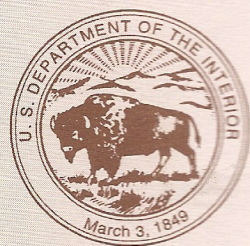


# Chemistry of the Subalkalic Silicic Obsidians

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# Chemistry of the Subalkalic Silicic Obsidians

By RAY MACDONALD, ROBERT L. SMITH, *and* JOHN E. THOMAS

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U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1523

Compilation of analyses of subalkalic silicic obsidians, assessment of compositional variations in terms of tectonic setting and genetic mechanisms, and systematic discussion of element distribution in these rocks



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**MANUEL LUJAN, JR.,** *Secretary*

**U.S. GEOLOGICAL SURVEY**

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## ABBREVIATIONS

---

CLPD	Crystal-liquid processes dominated
CIPP	Complex interaction of petrogenetic processes



# CHEMISTRY OF THE SUBALKALIC SILICIC OBSIDIANS

By RAY MACDONALD, ROBERT L. SMITH and JOHN E. THOMAS

## ABSTRACT

Nonhydrated obsidians are quenched magmatic liquids that record in their chemical compositions details of the tectonic environment of formation and of the differentiation mechanisms that affected their subsequent evolution. This study attempts to analyze, in terms of geologic processes, the compositional variations in the subalkalic silicic obsidians ( $\text{SiO}_2 \geq 70$  percent by weight, molecular  $(\text{Na}_2\text{O} + \text{K}_2\text{O}) < \text{Al}_2\text{O}_3$ ). New major- and trace-element determinations of 241 samples and a compilation of 130 published major-element analyses are reported and interpreted.

Obsidians from five different tectonic settings are recognized: (1) primitive island arcs, (2) mature island arcs, (3) continental margins, (4) continental interiors, and (5) oceanic extensional zones. Tectonomagmatic discrimination between these groups is successfully made on Nb-Ta, Nb-FeO<sub>x</sub>, and Th-Hf-Ta plots, and compositional ranges and averages for each group are presented. The chemical differences between groups are related to the type of crust in which magmas were generated. With increasingly silicic (continental type) crust, the obsidians show overall enrichment in F, Be, Li, Mo, Nb, Rb, Sn, Ta, U, W, Zn, and the rare-earth elements, and depletion in Mg, Ca, Ba, Co, Sc, Sr, and Zr. They become more potassic, have higher Fe/Mg and F/Cl ratios, and lower Zr/Hf, Nb-Ta, and Th/U ratios. Higher values of total rare-earth elements are accompanied by light rare-earth-element enrichment and pronounced negative Eu anomalies.

An attempt is made to link obsidian chemistry to genetic mechanism. Two broad groups of rocks are distinguished: one generated where crystal-liquid processes dominated (CLPD types), which are the products of crustal anatexis, possibly under conditions of low halogen fugacity,  $\pm$  crystal fractionation  $\pm$  magma mixing; and a second group represented by rocks formed in the upper parts of large magma chambers by interplays of crystal fractionation, volatile transfer, magma mixing, and possibly various liquid-state differentiation mechanisms, or in other words a complex interaction of petrogenetic processes (CIPP types). Such rocks may also form by volatile-fluxed partial melting of the wallrocks, and subsequent mixing into the magma reservoir. Compositional ranges and averages for CLPD and CIPP obsidians are given.

It is shown by analogy with well-documented, zoned ash-flow tuffs that obsidians fractionated by CIPP have very low Mg, P, Ba, and Sr contents, flat rare-earth-element patterns with extensive Eu anomalies, low K/Rb and Zr/Nb ratios, and relatively high  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratios. There is, however, considerable compositional overlap between CLPD and CIPP obsidians. The effects of magma mixing, assimilation, and vapor-phase transport in producing compositional variations in the obsidians are briefly assessed.

The geochemistry of the subalkalic silicic obsidians is described on an element-by-element basis, in order to provide a data base for silicic magma compositions that will hopefully contribute to

studies of granitic rocks. Attempts are also made to isolate the geochemical effects of tectonic environment and genetic mechanism for each element, by comparison with data from crystal-liquid equilibria-controlled systems, from ash-flow sheets zoned by CIPP, and from mixed-magma series. A final tabulation relates the complexities of obsidian geochemistry to all the tectonic and genetic variables.

## INTRODUCTION

This study of the chemistry of obsidians has been undertaken primarily to further our understanding of granitic igneous rocks. The literature on the chemistry of granites, rhyolites, and related rocks is extensive; much of it is useful, much is controversial, and much is totally useless. The study of granites per se is handicapped by difficulties inherent in sampling techniques and the recognition of significant samples, in obtaining accurate and precise chemical analyses, and in the distinct probability that many granites, though clearly of magmatic origin, may or may not represent liquid magmatic compositions, but instead reflect post-magmatic alteration or partial cumulate conditions.

This study of obsidians (nonhydrated rhyolitic glasses) is therefore a study of quenched, liquid, magmatic compositions. Its main aims are:

1. To determine the range of major- and trace-element compositions of subalkalic (mol.  $(\text{Na}_2\text{O} + \text{K}_2\text{O}) < \text{Al}_2\text{O}_3$ ) rhyolitic liquids as expressed by obsidians. Although certain volatile constituents are lost before obsidian forms (for example,  $\text{H}_2\text{O}$ , S,  $\text{CO}_2$ , and perhaps Cl in some cases), most elements are relatively undisturbed, and thus obsidian represents a very close approximation to original rhyolitic melt.

2. To relate compositional variations in the obsidians broadly to tectonic setting and, more specifically, to the type of crust in which the rhyolites were generated.

3. To interpret the data in terms of the main differentiation mechanisms operative in silicic magmas and to suggest preliminary criteria whereby the effects of each process might be identified.

4. To provide a comprehensive, systematic, element-by-element discussion of the data which will be the first of its kind specifically devoted to high-silica rocks.

## ACKNOWLEDGMENTS

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Obsidian samples were kindly provided by so many individuals that we deemed it best to acknowledge these critical contributions separately, in the annotated locality lists in appendixes I–IV.

David Gottfried provided unpublished data on the Woodson stock, and a wealth of geochemical experience. R.J. Banks, B. Robinson and T.L. Wright helped with computing problems. Karen Gray and Susan Russell-Robinson kept the project on the road, in many ways. Frank Dodge and Jim Rytuba provided detailed, constructive reviews of the manuscript.

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## THE DATA BANK

An initial objective of this project was to collect from the literature all good-quality analyses of nonhydrated obsidians and glasses having  $\text{SiO}_2 \geq 70$  percent and to assess the chemical variations in terms of rhyolite petrogenesis. Analyses were screened using the following criteria for rejection:

1. The total weight percent for major oxides did not lie within the limits 99–101 percent.
2. Any one of the oxides  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ , and  $\text{H}_2\text{O}^+$  was not reported.
3. Two or more of the oxides  $\text{TiO}_2$ ,  $\text{MnO}$ ,  $\text{MgO}$ , and  $\text{P}_2\text{O}_5$  were not reported.
4.  $\text{H}_2\text{O}^+$  content exceeded 1 weight percent. The original conclusion of Ross and Smith (1955), that obsidians with more than 1 percent  $\text{H}_2\text{O}$  have been secondarily hydrated, has been confirmed by stable isotope studies (Friedman and Smith, 1958; Taylor, 1968)<sup>1</sup>.

<sup>1</sup>More recent studies have shown that nonhydrated obsidian *pyroclasts* may contain up to about 3 percent  $\text{H}_2\text{O}$ . The significance of these results to this work is discussed in the section "Water and the Isotopes of Hydrogen and Oxygen."

More than 200 major-element analyses were assembled. Despite the screening, it was apparent that the quality of many analyses was suspect, particularly alkali determinations.

Our experience with American silicic obsidians led us to expect a broad positive correlation between  $\text{CaO}$  contents and  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratios. The compilation of published analyses showed many exceptions to this rule. Comparison of our new data bank with the published analyses clearly demonstrates this (fig. 1). Published data may include chemical variants not sampled by our analytical program, but our reanalyses of glasses from some of the same localities that had previously provided "suspect" analyses have invariably indicated more normal alkali values for those rocks (table 1). In these examples,  $\text{Na}_2\text{O}$  determinations appear to be more in error than those of  $\text{K}_2\text{O}$ . The series of analyses of obsidians presented by Friedman and Long (1976), on the other hand, have systematically low  $\text{K}_2\text{O}$  values, by an average of about 10 percent, compared with our new data.

Other analytical problems may be suspected. For example, the analysis of an obsidian from Talasea, New Britain, given by Lowder and Carmichael (1970, sample 343) shows considerably higher  $\text{Fe}_2\text{O}_3$  than  $\text{FeO}$  contents (1.58 pct, 0.88 pct, respectively;  $\text{FeO}_t = 2.30$  pct), a reversal of the situation in most obsidians. This unusual oxidation ratio is coupled with a rather high analytical total (100.46 pct). A high Fe determination seemed possible and

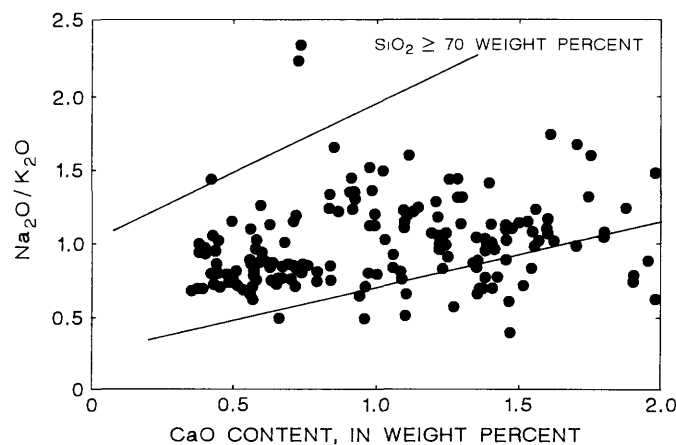


FIGURE 1.— $\text{CaO}$  content versus ratio of  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  in subalkalic silicic obsidians having  $\text{CaO}$  less than 2 percent by weight. Rocks analyzed as part of this project fall between solid lines; dots represent published analyses: 27 rocks (15 percent) fall outside field bounded by solid lines.



TABLE 1.—Comparison of alkali determinations from published studies and the present paper

[Values are in weight percent]

	Na <sub>2</sub> O		K <sub>2</sub> O		Reference (published; this paper)
	Published	New	Published	New	
Wadatoge, Japan -----	2.84	3.97	3.37	4.50	Kawano, 1950; app. I, No. 188
Kawago daira, Japan -----	5.16	3.85	2.12	2.40	Kurasawa, 1959; app. I, No. 189
Hrafninnuhryggur, Iceland ----	3.36	4.42	2.80	2.70	Wright, 1915; app. I, No. 175
Rocche Rosse, Italy -----	3.7	4.23	5.1	5.05	von Platen, 1965; app. I, No. 180

indeed our reanalysis of Talasea obsidian gives  $\text{FeO}_t = 1.12$  percent. Smith and Johnson (1981) have also redetermined Talasea obsidian and found  $\text{FeO}_t$  to be 1.14 percent. Lowder and Carmichael's total Fe value would seem to be in error, and doubt is immediately cast upon other Fe determinations in that suite of analyses, including a glassy rhyodacite having  $\text{SiO}_2 = 72.19$  percent (their sample 279B).

The situation regarding trace elements proved equally unsatisfactory. Many available determinations were made for purposes of archaeological characterization and, for various reasons, were of limited use in our study.

1. Major-element analyses of the samples were not presented (for example, Cann and Renfrew, 1964; Renfrew and others, 1965, 1966, 1968; Jack and Carmichael, 1969; Jack, 1971; Rutherford, 1978).

2. Only a small number of supposedly diagnostic trace elements were determined (Gordus and others, 1968; Griffin and others, 1969; Stevenson and others, 1971).

3. Many samples were poorly located, geographically and (or) geologically (for example, Stevenson and others, 1971).

Interlaboratory consistency of data proved to be variable. Selected data from various studies of the Big Glass Mountain flow, Medicine Lake, California, indicate that for many elements interlaboratory agreement is good, but for others (for example, Ce, Co, and Nb) rather less satisfactory (table 2). Although this flow has been contaminated by incorporation of mafic rocks, the close similarities of the Ba, Rb, and Zr values suggest that analytical problems, rather than natural contamination, are the main cause of the discrepancies in the data.

A comparison of the trace-element analyses of the Talasea obsidian, New Britain, published by Lowder and Carmichael (1970) and Smith and Johnson (1981), and presented in this paper (sam-

ple 215), also shows some notable differences (table 3). As Smith and Johnson (1981, p. 10261) point out, Lowder and Carmichael's (1970) Ni, Ba, light rare-earth-element, and Th values are too high. Our Y and Zn determinations may be slightly on the high and low sides, respectively, but our Pb value is closer to Lowder and Carmichael's than to Smith and Johnson's.

Other inconsistencies in the published data, almost certainly due to analytical error, are noteworthy. For example:

1. The analysis of an obsidian from Forgia Vecchia, Lipari, presented by Cann and Renfrew (1964), does not lie within the limits for this unit given by Belluomini and Taddeucci (1971) for Nb, Rb, Y, or Zr.

2. The reanalysis by Wright and Gordus (1969) of Renfrew and others' (1966) specimens 82 and 83 from eastern Turkey show satisfactory agreement for Rb but not for La. We suspect that Renfrew and others' La results are all, in fact, systematically too high.

3. The Y data of Higgins (1973) for obsidians from the Newberry Volcano, Oregon, are consistently higher than those of Jack and Carmichael (1969) for the Newberry rocks. Jack and Carmichael's (1969) Zn determinations, by contrast, are lower than those given by Laidley and McKay (1971) for Newberry glasses.

In view of these difficulties with the published analyses, we decided to build up a major- and trace-element data bank of subalkalic silicic obsidians, utilizing, for each element, the most precise analytical method available to us on a routine basis. Using our own collections and donated specimens, the number of samples reached 226. Major-element (including F and Cl) analyses and determinations of 32 trace elements were made on all samples, except for a very few where the small sample size resulted in certain elements being undetermined. Trace-element determinations only were subsequently made on a further 15 samples.

