in this work.

Table 19. Siletz River Volcanics (Older Unit).*

	45	46	47	49	BCR-1
Al ₂ O ₃ (%)	15.2	14.8	14.9	15.0	13.1
FeO	11.7	10.7	10.9	11.7	13.0
MgO	7.6	7.9	7.9	7.9	3.4
CaO	11.5	11.2	10.5	10.0	6.5
Na ₂ O	2.0	1.9	1.8	2.2	3.4
K ₂ O	--	0.10	--	0.095	1.66
MnO	0.190	0.170	0.186	0.198	0.196
Cr ₂ O ₃ (ppm)	480	420	420	450	19
Sc	42	40	38	41	32
Co	50	46	48	50	37
Ba	70	<50	<50	<50	730
La	6.4	5.8	5.8	6.7	25.4
Ce	18	16	15	18	58
Sm	3.4	3.4	3.2	3.9	7.0
Eu	1.14	1.16	1.03	1.28	1.9
Tb	0.75	0.57	0.72	0.63	1.01
Yb	2.1	1.9	1.9	2.3	3.5
Lu	0.39	0.38	0.34	0.37	0.60
Hf	2.4	2.2	2.1	2.9	5.0
Ta	0.80	0.49	0.56	0.70	1.2
Th	0.50	0.52	0.50	0.60	6.6
Sr	200	--	206	--	280

Sample Locations:

#45 - (SR59-28) SE 1/4 sec. 36, T10S, R5W, Benton Co., Ore.

#46 - (SR59-28) Same as sample 45 (200 yds. south).

#47 - (SR59-22) SW 1/4 sec. 27, T11S, R6W, Benton Co., Ore.

#49 - SW 1/4 sec. 7, T11S, R5W, Benton Co., Ore.

* These samples were analyzed by M. J. Dudas via INAA and atomic absorption analysis. Al₂O₃ was determined via INAA in this work.

Table 20. Siletz River Volcanics (Younger Unit).*

	39	40	41	42	43	44
Al ₂ O ₃ (%)	12.8	12.2	15.2	13.7	13.5	13.5
FeO	14.7	15.1	12.9	15.3	13.3	14.7
MgO	5.8	4.6	5.5	6.3	5.7	5.3
CaO	10.0	9.4	11.7	10.2	10.4	10.4
Na ₂ O	2.6	2.8	2.6	2.8	2.7	2.8
K ₂ O	0.26	0.72	0.14	0.13	0.20	0.22
MnO	0.239	0.213	0.181	0.220	0.205	0.234
Cr ₂ O ₃ (ppm)	160	140	290	73	160	160
Sc	38	38	41	40	37	39
Co	48	43	53	52	48	46
Ba	140	200	70	<60	100	100
La	15.6	32.8	10.2	12.4	18.4	15.3
Ce	39	81	26	30	46	39
Sm	6.3	11.5	4.9	6.1	7.3	6.6
Eu	1.9	3.0	1.6	1.9	2.4	1.7
Tb	0.99	1.9	0.86	1.01	1.20	1.09
Yb	3.0	5.5	2.4	2.9	3.2	3.1
Lu	0.47	0.84	0.42	0.50	0.54	0.53
Hf	4.6	9.5	3.3	4.6	5.2	5.2
Ta	1.9	3.8	1.1	1.5	2.1	2.2
Th	1.6	3.5	0.8	1.1	1.6	1.6
Sr	165	150	155	165	190	175

Sample Locations:

#39 - NE 1/4 sec. 28, T11S, R6W, Benton Co., Ore.

#40 - (SR52-25) SW 1/4 sec. 26, T10S, R6W, Benton Co., Ore.

#41 - NE 1/4 sec. 22, T10S, R6W, Benton Co., Ore.

#42 - (SR60-86) SW 1/4 sec. 25, T7S, R6W, Polk Co., Ore.

#43 - (SR65-81) SE 1/4 sec. 4, T7S, R6W, Polk Co., Ore.

#44 - (SAB59-1) NW 1/4 sec. 18, T10S, R5W, Benton Co., Ore.

* These samples were analyzed by M. J. Dudas via INAA and atomic absorption analysis. Al₂O₃ was determined via INAA in this work.

Table 21. Eocene Alkalic Basalts.*

	86	88	50	BCR-1
Al ₂ O ₃ (%)	18.2	15.0	17.3	14.0
FeO	9.0	12.8	8.0	13.1
MgO	1.8	6.5	0.95	3.2
CaO	5.5	6.6	3.4	6.3
Na ₂ O	4.5	2.9	4.4	3.4
K ₂ O	1.70	1.30	1.63	1.51
MnO	0.174	0.170	0.137	0.186
Cr ₂ O ₃ (ppm)	15	140	9	20
Sc	8.7	18	17	32
Co	15	42	11	37
Ba	600	420	460	730
La	98	46	60	26
Ce	216	101	130	61
Sm	14	10	12	7.1
Eu	3.9	2.6	3.3	1.9
Tb	1.5	1.3	1.5	1.1
Yb	4.3	2.9	4.1	3.8
Lu	0.54	0.41	0.51	0.62
Hf	9.4	8.4	10.9	5.0
Ta	6.2	2.8	3.5	1.0
Th	13	5.3	7.9	7.3
Sr	840	440	450	270

Sample Locations:

#86 - SE 1/4 sec. 36, T5S, R11W, Hebo, Ore.