TABLE 2.—Comparison of trace-element data for obsidian from Big Glass Mountain, Medicine Lake highlands, California

[All values in parts per million; —, not determined]

	Jack and Carmichael (1969)	Stevenson and others (1971)	Condie and Hayslip (1975)	Sample 42 (this paper)	Sample 43 (this paper)	Various authors, in Flanagan (1976)
Ba -----	850	850	856	855	810	705 - 826.7
Ce -----	60	—	—	44	45	46.3 - 60.4
Co -----	15	—	2.6	2.1	1.9	1.76 - 7.2
Cs -----	—	—	11	10.5	9.7	10.3
Cu -----	10	—	18	—	—	10.2 - 16.5
La -----	30	—	29	23	24	27.0
Nb -----	5	<30	—	9	9.4	5.44 - 9.44
Pb -----	25	—	—	22	22	20.9 - 21.2
Rb -----	155	140	157	156	154	96.3 - 193
Sc -----	—	—	—	4.5	4.36	4.60 - 6.3
Sr -----	105	121	95	115	115	100.1 - 132
Ta -----	—	—	—	1.00	1.03	0.54 - 0.90
Y -----	20	35	—	23	28	23.8 - 26.7
Zn -----	25	—	—	30	28	21.5 - 38.9
Zr -----	215	—	192	206	212	205 - 304

TABLE 3.—Comparison of trace-element data for Talasea obsidian

[All values in parts per million; —, not determined]

	Lowder and Carmichael (1970)	Smith and Johnson (1981)	Sample 215 (this paper)
Ba -----	645	480	540
Cr -----	5	4	<6
Cu -----	20	3	—
Nb -----	—	2	3
Ni -----	40	<1	—
Pb -----	20	8.5	19
Rb -----	55	55	55
Sc -----	—	5	4
Sr -----	200	206	216
Th -----	10	2.5	2.7
V -----	35	6	—
Y -----	20	21	27
Zn -----	40	38	31
Zr -----	150	150	162
Ce -----	50	29	24
La -----	20	13	13
Nd -----	20	13	14

## DESCRIPTION AND GEOGRAPHICAL DISTRIBUTION OF ANALYZED SAMPLES

This report compiles geochemical information on silicic volcanic glasses. The majority of analyses has been made on obsidian. Though the term obsidian simply means pristine volcanic glass, it has popularly been used for material of sufficient size and quality to be worked as artifacts. As such, obsidian occurs in lava flows, in extrusive domes, and as blocks in pyroclastic deposits.

Silicic volcanic glass may, of course, occur in other forms: as pumiceous glassy carapaces on crystalline flows and domes, as remnant obsidian nodules (apache tears, marekanite) in secondarily hydrated flows and pyroclastic deposits, as vitreous facies of welded ash-flow tuffs, and as a range of tephra from coarse pumice to ash. In all these forms, especially as tephra, the glass tends to be rapidly hydrated after emplacement and may show variable amounts of chemical modification.

Nevertheless, incorporating nonhydrated glasses from this wider range of occurrences extended the number of samples of natural volcanic glass relevant to this compilation. Details of the mode of occurrence of individual specimens are given in the annotated sample lists accompanying various tables. Table 4 summarizes these data and also the general geographic localities of the analyzed specimens.

The rationale of selecting nonhydrated obsidians for analysis is that they represent magmatic liquid compositions. Sixty-one (61) percent of the 297 rocks for which petrographic information is available are porphyritic, however, and it might be argued that accumulation of crystals modified liquid compositions. A histogram of modal phenocryst proportions (fig. 2) indicates that 71 percent of the porphyritic samples have less than 3 percent phenocrysts, whereas only 17 percent of the samples have greater than or equal to 6 percent phenocrysts. Almost all compiled specimens are, therefore, crystal poor. Furthermore, there is no evidence of any systematic chemical differences



TABLE 4.—Summary of generalized localities and types of occurrence of samples compiled in appendixes I-IV (excluding peralkaline rocks and those with SiO<sub>2</sub><70) weight percent)

Locality	Lava flow or dome	Ash-Flow tuff or agglutinate	Fragments in pyroclastic falls	Float	No information
<b>U.S.A.</b>					
Alaska -----	9	1	—	—	—
Oregon -----	37	1	—	1	—
California -----	70	—	—	—	—
Nevada -----	8	—	—	2	—
Idaho -----	4	2	—	—	—
Wyoming -----	13	2	—	—	—
Utah -----	16	—	—	—	—
Colorado -----	2	—	—	—	—
Arizona -----	6	—	—	—	—
New Mexico -----	13	—	—	—	—
<b>Central &amp; South America</b>					
Mexico -----	8	1	1	—	5
Guatemala -----	2	—	—	—	—
Colombia -----	1	—	—	—	—
Ecuador -----	1	3	—	—	—
Peru -----	—	—	—	9	1
Bolivia -----	—	—	—	1	—
Chile -----	5	—	—	—	—
<b>Africa</b>					
Cameroon -----	—	—	—	1	—
<b>Europe</b>					
Iceland -----	13	—	1	—	—
Hungary -----	1	—	—	—	1
Czechoslovakia -----	—	—	—	—	1
Italy -----	9	—	—	—	2
Greece -----	4	—	—	—	—
Turkey -----	2	—	—	—	1
<b>Asia</b>					
U.S.S.R. -----	3	—	—	—	1
China (Tibet) -----	—	—	—	—	1
Japan -----	24	1	2	—	3
Sumatra -----	—	—	—	—	1
Java -----	5	—	—	—	—
Sulawesi (Celebes) -----	2	—	—	—	—
Halmahera -----	4	—	—	—	—
<b>Australasia</b>					
Papua New Guinea -----	9	—	—	—	—
New Britain -----	2	—	—	—	—
New Zealand -----	6	—	1	—	—
Tonga -----	—	—	1	—	—
<b>Total -----</b>	<b>279</b>	<b>10</b>	<b>6</b>	<b>14</b>	<b>17</b>

Other types of occurrence, including sample numbers: dike-like mass intruded into maar, Mexico (146, 147, 279). There are also 9 glass separates in the compilation, from Alaska (5), Oregon (10, 12, 14, 16, 18), Japan (187), Halmahera (210), and Tonga (371).

between porphyritic and aphyric rocks. The data bank is therefore confidently taken to represent magmatic compositions (compare with Macdonald and Bailey, 1973, p. N4).

Some of our specimens were microvesicular. None was sufficiently rich in vesicles to be permeable, however, and we note that there is no relation between the degree of vesicularity of obsidians and the systematics of major- and minor-element chemistry.

#### ANALYTICAL TECHNIQUES

##### MAJOR-ELEMENT ANALYSES

Automated colorimetry, utilizing a Technicon Auto Analyzer, was used at the University of Reading, United Kingdom, to determine  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  concentrations in solutions prepared by sodium hydroxide fusion of 100-mg portions of sample powder; total iron (as  $\text{Fe}_2\text{O}_3$ ),  $\text{TiO}_2$ ,  $\text{P}_2\text{O}_5$  and  $\text{MnO}$  in solutions prepared by  $\text{HF-HClO}_4$  digestions of 500-mg portions of sample powder; and total iron (as  $\text{Fe}_2\text{O}_3$ ) and  $\text{FeO}$  after cold dissolution of 500-mg portions of powder with a mixture of  $\text{HF}$  and  $\text{H}_2\text{SO}_4$  in the presence of ammonium metavanadate (Whitehead and Malik, 1975). No significant difference was found between total iron (as  $\text{Fe}_2\text{O}_3$ ) determined by the alternative methods. The  $\text{Fe}_2\text{O}_3$  content was calculated from the total iron (as  $\text{Fe}_2\text{O}_3$ ) and  $\text{FeO}$  determinations. The basic colorimetric methods used in the automated colorimetry are as follows:

Si -----	Molybdenum-blue method using 1-amino-2-naphthol-4-sulphonic acid as reductant (Shapiro and Brannock, 1962).
Al -----	Solochrome cyanine R with ascorbic acid to suppress iron interference (Hill, 1959).
Ti -----	Tiron method as modified by Rigg and Wagenbauer (1961).
Total iron (as $\text{Fe}_2\text{O}_3$ ) and $\text{FeO}$ -----	2, 2'-dipyridyl method (Whitehead and Malik, 1975).
P -----	Blue molydophosphate complex (Whitehead and Malik, 1976).
Mn -----	Permanganate method with ammonium persulphate as oxidant and silver nitrate as catalyst (Shapiro and Brannock, 1962).
F -----	Determined utilizing the bleaching action of fluorine on the xylenol orange-zirconium complex (Fuge, 1976; Whitehead and Thomas, 1985).
Cl -----	Determined utilizing the stable colored iron (III) thiocyanate complex (Huang and Johns, 1967; Fuge, 1976).

Most F and Cl determinations were made on 100-mg portions of sample powder using a pyrohydrolytic separation technique followed by selective-ion determination of F and automated colorimetric determination of Cl (Whitehead and Thomas, 1985). Initially, F and Cl were determined by an automated colorimetric method modified from Fuge (1976), but subsequently the pyrohydrolytic technique was preferred.

All portions of sample powders were dried for 2 hours at 110 °C before analysis. Atomic absorption spectrometry was employed for the determination of  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  (with addition of  $\text{CsCl}$  as ionization buffer) and  $\text{CaO}$  and  $\text{MgO}$  (with addition of  $\text{LaCl}_3$  as releasing agent) using the solutions prepared by the  $\text{HF-HClO}_4$  digestions. Total water ( $\text{H}_2\text{O}^*$ ) content was determined by a modified Penfield method similar to that described by Shapiro and Brannock (1955) except that a mixed lead oxide-lead chromate flux was used.

Duplicate portions of powder were analyzed for each sample, and the results reported are the mean of at least four determinations in the case of elements determined colorimetrically, two determina-

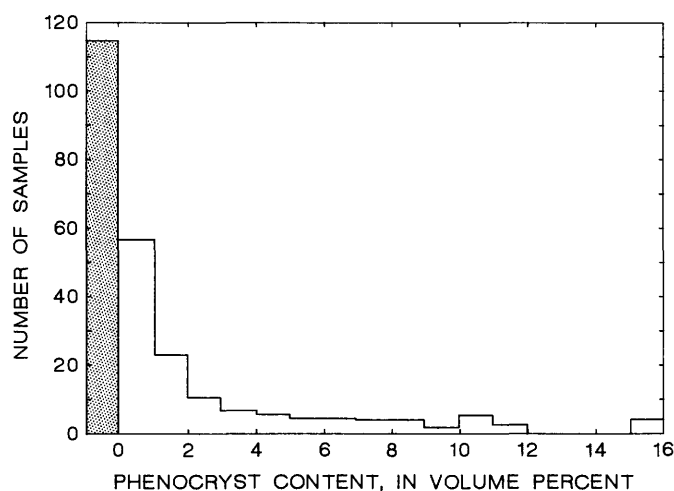


FIGURE 2.—Frequency diagram showing volume percent of phenocrysts in 124 samples of porphyritic obsidians. Shaded area represents 115 aphyric samples. Peralkaline and hydrated rocks and those having  $\text{SiO}_2$  less than 70 percent are excluded. Specimen 246, with 27 percent phenocrysts, is excluded.

tions for elements determined by atomic absorption spectrometry, and two determinations in the case of total water ( $\text{H}_2\text{O}^+$ ).

Analytical precision was monitored by including an obsidian from Pantelleria with successive batches of samples and also by including a sample from the preceding batch of test samples in with the next batch. The precision of results (in percent) is indicated by five replicate analyses of the Pantelleria rock :  $\text{SiO}_2$  66.5 (mean)  $\pm 0.11$  (one standard deviation),  $\text{Al}_2\text{O}_3$  10.61 $\pm 0.05$ ,  $\text{Fe}_2\text{O}_3$  2.23 $\pm 0.13$ ,  $\text{FeO}$  6.15 $\pm 0.07$ ,  $\text{MgO}$  0.15 $\pm 0.004$ ,  $\text{CaO}$  0.56 $\pm 0.005$ ,  $\text{Na}_2\text{O}$  7.47 $\pm 0.03$ ,  $\text{K}_2\text{O}$  4.52 $\pm 0.00$ ,  $\text{TiO}_2$  0.64 $\pm 0.007$ ,  $\text{P}_2\text{O}_5$  0.058 $\pm 0.04$ , and  $\text{MnO}$  0.34 $\pm 0.005$ .

The accuracy of the Reading data can be judged by comparing the analyses of specimens 42 and 43 (see appendix I). Both samples are from Big Glass Mountain, Medicine Lake, California, No. 42 having been prepared for this study and No. 43 being the USGS standard rock RGM-1. The agreement is good, except for  $\text{H}_2\text{O}^+$ . The four-fold difference between the values (0.08 and 0.34, respectively) is very much higher than those normally associated with the modified Penfield method used at Reading. The difference may be related to a nonuniform distribution of water in the flow, caused by superheating of the rhyolite by incorporation of dacitic and basaltic magma.

#### X-RAY FLUORESCENCE ANALYSES

Concentrations of Ba, Nb, Pb, Rb, Sr, Y, Zn, and Zr were determined by X-ray fluorescence (XRF) spectrometry at the University of Lancaster, United Kingdom, using rock powders. Estimates of precision, reported as one standard deviation in percent of the amount present and based on repeated analysis of RGM-1, are: Ba 3, Nb 5, Pb 5, Rb 2, Sr 2, Y 3, Zn 3, and Zr 2.

#### INSTRUMENTAL NEUTRON-ACTIVATION ANALYSES

Determinations of Co, Cr, Cs, Hf, Rb, Sb, Sc, Ta, Th, U, and the rare-earth-element contents were made by instrumental neutron-activation analysis (INAA) at the USGS, Reston, Va. Estimates of precision, based on replicate analyses of RGM-1 and given here as one standard deviation in percent of the amount present, are: Co 30, Cr 30, Cs 3, Hf 3, Rb 10, Sb 15, Sc 4, Ta 5, Th 4, U 12, La 6, Ce 5, Nd 11, Sm 8, Eu 17, Gd 20, Tb 4, Tm 13, Yb 5, and Lu 3. The Rb values determined by INAA were less precise than those determined by XRF; although both

are reported in appendix I, only the XRF data are used in discussions of Rb geochemistry.

#### OTHER ANALYTICAL METHODS

Analyses of the rare metals, Li, Be, Sn, Mo, Nb, and W, by the USGS, Reston, were determined as follows:

Li-----	Flame atomic absorption spectroscopy (AAS).
Be-----	Atomic absorption using electrothermal atomization (graphite furnace). Method details by Campbell and Simon (1978).
Sn-----	Iodide extraction into toluene followed by graphite furnace AAS (P. Aruscavage, oral commun., 1978 ).
Mo-----	Colorimetric using zinc dithiol (Aruscavage and Campbell, 1981).
W-----	Spectrophotometric method using zinc dithiol (Aruscavage and Campbell, 1978; Campbell and Aruscavage, 1982).
Nb-----	Spectrophotometric method described by Greenland and Campbell (1974).
Cl and F-----	USGS—Specific Ion Electrode. For F see Ingram (1970).

Both the USGS and University of Reading determinations of F and Cl are given in appendix I. For some samples, the differences exceed those related only to the quoted precision of each method. We have no independent checks of which value is correct in such cases, so for the purposes of plotting on diagrams, calculations, and discussion, we have averaged the two values of F and Cl data.

#### PRESENTATION OF THE DATA BANK

The data presented in appendix I are of three kinds. The great majority (171 samples) are previously unpublished. A second category (29 samples) consists of analyses recently published or provided by USGS colleagues and made using similar analytical techniques to those of the present study for at



least some elements. Thirdly, 17 analyses are of obsidians to which we have contributed part of the data. To this degree, appendix I thus provides an internally consistent body of data.

Certain specimens lie outside the arbitrarily imposed compositional limits of  $\text{SiO}_2 \geq 70$  percent and molecular  $(\text{Na}_2\text{O} + \text{K}_2\text{O}) < \text{Al}_2\text{O}_3$ . For completeness, these have been included in the data tables but have not been used in any figures and computations. Specimens which proved to have more than 1 weight percent  $\text{H}_2\text{O}^+$  are given in appendix II; an exception is specimen 15, which is listed in appendix I because it is one of a whole rock-separated glass pair, and comparison is facilitated. Rocks for which trace-element data only are available are given in appendix IV. Analyses from appendixes II and IV are not used in illustrations or computations unless specifically stated.

Published major-element analyses which we consider reliable are listed in appendix III. In practice, this means that these data show compositions broadly similar to our new analyses; gross departure from the chemical range of the new data warranted suspicion and rejection from the compilation. This may have resulted in our omitting genuinely magmatic chemistries from appendix III, but, as mentioned above, where we have been able to reanalyze such rocks, the published analyses have invariably been found to be in error.

Because of the difficulties listed earlier, published trace-element determinations were not compiled. Instead, frequent referenced use is made in the text of any published data relevant to the discussion, except for the compilations of radiogenic and stable isotope determinations on silicic obsidians (see tables 13–16).

Modal analyses of porphyritic specimens are given in appendix VII. The new modes were determined using a single thin section per specimen. The number of counts varied between 500 and 2,500, depending on the size of the section. We appreciate that a single thin section cannot give a truly representative value of the mode of an obsidian and, in some cases, may not even contain the full phenocryst assemblage. However, the modes are useful as an indication of the crystal-poor nature of the majority of specimens and in assessing the main mineralogical features of each obsidian group (table 5). In making intergroup comparisons, we acknowledge that phenocryst assemblages are partly a function of the degree of crystallinity. Sufficient multiphase samples are present from each group to promote modest confidence that apparent differences are real. Finally, there is some uncertainty about the optical identification of the acces-

sory phases (for example, zircon) due to their very small size.

#### COMPLETENESS OF THE DATA BANK

The numbers of specimens in each group are as follows:

Obsidian groups	Analyses	
	New	Published
Primitive island arcs -----	—	1
Mature island arcs -----	26	33
Continental margins -----	66	53
Continental interiors -----	80	28
Oceanic extensional zones ----	17	7
Other areas -----	3	8

The new data bank is least complete for calcic rhyolites from primitive and mature island arcs and, though published analyses (appendixes III, V) partially fill this gap, the number is still inadequate to describe fully the chemical variation in these rocks.

Though the lack of analyses of calcic varieties simply reflects absence from our collections, nonhydrated obsidians of this composition tend to be scarce in nature, as the most silica-rich members of calcic suites tend to be dacitic or rhyodacitic, with  $\text{SiO}_2 < 70$  percent. Even where higher silica calcic magmas exist, they are commonly erupted as ashes or as components of ash-flow tuffs. Furthermore, calcic rhyolites tend to be moderately porphyritic, a feature which promotes fracturing of the glass matrix and its subsequent rapid hydration.

It must also be noted that the data bank is heavily weighted toward rocks from the Western United States (57 percent of the total number of specimens). American samples comprise 85 percent of continental margin rhyolites and 77 percent of continental interior rhyolites, as defined below. There is no reason to believe that future analyses of obsidians from other areas will grossly modify the major-element compositional range established with this bias, but, in that every silicic province and complex are to some degree unique, the within-group ranges of trace-element abundances and ratios will almost certainly be extended.

#### REPRESENTATIVENESS OF SAMPLES

Many of the obsidian units described in this study are represented by a single specimen, consequently there is a question of how representative these specimens are of the eruptive units involved.

TABLE 5.—Generalized phenocryst assemblages of obsidian groups

[Accessory minerals excluded. Pl, plagioclase; Opx, orthopyroxene; Cpx, clinopyroxene; Ox, Fe-Ti oxides; Hb, amphibole; Q, quartz; Ol, olivine; Bi, biotite; Kf, alkali feldspar]

Obsidian group	Phenocryst assemblage
Primitive island arcs -----	Pl+Opx+Cpx+Ox+Hb+Q+Ol
Mature island arcs	
Calcic -----	Pl+Opx+Cpx+Ox+Ol+Hb+Q
Calc-alkalic -----	Pl+Ox+Opx+Hb+Cpx+Bi+Kf+Q+Ol
Continental margins	
Calcic -----	Pl+Opx+Ox+Cpx+Hb+Ol
Calc-alkalic -----	Pl+Ox+Opx+Cpx+Hb+Bi+Kf+Q
Continental interiors -----	Q+Kf+Pl+Ox+Cpx+Opx+Hb+Bi+Ol
Oceanic extensional zones -----	Pl+Cpx+Ol+Ox+Hb+Opx+Kf+Q

Two recent studies, employing high-precision analytical techniques, have indicated that some obsidian flows display within-flow variations in chemistry which are selectively marked for certain minor and trace elements. Laidley and McKay (1971) have concluded that though the "Big Obsidian flow" of Williams (1935) at Newberry Volcano, Oregon, has a high degree of homogeneity chemically, small but statistically significant differences do exist for such elements as Zn and Rb.

In a study of Californian glass units, Bowman and others (1973) have shown that the Napa Glass Mountain unit is extremely homogeneous, any variation being below the analytical precision of their neutron-activation method. On the other hand, in the "Mt. Konocti obsidian flow" (rhyolite of Thurston Creek), two geographically distinct groups of analyses can be shown to be chemically distinguishable, though again the differences are very small.

However, more recent work (B.C. Hearn, oral commun., 1985) has shown that the rhyolite of Thurston Creek is actually composed of flows from more than one source vent, and thus a more logical explanation for the chemical distinction, between geographic groups of analyses, is simply that the "Mt. Konocti obsidian flow" is not a single unit of magma at the surface. Our samples 46 and 47 from Camel Back Ridge and Thurston Canyon, respectively, are from different flows of the rhyolite of Thurston Creek; whereas these samples show minor chemical variations, the differences are so small that it is doubtful that they are analytically significant on the basis of two samples.

Outside the United States, the Forgia Vecchia flow in Lipari, Italy, may also display compositional heterogeneity. Belluomini and Taddeucci (1971) present the following ranges for 14 specimens from the flow: Rb, 180–240 ppm; Zr, 160–270 ppm; Y, 80–110 ppm. Although the precision of the determinations is not given, such variation is outside the precision of the

measurements commonly obtained by the XRF technique.

These examples serve to show that some, and perhaps many, obsidian flow units are not completely homogeneous chemically and that detailed study may reveal the nature and amount of any elemental variations present. Single specimens may not always give an accurate picture of the bulk chemistry of the unit being sampled. It should be stressed, however, that the California examples display element variations less than the precision usually obtained during routine, automated methods of analysis. Furthermore, in many examples from the Western United States (for example, Cove Creek, Utah; Bailey Ridge, Mineral Mountains, Utah; and the Mono Craters, California) the compositions of specimens collected from each of closely related groups of domes are virtually identical, indicating that variations within individual domes must be very small. We suggest that obsidian units are much more likely to be chemically homogeneous than heterogeneous and that where heterogeneity is present, it is normally visible in the field (for example, as xenoliths, as an uneven distribution of phenocrysts, or as evidence of the composite nature of the unit).

Finally, between-flow variations in trace-element abundances are many times greater than the within-flow variations revealed by the high-precision studies. Any geological conclusions reached are independent of such intraflow complications.

## CLASSIFICATION OF SUBALKALIC SILICIC OBSIDIANS

### CLASSIFICATION USED IN THIS PAPER

The reviews by Miyashiro (1974), Coleman (1975), Ewart and others (1977), Gill (1981), and various authors in Thorpe (1982) stressed the relations between the evolutionary stages of island arcs and the character

of the associated magmatism, using island arc in the broadest sense to include continental-margin settings. With increasing arc maturity, expressed by crustal thickening and increasingly sialic character, volcanism evolves from a low-K tholeiitic type to complex associations of tholeiitic, calc-alkalic, and alkalic rocks showing both geographic and temporal zonation.

Ewart (1979), Ewart and LeMaitre (1980), and Coulon and Thorpe (1981) provided further detail on the relations between magma associations and tectonic setting within orogenic belts. For example, Coulon and Thorpe (1981) tested the relations between the compositional characteristics of volcanic associations and such parameters as the rate of plate convergence, depth to the seismic zone, and the type and age of subducted and overriding lithosphere. They concluded that magma compositions are most strongly correlated with crustal thickness (Coulon and Thorpe, 1981). Because thickness, structure, and composition of developing continental-type crust are all interlinked, the magma composition is strongly related to the type of crust into which the magmas are emplaced (Smith and Macdonald, 1979).

Ideally, any classification of rhyolites should match rock composition to crustal environment. Chemistry can then be used to define the crustal type of ancient rhyolitic rocks as well as refine our knowledge of the structure of complex modern tectonic settings, such as mature island arcs and continental margins where more than one crustal component of quite different character may be involved. Unfortunately, knowledge of the composition, structure, and thickness of the deeper parts of the crust is so inadequate that formulation of a precise classification of this type—though it may be a longer term aim of our obsidian studies—is currently very difficult.

The classification of subalkalic rhyolitic obsidians used in this paper is a compromise. Rocks are assigned to broad, traditionally recognized, tectonic settings:

	Group	Normal occurrence of obsidians
Related to subduction	I	From primitive island arcs
	II	From mature island arcs
	III	From active continental margins
Related to extension	IV	From extensional zones in cratonic continental interiors
	V	From extensional zones in ocean basins

The rhyolites from each group are chemically distinct, because each tectonic setting is characterized by the host crust (and thus magma compositions). Hence, rhyolites of group IV normally occur in areas underlain by Precambrian crust, whereas the deep

crust of mature island arcs generally is no older than Paleozoic. In certain complex arcs, such as Japan, however, slivers of Precambrian crust occur. On the other hand, in continental interiors there may be areas of continental-margin-type crust lacking a Precambrian component. Rhyolites generated within such areas have the compositional characteristics of the crust rather than those of the broad tectonic setting. For example, rocks having group III compositions (continental margins) may occur in the continental interior or on an island arc. Thus, although rhyolites are generally classified into the correct crustal type, that is if sufficient geological information is available to estimate the type of the basement crust, the classificatory terms may be tectonically imprecise.

We recognize that a genetic classification might be considered out of place in a paper of geochemistry data, but we feel that in spite of the overlaps and uncertainties, this kind of classification conveys the profound significance of rhyolite geochemistry.

#### OBSIDIANS NOT ACCOMMODATED BY THE CLASSIFICATION SCHEME

The rhyolites within each tectonic group have compositional characteristics that distinguish them from rhyolites of the other groups. Certain obsidians, however, have compositions unlike the main body of rhyolites; we have not included them in our classification scheme, even though their tectonic setting may be known. The chemical features which distinguish these glasses are described in a later section.

#### COMPARISON WITH THE RHYOLITE GROUPINGS OF EWART (1979)

In a comprehensive review of the mineralogy and chemistry of sialic volcanic rocks of Tertiary to Holocene age, Ewart (1979) presented a dendrogram showing the interrelations and groupings between high-SiO<sub>2</sub> ( $\geq 73$  percent) rhyolites from a variety of orogenic and oceanic tectonomagmatic associations. The dendrogram was based on *Q*-mode cluster analysis using correlation coefficients calculated from major- and trace-element concentrations, phenocryst occurrence, and modal data.