#88 - SW 1/4 sec. 25, T6S, R10W, Hebo, Ore.

#50 - Neptune State Park, Ore. Hwy. 101, 124° 7' X 44° 16'.

*These samples were analyzed by M. J. Dudas via INAA and atomic absorption analysis. Al₂O₃ was determined via INAA in this work.

Miscellaneous

The sample locations for the samples obtained from Dr. Snavely of the USGS can be found by looking up the USGS designations (which are given on the tables in this paper) in the paper by Snavely et al. (1973). The sample locations for the samples gathered by Drs. M. J. Dudas and R. A. Schmitt are given in the tables in this paper.

The general locations of the Columbia River Plateau samples used for the U. of O. averages in Tables 5 through 8 are as follows: Lower Yakima basalt-Tygh River, Crescent Bar, Klickitat River and Vantage; Frenchman Springs basalt - Tygh River, Frenchman Springs Coulee, Klickitat River, Sand Hollow, and Wanapum Dam; Pomona basalt - Yakima, Sentinel Gap and Ice Harbor Dam. More specific locations for the samples from the Columbia River Plateau may be obtained by writing to the University of Oregon Center of Volcanology in Eugene, Oregon.

A basalt sample reported by Laul and Schmitt (1972) called the F. R. Basalt has a chemical composition very similar to the older unit of the Siletz River Volcanics and was picked up in the same general area as the samples from this unit. The K_2O content of this sample is fairly high (0.65%) but the REE pattern is very similar to that of the older unit basalts.

One of the Umpqua Volcanics samples (94a) was described in the field as being quite weathered and displayed uncharacteristic composition and REE patterns. Thus this sample was not considered in the REE plot or general discussion for this group.

Cove Palisades Volcanic Ash

Four samples from the late Pliocene Dalles Formation were collected by Dr. Schmitt and analyzed along with the other samples from this group. The samples were collected along the descent of the main parkroad to the canyon at Cove Palisades State Park 50 km north of Bend, Oregon. Samples 36L (light tan) and 36D (dark tan) were collected from a pinkish-tan ash-flow layer containing lumps of pumice. Below this layer is a dark gray sandstone of volcanic detritus from which sample 36a was obtained, and a light gray ash-flow tuff containing large lumps of pumice from which sample 36b was obtained.

On a major element basis (Table 22) the sandstone sample (36a) resembles the dark basic andesitic scoria at The Pennacles, Crater Lake National Park, Oregon (McBirney, 1968a, samples 5 and 6 of Table 1); the platy andesite, Unit 2, from the north wall at Newberry Crater, Oregon (Higgins and Waters, 1968); some of the lavas erupted from Mount Hood, Oregon (Wise, 1968); and a platy andesite below Spire Rock on Mt. Jefferson, Oregon (McBirney, 1968b, sample 2,

Table 22. Cove Palisades Volcanic Ash.*

	CPL	CPD	CPa	CPb
TiO ₂ (%)	0.5	0.5	1.2	0.8
Al ₂ O ₃	14.8	15.1	17.7	15.8
FeO	3.4	3.0	8.2	4.3
MgO	1.4	0.9	4.3	1.8
CaO	2.3	2.0	7.7	2.8
Na ₂ O	4.1	3.8	3.6	4.2
K ₂ O	3.4	3.6	1.1	2.3
MnO	0.085	0.080	0.141	0.100
Cr ₂ O ₃ (ppm)	7	7	87	19
Sc	10	9	25	13
V	20	10	200	60
Co	3.3	2.4	25	7.2
Zr	230	220	60	260
Ba	600	590	400	590
La	22.8	24.8	15.1	24.2
Ce	57	58	36	55
Nd	32	33	24	33
Sm	5.7	6.3	5.0	6.8
Eu	1.39	1.29	1.55	1.72
Tb	0.81	0.82	0.64	0.89
Dy	4	7	4	6
Yb	3.1	3.1	2.2	3.5
Lu	0.46	0.49	0.36	0.55
Hf	7.2	7.3	3.3	6.3
Ta	0.80	0.87	0.39	0.80
Th	5.1	5.1	1.1	3.1
Cs	2.1	2.2	0.5	1.5

* Sample designations are explained in text.

Table 1). The bulk compositions of the dacitic ash samples (36L, 36D, 36b) resemble the compositions of the white pumice deposit (McBirney, 1968a, sample 3, Table 1).