Ewart's (1979) groupings were not intended to be a formal classification, but, as they were based in part on chemistry and tectonic settings, as in our classification, it is of interest to compare the two (table 6). Direct comparison is hampered by the facts that Ewart was dealing with a wider range of rocks



TABLE 6.—*Comparison, for the high-SiO<sub>2</sub> rhyolites of certain orogenic and oceanic areas, of the classification scheme of this paper and the groupings of Ewart (1979)*

[NC, not classified]

Classification scheme of this paper	Subregions/associations	Groupings of Ewart (1979)
IV	[Western U.S.A.--Eastern Belt (all data) Western U.S.A.--Eastern Belt biotite rhyolites	Potassic rhyolites of orogenic associations
III	[Western U.S.A.--Western Belt biotite rhyolites Western U.S.A.--Western Belt (all data) Western South America	
NC	[Mediterranean	
III,IV	[Middle America	
IV	[Yellowstone and Snake River Plain	Potassic rhyolites of bimodal associations
III	[Mono Lake area (California)	
I	[Low-K-rhyolites, Southwest Pacific South Sandwich Islands pumice	Low-K and calc-alkali orogenic rhyolites
II	[Low-K rhyolites, Japan-Kuriles-Saipan	
I,II,III,IV	[Japan, all data	
II	[Southwest Pacific (excluding New Zealand) Taupo Volcanic Zone, New Zealand	
III	[Medicine Lake (California) High Cascades (excluding Medicine Lake)- Alaska-Aleutians	Less potassic rhyolites of bimodal associations
V	[Iceland Salton Sea (California)	

(including secondarily hydrated and crystalline varieties) emplaced over a wider time spectrum (Tertiary to Holocene) and that he incorporated mineralogical data into his groupings. Nevertheless, many similarities may be noted. His "low-K and calc-alkali orogenic rhyolites" are essentially groups I and II of our classification, although in some complex arcs, such as Japan, we recognize rocks of groups III and IV.

Ewart's "potassic rhyolites of orogenic associations" incorporate rocks of groups III and IV; we argue that many of the samples from his Eastern Belt of the Western United States (even those of Tertiary age) are intracratonic rocks not related to subduction. Ewart recognizes the existence of this

continental interior type (group IV), calling them "potassic rhyolites of bimodal associations." The rocks within his "less potassic rhyolites of bimodal associations" are essentially those of group V of this paper.

#### RELATIONS AMONG SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO, AND (Na<sub>2</sub>O+K<sub>2</sub>O) IN SUBALKALIC OBSIDIANS

We consider here aspects of the interrelations among the most abundant oxides in the various obsidian groups. Several terms are described as used in this report, and normative projections in the Q-Ab-Or and Or-Ab-An systems are presented.

## THE TERMS CALCIC, CALC-ALKALIC, AND ALKALI-CALCIC

Peacock (1931) used alkali-lime relations to classify igneous suites into calcic, calc-alkalic, alkali-calcic, and alkalic. Alkalic, by definition, is not applicable to the obsidians compiled in this paper. The classification was based on the  $\text{SiO}_2$  content for which the concentration of  $\text{CaO}$  equals that of  $(\text{Na}_2\text{O}+\text{K}_2\text{O})$  in a genetically related, mafic to silicic suite of rocks. Because many rhyolites occur either as members of bimodal basalt-rhyolite associations or as masses commonly independent of more mafic rocks, Peacock's classification cannot be formally applied to such occurrences.

The terms have proved so useful that they are still commonly employed in the literature, but unfortunately, either undefined or with contrasting definitions. For example, Zielinski (1978) defines calc-alkalic rhyolites as "having atomic  $\text{Al} > (\text{Na}+\text{K})$  and with plagioclase as phenocrysts," whereas Tatlock and others (1976) consider the rhyolite from Glass Mountain, California, calc-alkalic "because of the high ratio of  $\text{CaO}$  to total iron and the relatively high \*\*\* An content of its normative plagioclase ( $\text{An}_{13-14}$ )." Robinson and others (1976) employ the term "low  $\text{CaO}$ , alkali rhyolite" for rocks "intermediate in composition between peralkaline comendites and metaluminous rhyolites." For apparently the same compositions, that is, "atomic  $\text{Al} = (\text{Na}+\text{K})$ , plagioclase absent," Zielinski (1978) coins the term "transitional rhyolite". Clearly, it is desirable for continued employment of these terms in rhyolite geochemistry that, first, they are formally defined and, second, that to avoid confusion, definitions are in accord with the usage of Peacock (1931). Any attempt to define the terms for highly silicic rocks will run into severe difficulties, as the following examples show.

The ratio  $\text{CaO}/(\text{Na}_2\text{O}+\text{K}_2\text{O})$  is plotted against  $\text{SiO}_2$  for obsidians from four volcanic complexes in the Western United States continental margin (fig. 3). On the basis of Peacock's classification, two complexes are calcic (Crater Lake: Williams, 1942; and Clear Lake: Anderson, 1936) and two are calc-alkalic (Newberry: Williams, 1935, Higgins, 1973; and Medicine Lake: Williams, 1935). Tielines connect whole rock and separated glass pairs from Crater Lake. Whole rock trends for a calcic granodiorite (Woodson stock, southern California: Tilling and Gottfried, 1969) and for a calc-alkalic granitoid suite (Tuolumne Intrusive Suite, California: Peck, 1980, data from Bateman and Chappell, 1979) are also shown. There is an overlap of calcic and calc-alkalic rock suites such that they are essentially indistinguish-

able on this plot. The differences in the alkali-lime index utilized by Peacock are maximized in rocks of intermediate composition. As rock compositions trend toward the minima in the system  $\text{Q-Or-Ab-An-H}_2\text{O}$ , intersuite differences in major-element abundances are made much less distinct.

It is possible to subdivide rhyolites into the various groups by erecting arbitrary boundaries at constant values of  $\text{CaO}/(\text{Na}_2\text{O}+\text{K}_2\text{O})$  ratio rather than parallel to the tielines and rock trends. Individual rock suites could then show more than one affinity, which is unnecessarily confusing.

An alternative approach to the problem is shown in figure 4. As  $\text{CaO}$  and, even more so, the sum  $(\text{Na}_2\text{O}+\text{K}_2\text{O})$  show wide variations with changing  $\text{SiO}_2$  and at constant  $\text{SiO}_2$ , the  $(\text{Na}_2\text{O}+\text{K}_2\text{O})$  values are normalized by calculation of the ratio  $\text{SiO}_2/(\text{Na}_2\text{O}+\text{K}_2\text{O})$ . Boundaries are drawn to be as consistent as possible with the nomenclature derived for relevant rocks using Peacock's (1931) scheme. The fields are termed alkali-calcic, calc-alkalic, and calcic and appear to have real geologic significance (fig. 4). Continental-interior rocks are overwhelmingly alkali-calcic. The calcic rocks of island arcs are largely those associated with tholeiitic volcanoes rather than calc-alkalic types associated with high- $\text{Al}_2\text{O}_3$ -series volcanoes (Miyashiro, 1974). There are also two groups of Icelandic rhyolites: a higher alkali group ( $\text{SiO}_2/(\text{Na}_2\text{O}+\text{K}_2\text{O}) < \sim 9$ ) found in alkalic complexes and a lower alkali group ( $\geq \sim 9$ ) associated with tholeiitic basalts.

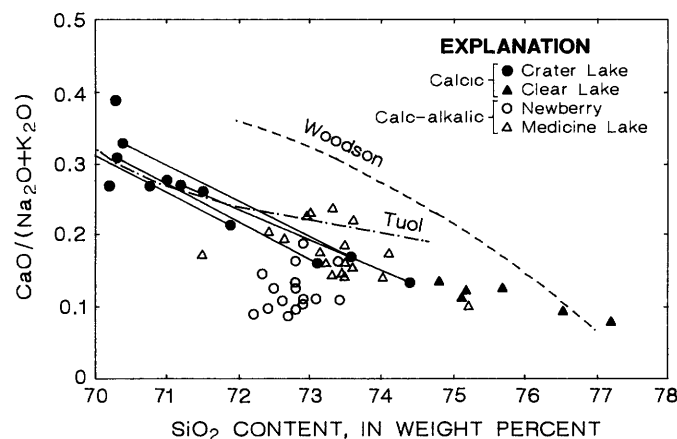


FIGURE 3.— $\text{SiO}_2$  content versus ratio of  $\text{CaO}/(\text{Na}_2\text{O}+\text{K}_2\text{O})$  showing overall similarity of calcic (Crater Lake and Clear Lake) and calc-alkalic (Newberry and Medicine Lake) suites in high- $\text{SiO}_2$  compositions. Data from appendixes I and III. Trends for Woodson granodiorite stock and granitoids of the Tuolumne Intrusive Suite (Tuol) are given for comparison (data sources are same as figure 5). Solid tielines connect whole rock and separated glass pairs from Crater Lake.

A drawback of the  $\text{SiO}_2/(\text{Na}_2\text{O}+\text{K}_2\text{O})$  versus CaO plot is that individual suites cross field boundaries (fig. 5), as the Bandelier, Bishop Tuff, Tuolumne and Woodson trends, the Crater Lake tielines, and the Borax Lake mixed magma trend show. However, no other classificatory scheme based on  $\text{SiO}_2$ , CaO, and  $(\text{Na}_2\text{O}+\text{K}_2\text{O})$  can be devised entirely consistent with Peacock's (1931) original scheme. The terms calcic, calc-alkalic, and alkali-calcic are useful descriptive terms firmly established in the literature of granites

and rhyolites, and we continue to use them, as defined on figure 4.

#### RELATIONS AMONG $\text{Al}_2\text{O}_3$ , CaO, AND $(\text{Na}_2\text{O}+\text{K}_2\text{O})$ AND THE SIGNIFICANCE OF NORMATIVE CORUNDUM

Shand (1949) stressed the importance of the relations among  $\text{Al}_2\text{O}_3$ , CaO, and  $\text{Na}_2\text{O}+\text{K}_2\text{O}$  by using them as the basis of his subdivision of igneous

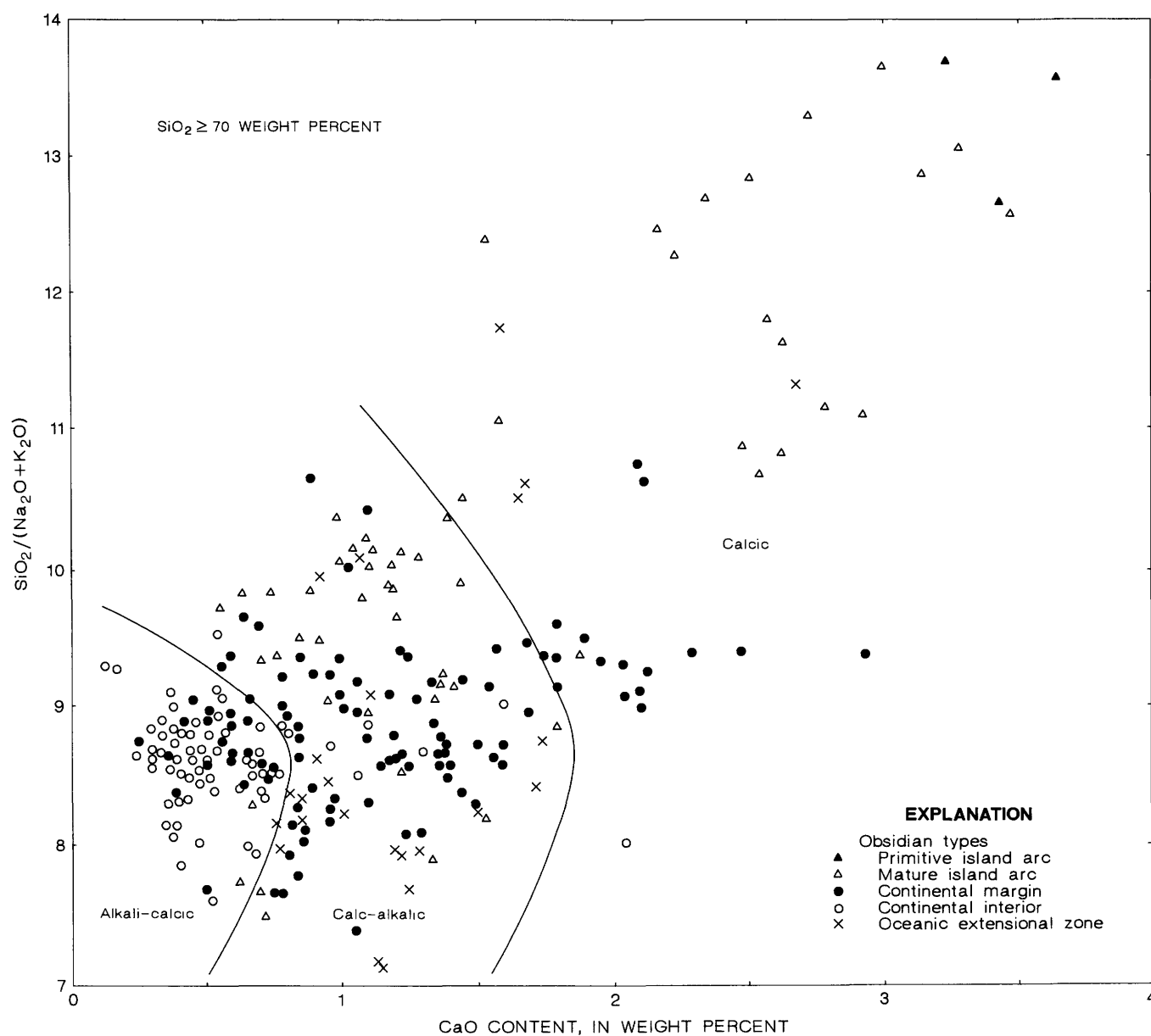


FIGURE 4.—CaO content versus ratio of  $\text{SiO}_2/(\text{Na}_2\text{O}+\text{K}_2\text{O})$  showing distribution of silicic subalkalic obsidians and their subdivisions into calcic, calc-alkalic, and alkali-calcic types. Boundaries between fields are drawn to coincide as nearly as possible with Peacock's (1931) scheme. Data from appendixes I and III (excluding samples 349, 351, and 371) and from appendix V (excluding samples A, F, and G).

rocks into peraluminous, metaluminous, subaluminous, and peralkaline. The distinction between subaluminous and metaluminous rocks is largely mineralogic, depending on the Al contents of the ferromagnesian minerals. The distinction is difficult to apply in most obsidians, and the term subaluminous is not used here to avoid any possible confusion with peralkaline.

<i>Chemical criteria</i>	<i>CIPW normative mineral criteria</i>
Peraluminous: molecular $\text{Al}_2\text{O}_3 \geq \text{CaO} + (\text{Na}_2\text{O} + \text{K}_2\text{O})$	[Normative C + an]
Metaluminous: molecular $(\text{Na}_2\text{O} + \text{K}_2\text{O}) < \text{Al}_2\text{O}_3 < \text{CaO} + (\text{Na}_2\text{O} + \text{K}_2\text{O})$	[Normative an + di]
Peralkaline: molecular $(\text{Na}_2\text{O} + \text{K}_2\text{O}) \geq \text{Al}_2\text{O}_3$	[Normative ac+ns]

The fields occupied by each type and by the rhyolite groups on a molecular  $\text{CaO}-\text{Al}_2\text{O}_3-(\text{Na}_2\text{O}+\text{K}_2\text{O})$  diagram are given in figure 6. With the exception of the primitive-island-arc and oceanic-extensional groups, which are almost exclusively metaluminous, the main rhyolite groups contain both peraluminous and metaluminous varieties. The ratios of the number of specimens of the two varieties in the different groups are as follows:

<i>Obsidian groups</i>	<i>Peraluminous/metaluminous</i>
Primitive island arcs (I) -----	0?
Mature island arcs (II) -----	1.8
Continental margins (III) -----	2.4
Continental interiors (IV) -----	0.72
Oceanic extensional zones (V) -----	0.05

Peraluminous rocks are apparently very rare in areas overlying basaltic crust (groups I and V).

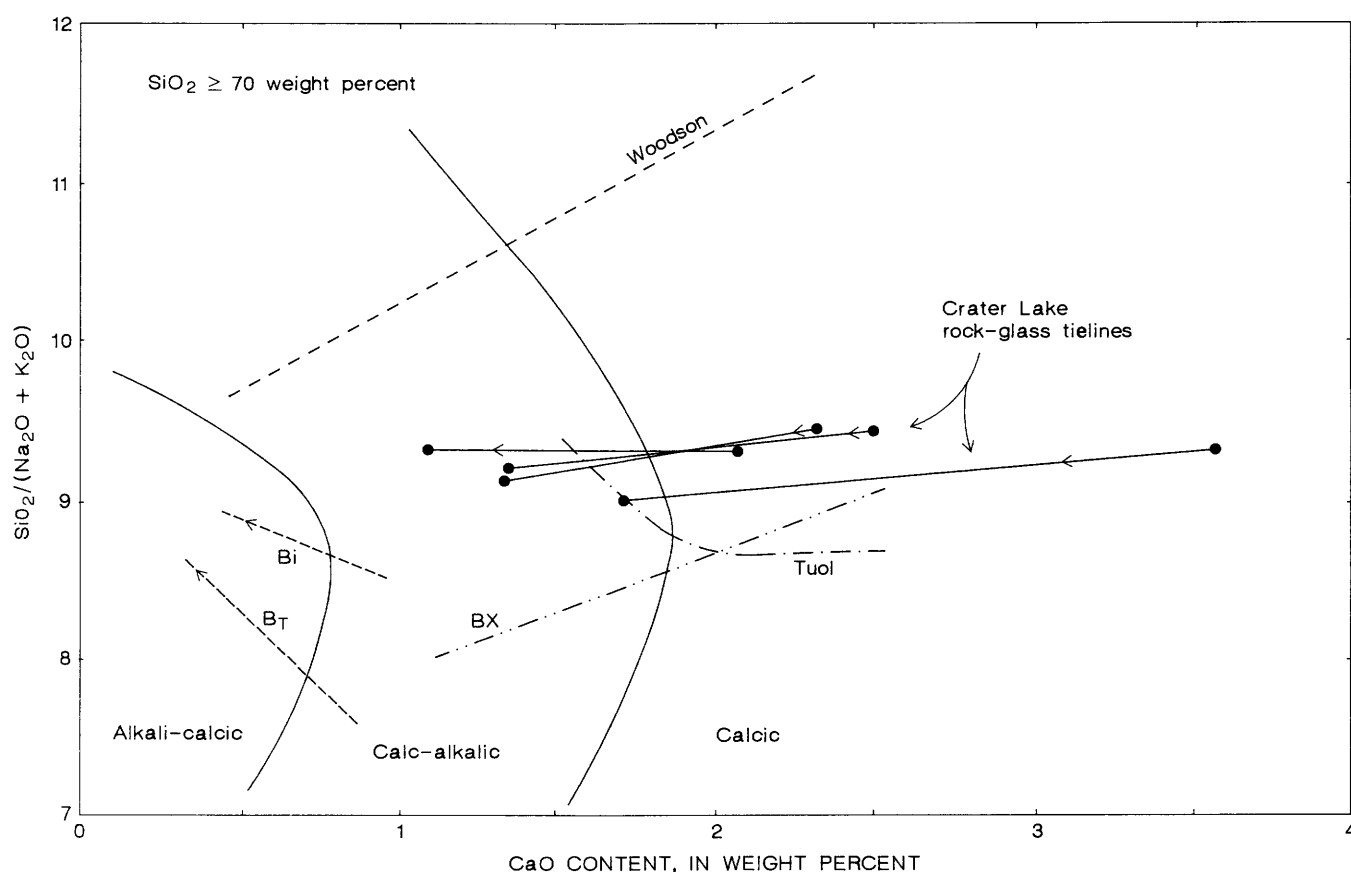


FIGURE 5.—CaO content versus ratio of  $\text{SiO}_2/(\text{Na}_2\text{O}+\text{K}_2\text{O})$  showing typical trends of various suites crossing field boundaries. Crater Lake data from appendix I. Other data sources for this and subsequent diagrams: Woodson granodiorite (Tilling and Gottfried, 1969; David Gottfried, written commun., 1975); Tuol, granitoids of Tuolumne Intrusive Suite

(Peck, 1980, data from Bateman and Chappell, 1979); BX, mixed obsidian of Borax Lake (Bowman and others, 1973);  $B_T$ , Tshirege Member of the Bandelier Tuff, Valles Mountains, New Mexico (R.L. Smith, unpub. data); Bi, Bishop Tuff, California (Hildreth, 1979, 1981). Arrows indicate direction of liquid fractionation.



Though it may be inferred that the presence of crust with a sialic component is necessary for the generation of peraluminous rhyolites, it must be noted that the proportion of such rhyolites is higher in arc obsidians than in those from the continental interior,

indicating that degree of  $\text{Al}_2\text{O}_3$ -saturation is not simply related to crustal type.

A similar situation exists in individual volcanic complexes. Obsidians from Crater Lake and Coso are dominantly metaluminous; whereas at Medicine

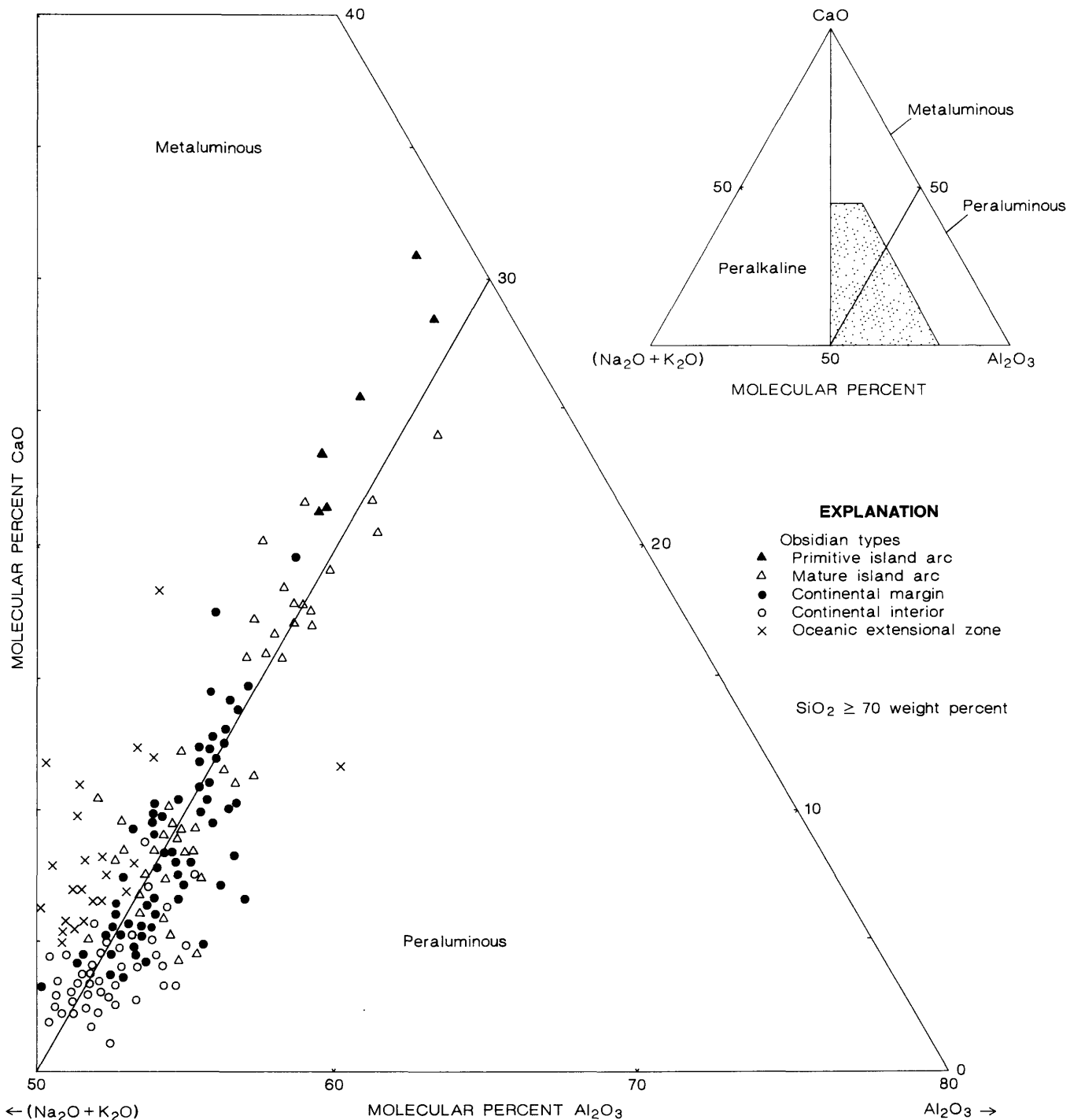


FIGURE 6.—Molecular proportions of  $\text{CaO}$ ,  $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ , and  $\text{Al}_2\text{O}_3$  in silicic obsidians. Inset shows compositional fields of peraluminous, metaluminous, and peralkaline rhyolites and field (stippled) occupied by larger diagram. Data from appendixes I, III, and V.

Lake and Yellowstone, metaluminous and peraluminous varieties are present in about equal numbers. In the Newberry and Jemez Mountain complexes, the ratios of peraluminous to metaluminous obsidians are about 2:1 and 1:2, respectively.

There appears to be some doubt in the literature as to whether normative corundum actually exists in silicic magmas and, if so, in what amounts. Normative corundum (C) in volcanic rocks has traditionally been regarded as an indication of a faulty chemical analysis or of secondary alteration of the rocks. Chayes (1970, p. 181–182) states, "Whatever the detailed interpretation of C \*\*\* there seems little doubt that its occurrence in amounts of the order of 2 percent or less is either a consequence of surficial or hydrothermal alteration or a combined analytical-computational artifact."

Because post eruptive alteration can be discounted as having affected nonhydrated obsidians, it is of interest to examine the distribution of normative corundum in terms of the reality of its existence in silicic magmas and the magmatic affinities of the rocks in which it occurs. Of the 322 rocks compiled, 166 (52 percent) are peraluminous, that is, C-normative. The normative corundum has either been produced by a "combined analytical-computational artifact" (Chayes, 1970) or is a genuinely magmatic feature (compare with Cawthorn and others, 1976). Because the analyses have been made by numerous analysts using a variety of techniques and because C is present in such a large proportion of the rocks, we suggest that normative corundum is a real feature of the relevant magmas and is related to the petrogenesis of the rocks.

*Distribution of normative corundum (C)*

Range of C, in percent	0–0.49	0.5–0.99	1.0–1.49	1.50–1.99	≥ 2
Number of analyses -----	114	34	9	6	3
Mature island arcs (II) -----	23	11	3	1	0
Continental margins (III) ---	59	18	4	2	0
Continental interiors (IV) --	32	5	2	3	2
Oceanic extensional zones (V) -----	0	0	0	0	1

It should be stressed that the amount of normative corundum is typically small, (C<1 percent in 90 percent of the samples that yield normative corundum, and C<0.5 percent in 70 percent of those

samples). Only three rocks have C≥2 percent. The maximum value is 6.34 percent, recorded in a chemically unique glass block from Cameroon (No. 337). Thus, the majority of subalkalic obsidians contain neither a substantial excess nor deficit of mol.  $\text{Al}_2\text{O}_3$  over  $(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ .

#### NORMATIVE Q-Ab-Or- $\text{H}_2\text{O}$ AND Or-Ab-An- $\text{H}_2\text{O}$ PLOTS

The fields and average compositions of each of the rhyolite groups are shown in the ternary quartz-feldspar and feldspar-feldspar plots in figures 7 and 8 and are compared to the various quartz-feldspar and two-feldspar boundary curves at 1 kbar  $P_{\text{H}_2\text{O}}$  determined by James and Hamilton (1969). The distributions are similar to those established by Ewart (1979) in his review of the chemistry of Tertiary and Holocene silicic volcanic rocks.