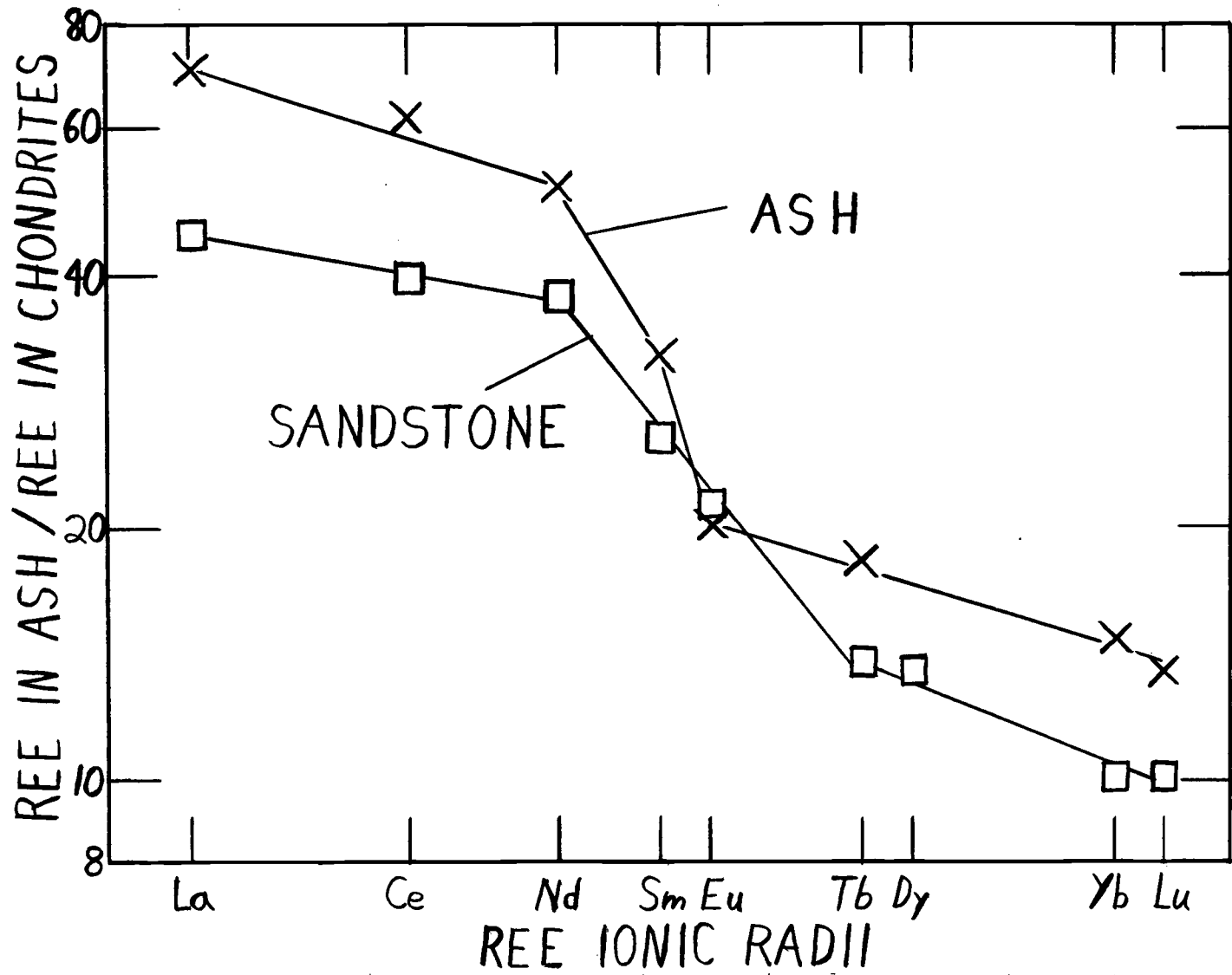
The general REE pattern for the ash-flow tuff samples (Figure 22) are similar to those for the Newberry Crater ash, but differ from the others in Randle *et al.* (1971). The Cs, Th, and Hf values and the Eu/Sm ratio do not agree with the Newberry Crater ash however.

The REE patterns for the group of three ash-flows (36L, 36D, and 36b) do not agree with the 36a pattern; therefore, it is evident that these two groups of samples originated from eruptive vents that were composed of very different magmas chemically. It is also noted that the higher abundances of Cr, Sc, V, and Co in the sandstone-volcanic detritus sample 36a, relative to the three ash-flow tuff samples, correlate with higher FeO and MgO abundances in the sandstone-volcanic detritus sample.

The REE patterns for these samples are all highly enriched in the light REE over the heavy REE which is typical of dacitic and andesitic rocks.

All these ash samples show a negative Eu anomaly as was observed by Borchardt (1970) in glass separates of the Mount Mazama ash layers. The average Sm/Eu ratio is 4.0 for the Cove Palisades ash-flow tuffs and sandstone-volcanic detritus and 5.4 in the Mount Mazama ash layers. This compares to the chondritic Sm/Eu ratio

Figure 22. Average REE abundances of the volcanic ash and REE abundances of the sandstone from Cove Palisades State Park, Ore., are normalized to the average abundances in ordinary chondrites.



of 2.8. By drawing a smooth curve from the average Sm through the average Tb and Dy normalized abundances in the ash-flow tuff samples, one can determine what the average undepleted Eu abundance would have been. Comparison with the experimental Eu abundance shows a depletion of about 25%. Prior plagioclase fractional crystallization in the magma chamber may have been responsible for such a depletion of Eu.