The field for obsidians from the continental interiors straddles the quartz-saturated, two-feldspar boundary curve for 1 kbar  $P_{\text{H}_2\text{O}}$  and lies just to the

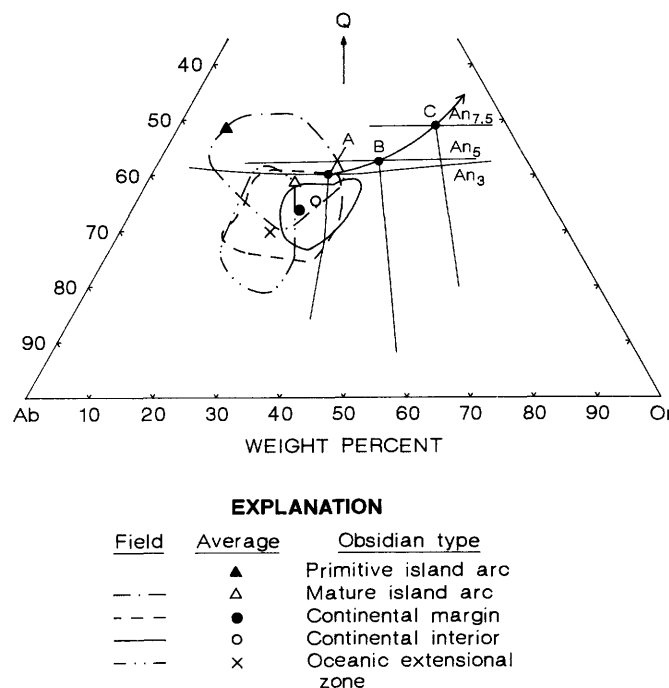
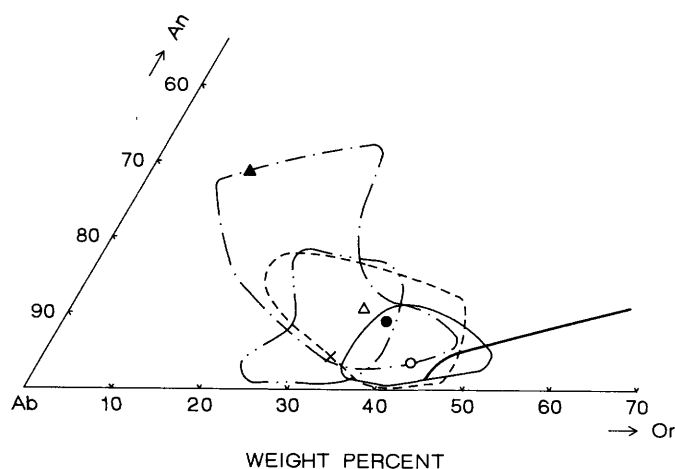


FIGURE 7.—CIPW normative proportions of quartz (Q), albite (Ab), and orthoclase (Or) showing fields (except that of primitive island arcs) and averages for obsidian groups. Also shown are quartz-feldspar and two-feldspar boundary curves at 1 kbar  $P_{\text{H}_2\text{O}}$  for compositions  $\text{An}_3$ ,  $\text{An}_5$ , and  $\text{An}_{7.5}$  (from James and Hamilton, 1969). Points A–C mark trend of low-temperature piercing points with increasing An content (arrow). Diagram may be compared with similar plots by Ewart (1979, fig. 21).

SiO<sub>2</sub>-poor side of the An<sub>3</sub> piercing point in this system (point A, fig. 7). This is largely consistent with the observed phenocryst mineralogy, which commonly includes alkali feldspar+plagioclase+quartz. The presence of quartz phenocrysts suggests, however, that somewhat higher pressures than 1 kbar were involved during the final equilibration of many of these magmas.

The field for obsidians from the continental margins overlaps the field for interior rocks for more potassic compositions, but extends to more sodic and calcic compositions. The rocks are not, however, richer in SiO<sub>2</sub>. The margin rocks as a group do not trend toward the ternary minimum. The field of most SiO<sub>2</sub>-rich types is elongate parallel to the quartz-sodic feldspar boundary curve for low An contents, and the field mainly projects into the sodic feldspar stability field. The position of the field is consistent with the relative scarcity of potassic feldspar in continental-margin rocks, magma compositions in most cases apparently reaching the quartz-plagioclase saturation surface but not evolving to the two-feldspar+quartz surface.



#### EXPLANATION

Field	Average	Obsidian type
---	▲	Primitive island arc
---	△	Mature island arc
---	●	Continental margin
---	○	Continental interior
---	x	Oceanic extensional zone

FIGURE 8.—CIPW normative proportions of anorthite (An), albite (Ab), and orthoclase (Or) showing fields (except that of primitive island arcs) and averages for obsidian groups. Bold curve is projection of quartz-saturated two-feldspar boundary at 1 kbar  $P_{H_2O}$  (from James and Hamilton, 1969). Diagram may be compared with similar plots by Ewart (1979, fig. 22).

The field for obsidians from mature island arcs partially overlaps those from the continental margins and interiors but extends to more quartz- and anorthite-rich compositions. As Ewart (1979, p. 74) points out, these can be grossly correlated with the shift of the quartz-feldspar boundary curve toward more quartz-rich compositions with increasing An content within the Q-Or-Ab-An-H<sub>2</sub>O system. The data field does not, however, follow the trend of low-temperature piercing points (fig. 7) with increasing An content but plots well to the sodic side of the trend. This precludes the involvement of alkali feldspar in the higher temperature genesis of the majority of the rocks, because only a few of the obsidians plot close to the quartz+two-feldspar surface.

Absence of alkali feldspar from the phenocryst assemblages of the oceanic extensional rhyolites is consistent with their plotted fields (figs. 7, 8).

#### NOTES ON THE OCCURRENCE, GEOLOGY, AND PETROGRAPHY OF THE OBSIDIAN SUBGROUPS

##### GROUP I: OBSIDIANS FROM THE EARLY STAGES OF ARC DEVELOPMENT

Obsidians from the early stages of arc development are members of the magmatic association termed the "island arc tholeiitic series" by Jakes and Gill (1970) and "primitive island arc series" by Donnelly and Rogers (1980); they would be incorporated into the low-K group of rhyolites of Ewart (1979). They occur typically in areas of subcontinental and relatively young crust including intraoceanic island arcs that appear to be underlain by thin (<20 km) basaltic crust.

This magmatism represents the earliest stages of arc development, and it is implicit in many accounts that there is a structural and magmatic transition to the mature-arc phase. Bryan (1979, p. 598) specifically refers to the silicic members as "first cycle siliceous derivatives," implying a more or less direct origin from mantle materials.

Rhyolites of this group have been reported from the Tonga-Kermadec Islands (Ewart and others, 1977; Bryan, 1979), the South Sandwich Islands (Baker, 1978, 1982), the Caribbean arc (Donnelly and Rogers, 1980), parts of New Britain (Smith and Johnson, 1981, p. 10262), the southern Kuriles, the Huzi volcanic zone, Japan, and the Izu-Mariana Islands (Jakes and Gill, 1970; Baker, 1972; Ewart, 1979).

Silicic rocks, especially those with SiO<sub>2</sub> ≥ 70 percent, are normally minor members of suites dominated by basalts and basaltic andesites (for

example, in the Tonga-Kermadec arc and the South Sandwich Islands). Some exceptions do occur, however, such as the voluminous dacites and associated trondhjemitic plutons emplaced during Miocene time in Fiji (Gill and Stork, 1979). The eruptive products may be represented by massive lava flows and domes, but a considerable percentage of these products is pyroclastic.

The data bank contains too few examples of this group to generalize about phenocryst assemblages. According to Ewart (1979, p. 50), however, his low-K rhyolites are dominated by plagioclase (Pl)-hypersthene (Opx)-augite (Cpx)-Fe-Ti oxides (Ox) assemblages, with amphibole (Hb), quartz (Q), and olivine (Ol) of more sporadic occurrence. Similarly, Gill and Stork (1980) report Pl+Ox±Q±Cpx±Opx (rare)±Hb (very rare)±apatite (Ap) as a generalized phenocryst assemblage in the Undu dacite, Fiji. Particularly noteworthy is the absence of biotite and alkali feldspar as phenocrysts in group I rhyolites.

#### GROUP II: OBSIDIANS OF MATURE ISLAND ARCS

Rhyolites of the developing to mature island arcs show a range in compositions that at least partly reflects a zonation of magmatic associations within many such arcs (Miyashiro, 1974). Thus, a distinction has been made (Kuno, 1966; Miyashiro, 1974; Katsui and others, 1978) between rhyolites that are members of tholeiitic magmatic associations and those of calc-alkalic associations; the tholeiitic magmas are higher in CaO and lower in alkalis, particularly  $K_2O$ , at given  $SiO_2$  concentrations. The two subgroups plot in the calcic and calc-alkalic fields, respectively, of the CaO versus  $SiO_2/(Na_2O+K_2O)$  diagram (fig. 4). They show consistent chemical differences apparently related to the stage of arc development.

The calcic group of rhyolites is most commonly found on the trench side of developing or mature island arcs in zone 2 or on the border between zones 1 and 2 of Miyashiro's (1974) arc zonation. The crust is 20–30 km thick and is believed to be transitional from oceanic to continental (Miyashiro, 1974), though details of its structure and composition are poorly known. The rhyolites are normally members of a tholeiitic magmatic association, though they may be provincially (for example, Japan) or locally (for example, Hakone volcano) associated with rocks of calc-alkalic series.

Rhyolites of this group are present in Japan (Miyashiro, 1974; Katsui and others, 1978), the Kuriles (Gorshkov, 1970), and Indonesia and the Caribbean (Smith and others, 1980; Donnelly and Rogers, 1980).

The most common phenocryst assemblage in these rocks is Pl+Opx+Cpx+Ox, and the generalized assemblage Pl+Opx+Cpx+Ox±Ol±Hb±Q incorporates the majority of samples. Alkali feldspar (Kf) has not been recorded as a phenocryst in such rhyolites, and biotite (Bi) appears in only three specimens.

Recorded phenocryst assemblages, excluding accessory phases, are as follows (sample numbers in parentheses):

Pl+Opx+Cpx+Ox	(189, 193, 194)
Pl+Opx+Cpx+Ox+Ol	(205)
Pl+Opx+Cpx+Ox+Q	(338, 347)
Pl+Opx+Cpx+Ox+Hb	(344)
Pl+Opx+Cpx+Ox+Hb+Bi	(341, 342, 343)
Pl+Opx+Cpx+Ol+Q+Hb	(350)
Pl+Opx+Ox+Q+Hb	(195)
Pl+Cpx+Ox+Ol	(354)
Pl+Opx+Q	(335, 336, 352)
Q+Hb	(340)

As the island-arc system develops, the underlying crust becomes thicker ( $\geq 30$  km) and is increasingly of "continental-type" (that is, of more sialic composition). Recycling of such crustal materials becomes a distinct possibility and may contribute a significant percentage of silicic volcanic rocks. The circum-Pacific arcs and those of the lesser Antilles and Indonesia would be included in this category, which characteristically would be considered to represent orogenic volcanism. We include New Zealand and Java as arc systems, although some would consider them continental margins.

The main rocks of these arcs are andesites and dacites of the calc-alkalic association, though tholeiitic and alkalic lineages also occur (Miyashiro, 1974). The proportions of rhyolitic types vary but are generally low (Baker, 1972, fig. 2). Characteristically, much of the silicic volcanism occurs as pyroclastic deposits.

Petrographically, the calc-alkalic group II rhyolites vary greatly. Phenocryst assemblages recorded are:

Pl+Opx+Cpx+Ox	(209)
Pl+Cpx+Ox	(200, 203)
Pl+Opx	(367)
Pl+Opx+Ox	(204, 206)
Pl+Cpx+Ol	(2)
Pl+Opx+Hb+Ox	(208)
Pl+Opx+Cpx+Hb+Ox+Q	(201)
Pl+Opx+Hb+Ox+Q+Kf	(198)
Pl+Hb	(368)
Pl+Hb+Ox	(199)
Pl+Opx+Ox+Kf	(216)
Pl+Ox+Kf	(202)
Pl+Ox+Q+Bi	(186)
Pl+Ox+Kf+Bi	(190)
Pl+Ox+Hb+Bi	(1, 192)



Thus, there is no single, common assemblage, although Pl+Ox is virtually ubiquitous. A generalized assemblage could be written  $Pl+Ox \pm Opx \pm Hb \pm Cpx \pm Bi \pm Kf \pm Q \pm Ol$ , with the phases ordered by frequency of appearance. It is worthy of note that alkali feldspar appears in several specimens; biotite probably also is commonly present (Ewart, 1979, p. 51). In addition, a significant percentage (~33 percent) of the samples are aphyric.

### GROUP III: OBSIDIANS OF ACTIVE CONTINENTAL MARGINS

Continental margins tend to have thicker (30–70 km) crusts than island arcs, thereby producing more granitic (silicic) magmas. The tectonic distinction is rather arbitrary, as many margins may be island arcs accreted to continental crust. In some areas, active arcs that overlie oceanic crust may extend into continental areas where they overlie continental-type crust. For example, the Aleutian arc extends eastward into the Alaska Peninsula, and the Kurile arc continues into Kamchatka.

Included in the group of obsidians of active continental margins are the recent silicic volcanic rocks of the western Americas, extending from Alaska and Canada down through the Cascades and central California and linking, via Central America, to the Andes. The crust forming these areas consists largely of Paleozoic and younger geosynclinal materials of generally andesitic composition, including a large graywacke-type sedimentary component. Precambrian rocks, present in some cases, are not volumetrically important as crustal components. The scarcity of Precambrian rocks is a critical part of the definition of this group; crust, and therefore rhyolites, of this type may occur within continental interiors far from the continental margin. Thus, group III rhyolites occur in parts of Nevada (Nos. 76–79) where Precambrian crust is apparently missing. The example serves to stress the point made earlier that the chemistry of rhyolites is primarily dependent on the type of crust in which they were emplaced. It also, perhaps, suggests that the term "continental margin" is not totally satisfactory for this group, but the data required to construct a more ideal classification based on crustal type and thickness are not yet available.

Furthermore, the broad tectonic setting of continental margin may include areas where extensional tectonics have been superimposed on the subduction regime. These extensional zones may produce rhyolites with distinctive chemistries, such as those of

the Brothers fault zone in Oregon, which include high-Fe, even peralkaline, varieties which are in some respects transitional to group V rhyolites of oceanic extensional zones. A possible explanation is that the crust in such zones is also transitional, perhaps due to intrusion into the sialic crust of substantial amounts of mafic material.

Continental-margin volcanism is dominated by andesites of calc-alkalic affinity, as is the case for the mature island arcs. An important difference is that rhyolitic volcanics are much more abundant on continental margins, much of the additional material being accounted for in voluminous pyroclastic deposits. Examples of large Cenozoic rhyolitic ash-flow provinces include the Central Andes ( $\geq 70,000$  km<sup>3</sup>, Pichler and Zeil, 1972) and Central America ( $\geq 10,000$  km<sup>2</sup>, Pushkar and others, 1972). The mid-Tertiary ash-flow tuffs of the Sierra Madre Occidental of western Mexico, thought to have been part of a continental arc, cover an area of more than 250,000 km<sup>2</sup> (Cameron and others, 1980).

As in the island-arc groups, there is a range of rhyolitic compositions within the active-continental-margin group. Affinities range from relatively CaO-rich types, many of which belong to calcic associations as defined by Peacock (1931), through rhyolite of calc-alkalic associations to alkali-calcic, relatively potassic, rhyolites. Though the major-element chemistry of the low-CaO types is comparable to rhyolites from epicontinental settings, the Nb and Ta abundances normally fingerprint them as of margin type.

The calcic rhyolites of the continental margins are more restricted geographically and volumetrically than their calc-alkalic associates. Their fullest development in Holocene time has been in the Cascades, Alaska, and Kamchatka. The alkali-calcic types have been found in several areas, including eastern Oregon, Mono Craters, north-western Nevada, Japan, and Turkey. They probably represent the highly differentiated end-members of calc-alkalic suites.

Pl+Opx+Ox occur in all seven porphyritic, calcic specimens in the continental margin for which we have data, and the generalized assemblage  $Pl+Opx+Ox \pm Cpx \pm Hb \pm Ol(?)$  describes all the samples. Only one calcic rhyolite of this group is aphyric (No. 243). Recorded assemblages (accessories excluded) are:

Pl+Opx+Ox	(8, 9)
Pl+Opx+Ox+Cpx	(20, 21)
Pl+Opx+Ox+Hb	(19, 247)
Pl+Opx+Ox+Cpx+Hb	(246)
Pl+Opx+Ox+Cpx+Hb+Ol?	(13, 15, 17)

A notable feature of the calc-alkalic specimens from the continental margins is that 54 percent, generally the more silicic, of them are aphyric. The porphyritic specimens show a variety of phenocryst assemblages:

Pl	(45)
Pl+Opx	(279)
Pl+Opx+Ox	(24, 41, 46, 47, 280)
Pl+Opx+Cpx+Ox	(22, 278)
Pl+Cpx+Ox	(261)
Pl+Cpx	(6)
Pl+Opx+Cpx	(48)
Opx+Cpx+Ox	(273)
Pl+Opx+Ox+Bi	(53)
Pl+Ox+Bi	(4, 154, 328)
Pl+Bi	(36, 329)
Pl+Hb	(31, 162, 166)
Pl+Hb+Ox	(163)
Cpx?+Hb	(248)
Pl+Opx+Cpx+Hb	(281)
Pl+Opx+Cpx+Hb+Bi+Ox+Kf	(51)
Pl+Opx+Cpx+Hb+Bi+Ox+Kf+Q	(283, 284)
Pl+Opx+Cpx+Ox+Kf+Q	(3)

There is an overall similarity to the assemblages recorded in the calc-alkalic rhyolites of mature island arcs. Pl+Ox+Opx occurs in a majority of specimens, whereas a generalized assemblage is Pl+Ox+Opx+Cpx+Hb+Bi+Kf+Q.

Twelve of the 19 alkali-calcic specimens are aphyric, and the remaining 7 are phenocryst-poor ( $\leq 1$  percent modal). The assemblages noted are:

Pl+Opx+Cpx+Ox+Hb	(188)
Pl+Cpx+Ox+Bi	(184)
Pl+Ox+Hb+Bi+Kf	(54)
Opx+Ox	(285, 287, 288)
Ox	(49)

#### GROUP IV: OBSIDIANS OF THE CONTINENTAL INTERIORS

Obsidians of the continental interiors are emplaced within stable continental cratonic areas. The crust varies in thickness from 25–50 km, where its lower parts consist of Precambrian and (or) lower Paleozoic rocks. Though most commonly found in the stable continental interiors, such crust may also occur in complex arc/margin settings. For example, the obsidians of Wadatoge and Imari in Japan (Nos. 188, 191) occur in areas underlain by lower Paleozoic and (or) Precambrian crust (Doe and Zartman, 1982).

Rhyolites are part of several types of magmatic systems in the continental setting: basalt-andesite-dacite-rhyolite suites, bimodal associations with basalts, entirely silicic dome fields, and enormous

volumes of ash-flow tuffs. Associated basalts form a spectrum of compositions: tholeiitic, high- $\text{Al}_2\text{O}_3$ , and alkalic types have all been recorded.

Group IV alkali-calcic rocks vary petrographically. Phenocryst assemblages recorded in the data bank are:

Pl	(98, 105, 109, 141, 146, 147)
Cpx	(151)
Ox	(161)
Pl+Ox	(143)
Pl+Cpx+Ox	(101)
Pl+Cpx+Bi+Ox	(178)
Pl+Bi	(107)
Pl+Kf+Ol	(300)
Pl+Kf+Ox	(119, 124)
Pl+Kf+Opx+Cpx+Ox	(85)
Pl+Kf+Opx+Cpx+Hb+Bi+Ox	(121)
Kf+Bi+Ox	(110, 305)
Kf+Bi	(306)
Kf	(295)
Q+Pl	(111)
Q+Kfs	(92, 296, 297, 298, 299)
Q+Pl+Kfs	(89, 102, 116, 294)
Q+Pl+Kfs+Ox	(90, 95, 108, 303, 304)
Q+Pl+Kfs+Opx+Ox	(144)
Q+Pl+Kfs+Opx+Cpx+Ox	(84)
Q+Pl+Kfs+Cpx?+Opx?+Hb+Ox	(310)
Q+Pl+Kfs+Hb+Ox	(86)
Q+Pl+Kfs+Bi+Ox	(87)
Q+Pl+Kfs+Bi+Hb+Ox	(88)
Q+Pl+Kfs+Opx+Cpx+Hb+Bi+Ox+Ol	(307, 308, 309)
Q+Pl+Kfs+Bi+Hb	(145)
Q+Kfs+Cpx+Ox	(91)

In addition, a simplified assemblage for 15 specimens from the Coso Range, California (Nos. 57–72, excluding 67) is  $\text{Q}+\text{Kf}+\text{Pl}+\text{Ox} \pm \text{Cpx} \pm \text{Opx} \pm \text{Hb} \pm \text{Bi} \pm \text{Ol}$ .

Quartz and alkali feldspars are common phenocryst phases, and biotite is also more frequently present than in any other rhyolite group.

A large proportion (42 percent) of the samples are aphyric. These rhyolites have the highest average  $\text{SiO}_2$  (table 7), and the absence of phenocrysts may be a reflection of low solidus temperatures and high viscosities (Ewart and Le Maitre, 1980).

#### GROUP V: OBSIDIANS FROM ISLANDS OVERLYING OCEANIC EXTENSIONAL ZONES

Group V silicic rocks from islands overlying regions of high heat flow at or near spreading axes with relatively thin ( $< 25$  km) oceanic-type crust are most extensively developed on Iceland but are also found on the volcanic islands of St. Andrew Strait, Papua New Guinea, in the Bismarck Sea, a marginal basin where sea-floor spreading is apparently taking place (Johnson and others, 1978). Group V

rhyolites have also been erupted from the Alcedo caldera, Galapagos Islands.

Included in this group are rhyolites forming a series of domes in the Salton Sea, California. These occur within an area of rapid, active spreading in a continental setting and are underlain by a crust intermediate in type between oceanic and continental. The chemistry of the Salton Sea rhyolites reflects this transition, but we consider them to be of group V affinity.

A feature of this group is that they almost invariably occur in bimodal association with basalt; where intermediate rocks are present (for example, in the tholeiitic centers of eastern Iceland), they are relatively uncommon.

Petrographically, group V rhyolites are rather uniform, and the phenocryst assemblage Pl+Cpx+Ol+Ox is present in the majority of specimens. Hb, Opx, Kf, and Q are less common phases. Recorded assemblages are:

Pl+Ox	(213)
Pl+Ox+Cpx+Opx	(176)
Pl+Cpx+Ox	(171, 321)
Pl+Cpx+Ox+Ol	(156, 157, 158, 174, 178)
Pl+Cpx+Ol	(319)
Pl+Ox+Ol	(214)
Pl+Cpx+Ox+Ol+Hb	(172)
Pl+Cpx+Ox+Ol+Q	(169, 170)
Pl+Cpx+Ox+Ol+Hb+Kf	(74)
Pl+Cpx+Ox+Hb+Kf	(73)

## GEOCHEMISTRY

### INTRODUCTION

The ranges of elemental abundances in the obsidians are given in table 7. Despite the restricted range of major-element abundances imposed by the 70-percent-SiO<sub>2</sub> lower limit, the minor and trace elements can show order-of-magnitude variations (for example, Ba and Sr). Compositional variations in the rhyolites are related to the type of crust through which the magma is emplaced and to the types and relative efficiencies of the genetic mechanisms operative on the silicic magmas, which may be specific to a given crustal environment. As previously stated, the type of crust through which the magma is emplaced forms the basis of the classification scheme used in this paper. The compositional variations must in some way be related either to the composition of the crust, its control on magma evolution, or to subcrustal processes themselves, which are related to the overlying crust.

One further level of chemical variation must also be mentioned. Numerous examples of restricted geo-

chemical anomalies are apparent in the data bank. Three may be mentioned here. The obsidian from Xalapasco, Mexico (Nos. 146, 147) is unique in having Th/U ratio <1. The obsidian from the U.S. Gypsum Company perlite mine in Nevada (No. 78) shows extreme HREE depletion, with Yb at almost chondritic levels. The Superior, Arizona, obsidian (No. 106) has notably low contents of Cs, Sb, Th, and U for a continental interior rhyolite. Many more examples are provided in later sections. It is possible that these restricted anomalies are a result of source rocks of unusual composition, reflecting very localized modifications of crustal composition. Alternatively, they may be process-related in some way. Whatever their cause, they add some nonsystematic scatter to the within-group compositional variations.

### BETWEEN-GROUP COMPOSITIONAL VARIATIONS

Ranges and average compositions for the obsidians from various settings are given in table 7. The main features of the average analyses can be shown as geochemical patterns (fig. 9). The normalizing factor for these patterns is the hypothetical ocean-ridge granite (ORG) of Pearce and others (1984), which was calculated as the residual liquid after 75 percent fractional crystallization of average N-type MORB (normal midocean ridge basalt as opposed to E-type, enriched MORB). This calculation attempts to produce a model granitic liquid by simple fractionation from a basalt having a plagioclase-olivine-clinopyroxene-magnetite assemblage, with no crustal interaction and without involvement of a dominant volatile phase. Any deviation from a flat pattern reflects a more complex magma genesis, which varies from setting to setting.

In general, the patterns show an overall slope from left to right (see fig. 9), that is, enrichment in K, Rb, Ba, and Th relative to the other elements shown (Ta, Nb, Ce, Hf, Zr, Sm, Y, Yb), though the details of the patterns are different. Those patterns from the continental-margin and mature-island-arc obsidians are the most similar. They show a slight depletion in Ba relative to Rb and Th, and small troughs at Nb and Ta (especially in the mature-island-arc average) which mimic the Nb-Ta depletion typical of mafic rocks in subduction zones (Pearce, 1982, 1983). The combination of a deep Ba trough and low Ce concentrations relative to Nb distinguish the continental-interior average from that of the other groups. The oceanic-extensional-zone average closely follows those of the mature island arcs and continental margins from K to Th but is much higher in the Ce to Yb elements than the other types.

TABLE 7.—*Ranges and average compositions of the various obsidian groups*(First average (X) in each column was calculated using new data only (appendix I); ranges and second average ( $X_T$ ) using all data. —, not determined)

	Primitive island arcs			Mature island arcs			Continental margins			Continental interiors*			Oceanic extensional zones		
	Range	X	$X_T$	Range	X	$X_T$	Range	X	$X_T$	Range	X	$X_T$	Range	X	$X_T$
Major elements—(weight percent)															
SiO <sub>2</sub> .....	70.1–73.5	—	71.6	70.6–77.2	75.2	74.6	70.2–77.3	74.5	74.1	70.6–77.5	75.9	75.8	70.0–76.9	72.9	73.1
Al <sub>2</sub> O <sub>3</sub> .....	11.90–14.31	—	13.04	11.39–15.26	13.14	13.26	11.92–15.37	13.58	13.65	11.90–16.30	12.85	12.87	11.82–14.59	13.21	13.13
Fe <sub>2</sub> O <sub>3</sub> .....	.69–1.57	—	1.05	.04–1.52	.44	.56	.09–1.67	.49	.50	.09–1.33	.43	.45	.27–1.97	.74	.78
FeO .....	1.84–4.84	—	3.24	.37–4.03	1.15	1.17	.32–2.62	.92	1.14	.12–1.76	.59	.65	1.10–3.88	2.00	1.94
MgO .....	.50–1.1	—	.84	.07–1.38	.25	.36	.01–.93	.21	.24	.00–.66	.06	.07	.00–.73	.22	.23
CaO .....	3.25–4.61	—	3.80	.66–3.70	1.34	1.64	.27–2.94	1.00	1.11	.16–2.07	.51	.54	.48–2.79	1.20	1.25
Na <sub>2</sub> O .....	2.81–4.88	—	3.85	2.72–5.19	4.13	4.13	3.40–5.38	4.32	4.29	3.00–5.07	4.14	4.05	3.16–5.93	4.97	4.87
K <sub>2</sub> O .....	.64–1.52	—	.92	.98–5.01	3.46	3.22	2.43–5.26	4.11	4.12	3.60–6.60	4.61	4.73	2.30–4.43	3.64	3.59
H <sub>2</sub> O <sup>+</sup> .....	—	—	—	.05–.78	.17	.32	.04–1.10	.20	.27	.01–.98	.24	.25	.04–.63	.14	.19
TiO <sub>2</sub> .....	.30–.58	—	.47	.08–.73	.22	.27	.03–.54	.21	.22	.00–.31	.10	.11	.10–.92	.29	.29
P <sub>2</sub> O <sub>5</sub> .....	.07–.12	—	.09	.01–.33	.03	.08	.01–.22	.04	.05	.00–.55	.02	.02	.00–.44	.04	.06
MnO .....	.06–.14	—	.11	.01–.20	.08	.08	.02–.12	.06	.05	.02–.14	.06	.05	.04–.18	.09	.08
Cl .....	—	—	—	.06–.19	.11	—	.01–.17	.07	—	.04–.20	.08	—	.03–.36	.17	—
F .....	—	—	—	.02–.08	.05	—	.02–.12	.05	—	.05–1.36	.15	—	.05–.20	.12	—
Trace elements (parts per million)															
Ba .....	68–610	—	286	392–1285	637	—	13–1440	730	—	1–1040	164	—	400–880	619	—
Be .....	—	—	—	.86–3.2	1.59	—	1.3–5.5	2.62	—	1.8–32	6.90	—	1.9–5.8	4.67	—
Co .....	2.8–10	—	6.6	.2–4.6	1.2	—	.1–4.5	1.1	—	.09–3.9	.4	—	<.2–4.0	1.29	—
Cr .....	—	—	—	1.1–2.2	1.7	—	1.1–10.7	2.3	—	1.0–13.2	3.2	—	.4–3.8	1.4	—
Cs .....	—	—	—	1.3–12.7	6.2	—	1.8–21.1	5.8	—	2.0–503	6.4	—	.7–4.0	1.5	—
Hf .....	—	—	—	2.0–10.9	4.7	—	1.9–11.5	5.0	—	1.3–14.5	5.6	—	7.6–21.8	12.8	—
Li .....	—	—	—	18–68	35	—	25–110	49	—	34–3400	84	—	18–81	32	—
Mo .....	—	—	—	1.2–4.7	2.3	—	.58–8.1	3.2	—	.26–9.9	4.1	—	2.3–6.2	4.2	—
Nb .....	.6–3	—	2	3–15	8.2	—	5–36	13.8	—	14–288	55.2	—	30–131	68.5	—
Pb .....	4–10	—	7	6–44	20	—	9–49	21	—	15–101	32	—	9–19	14	—
Rb .....	6.8–23	—	16	23–200	112	—	52–270	135	—	103–1174	232	—	62–158	106	—
Sb .....	—	—	—	<.1–2.3	.74	—	.2–1.9	.80	—	.1–3.9	.79	—	.3–.6	.48	—
Sc .....	—	—	—	1.72–12.4	6.4	—	1.07–9.04	3.6	—	.12–7.69	2.0	—	.43–11.1	3.9	—
Sn .....	—	—	—	.5–3.6	1.9	—	.7–7.9	2.6	—	1.3–250	5.6	—	2.2–8.4	6.0	—
Sr .....	110–255	—	157	37–290	125	—	2–402	120	—	<1–202	23	—	25–128	73	—
Ta .....	—	—	—	.21–1.03	.60	—	.44–2.95	1.24	—	1.93–29.4	5.7	—	2.58–8.52	4.9	—
Th .....	.7–4	—	2.2	2.1–24.8	10.6	—	4.9–26.6	12.9	—	1.3–52.7	23.6	—	7.3–20.8	12.7	—



U -----	.39-.84	—	.64	7-7.2	3.1	—	2.1-13.2	4.9	—	3.5-35.1	10.9	—	2.1-5.7	3.6	—
W -----	—	—	—	.43-3.2	1.7	—	.50-3.9	1.8	—	1.0-76	2.7	—	.94-3.3	1.5	—
Y -----	25-41	—	34	10-85	35	—	8-108	30	—	8-245	55	—	31-155	89	—
Zn -----	43-101	—	69	8-108	39	—	16-95	38	—	18-282	54	—	42-179	97	—
Zr -----	51-178	—	98	39-420	164	—	40-447	165	—	22-367	136	—	185-860	526	—
La -----	—	—	—	11-37	22	—	9-90	28	—	1-95	32	—	41-95	63	—
Ce -----	—	—	—	24-79	43	—	18-142	51	—	3-185	64	—	78-176	130	—
Nd -----	—	—	—	11-46	21	—	8-51	22	—	4-71	28	—	31-78	59	—
Sm -----	—	—	—	2.8-11.8	5.0	—	2.0-10.5	4.7	—	1.5-15.9	6.7	—	6.4-17.9	14.1	—
Eu -----	—	—	—	.37-1.65	.76	—	.08-1.11	.55	—	.02-.98	.24	—	.94-3.29	2.0	—
Gd -----	—	—	—	2.5-10.5	4.6	—	1.6-10.8	4.3	—	<2-16.6	6.2	—	5.3-16.8	11.7	—
Tb -----	—	—	—	.32-2.01	.85	—	.24-2.25	.67	—	<.03-4.26	1.28	—	.93-3.00	2.18	—
Tm -----	—	—	—	.26-1.29	.54	—	<.10-1.82	.45	—	<.20-3.22	.91	—	.60-1.96	1.26	—
Yb -----	—	—	—	1.7-8.9	3.8	—	.2-11.7	2.9	—	.3-23.6	5.7	—	4.2-13.6	8.3	—
Lu -----	—	—	—	.27-1.30	.56	—	<.1-1.66	.42	—	.04-3.04	.93	—	.62-1.87	1.06	—
<hr/>															
Nb/Ta -----	—	—	—	9.6-21.5	13.7	—	7.4-21.2	11.1	—	2.5-18.9	9.7	—	11.0-15.5	14.0	—
K/Rb -----	385-781	—	540	167-571	256	—	138-394	253	—	25-380	165	—	220-356	285	—
Rb/Sr -----	.04-.16	—	.11	.1-5.3	.9	—	.1-65	1.1	—	.8-1533	10.3	—	.5-5.8	1.5	—
Ca/Sr -----	112-211	—	176	40-149	77	—	35-965	60	—	39-12863	158	—	91-243	118	—
Th/U -----	1.0-2.5	—	1.8	1.4-9.1	3.5	—	1.4-3.6	2.6	—	.1-5.1	2.2	—	3.0-4.1	3.5	—
Zr/Hf -----	—	—	—	20-48	35	—	17-48	33	—	10-43	24	—	23-46	41	—
Ce/Yb -----	—	—	—	6.4-24.5	11.5	—	4.7-230	18.0	—	2.4-12.0	11.2	—	9.0-26.4	15.6	—
Eu/Eu* -----	—	—	—	.20-.78	.51	—	.04-.75	.38	—	.01-.56	.12	—	.32-.68	.48	—
<hr/>															
Maximum number of determinations:															
major elements -----	7			59			119			108			24		
trace elements -----	5			26			66			80			17		

<sup>1</sup>By weight<sup>2</sup>Molecular\*Averages exclude P<sub>2</sub>O<sub>5</sub>, F, Cs, Li, Rb, Sb, Sn, and W data for sample 160.

The plot distinguishes elements which are potentially valuable at separating the obsidian groups, for example, Nb, Ta, and Th (although averaging tends to blur the value of Th), from those less valuable, for example, Zr and Hf. In fact, the overlap between the groups is sufficiently large that no one element or ratio can separate all five groups. Combinations of elements provide more successful discriminants, such as the Nb-Ta, Nb-FeO<sub>3</sub>, and Th-Ta-Hf plots presented below.

The compositional differences must have petrogenetic significance, reflecting in some way the differ-

ing source materials and evolutionary histories of the rhyolites in each setting. In the next section, we assess the usefulness of tectonomagmatic discrimination diagrams for silicic rocks, using some standard variation diagrams and plots based on stable trace-element abundances.

#### TECTONOMAGMATIC DISCRIMINATION DIAGRAMS

##### ASSESSMENT OF STANDARD VARIATION DIAGRAMS

The (Na<sub>2</sub>O+K<sub>2</sub>O) content versus SiO<sub>2</sub> content for obsidians, as shown in figure 10, are plotted with respect to the fields for tholeiitic, high-Al<sub>2</sub>O<sub>3</sub>, and alkalic basalt series of Kuno (1966), although these fields are shown for reference only and carry no implication that the rhyolites are necessarily parts of differentiation sequences involving basaltic members. The plot demonstrates two points relevant to the relation between rhyolite chemistry and crustal maturity. (1) The obsidians show narrower ranges, in terms of total alkalis, in more silicic settings. Island-arc rocks are present in all three fields, continental-margin rocks plot in the alkalic and high-alumina fields, and the continental-interior rhyolites are mostly restricted to the alkalic field. (2) The proportions of each rhyolite type in the three series also vary widely, as the following tabulation stresses.

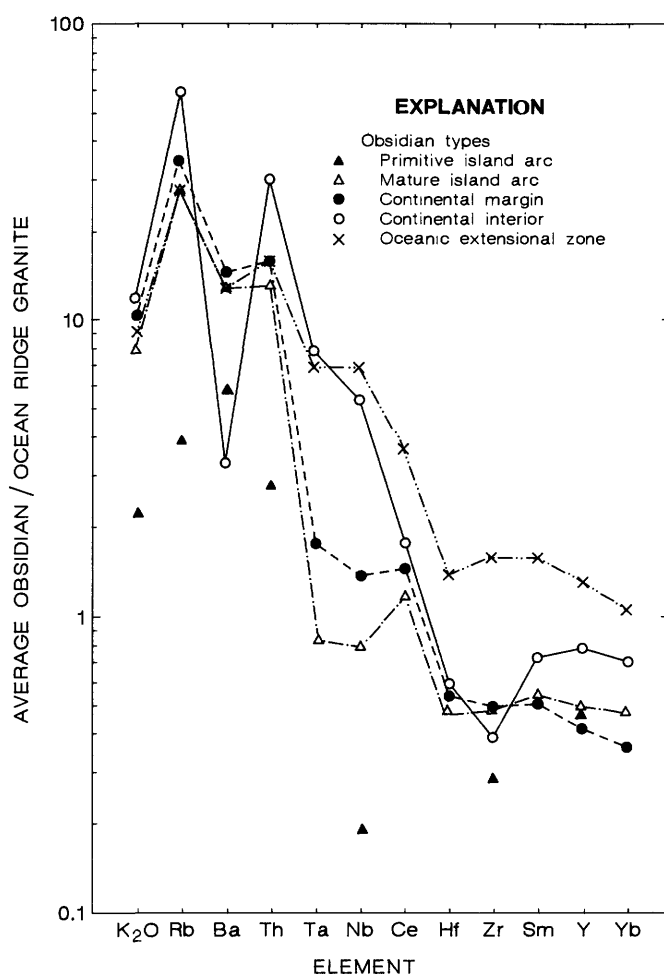


FIGURE 9.—Geochemical patterns, normalized to ocean ridge granite, for average obsidian from different tectonic settings (table 7). Available data for primitive island arcs are shown, but pattern is incomplete because values for several elements were not determined. Order of elements and normalizing values from Pearce and others (1984); values are: K<sub>2</sub>O, 0.4; Rb, 4; Ba, 50; Th, 0.8; Ta, 0.7; Nb, 10; Ce, 35; Hf, 9; Zr, 340; Sm, 9; Y, 70; Yb, 8 (K<sub>2</sub>O, in weight percent; others, in parts per million). The Yb value is incorrectly reported as 80 in Pearce and others (1984, table 3).

Obsidian group	Number of specimens in each series		
	Tholeiitic	High-Al <sub>2</sub> O <sub>3</sub> basalt	Alkalic
Primitive island arcs (I)-----	6	—	—
Mature island arcs (II)-----	18	31	10
Continental margins (III)-----	—	41	78
Continental interiors (IV)-----	—	7	99
Oceanic extensional zones (V)-----	2	5	17

In a crude way, therefore, the arrow shown in figure 10 indicates the trend of increasingly silicic crust. Major exceptions are the rhyolites of oceanic extensional zones, the majority of which plot in the alkalic field and were emplaced on basaltic crust.

Use of the (Na<sub>2</sub>O+K<sub>2</sub>O) versus SiO<sub>2</sub> plot as a tectonomagmatic discrimination diagram is limited. Rocks from four rhyolite groups plot within the alkalic field; trace-element plots much more successfully separate these groups. The diagram can be used as an indicator of crustal type in a partly negative

way, for example, rocks that plot below the alkalic-high alumina boundary are not likely to have originated in a within-plate continental setting, and rocks that plot below the high alumina-tholeiite line are not likely to have a substantial sialic component.

Increasing maturity of orogenic zones, expressed in terms of crustal thickening and increasingly sialic character, is matched by an evolution of the associated volcanism from low-K tholeiitic rocks to complex associations of tholeiitic, calc-alkalic, and alkalic rocks with chemical variations both along the zone and with vertical height within the stratigraphic sequence. This compositional evolution is often most notable in potassium and related elements, and certain workers (for example, Jakes

and Gill, 1970; MacKenzie and Chappell, 1972; Peccerillo and Taylor, 1976) have employed  $\text{SiO}_2$  versus  $\text{K}_2\text{O}$  plots as a simple classification scheme for orogenic volcanic rocks. Thus, Peccerillo and Taylor (1976) have recognized low-K, calc-alkalic, and high-K series on the basis of arbitrary boundaries on a  $\text{K}_2\text{O}$ - $\text{SiO}_2$  plot.

Ewart (1979) divided rhyolites, which he defined as having  $\text{SiO}_2 \geq 69$  percent by weight, into a series of regional groupings based on geography and (or) tectonic setting. The data were further divided into low-K, calc-alkalic, and high-K types (fig. 11) using chemical subdivisions slightly modified from those of Peccerillo and Taylor (1976). Obsidian data plot in the three fields as follows:

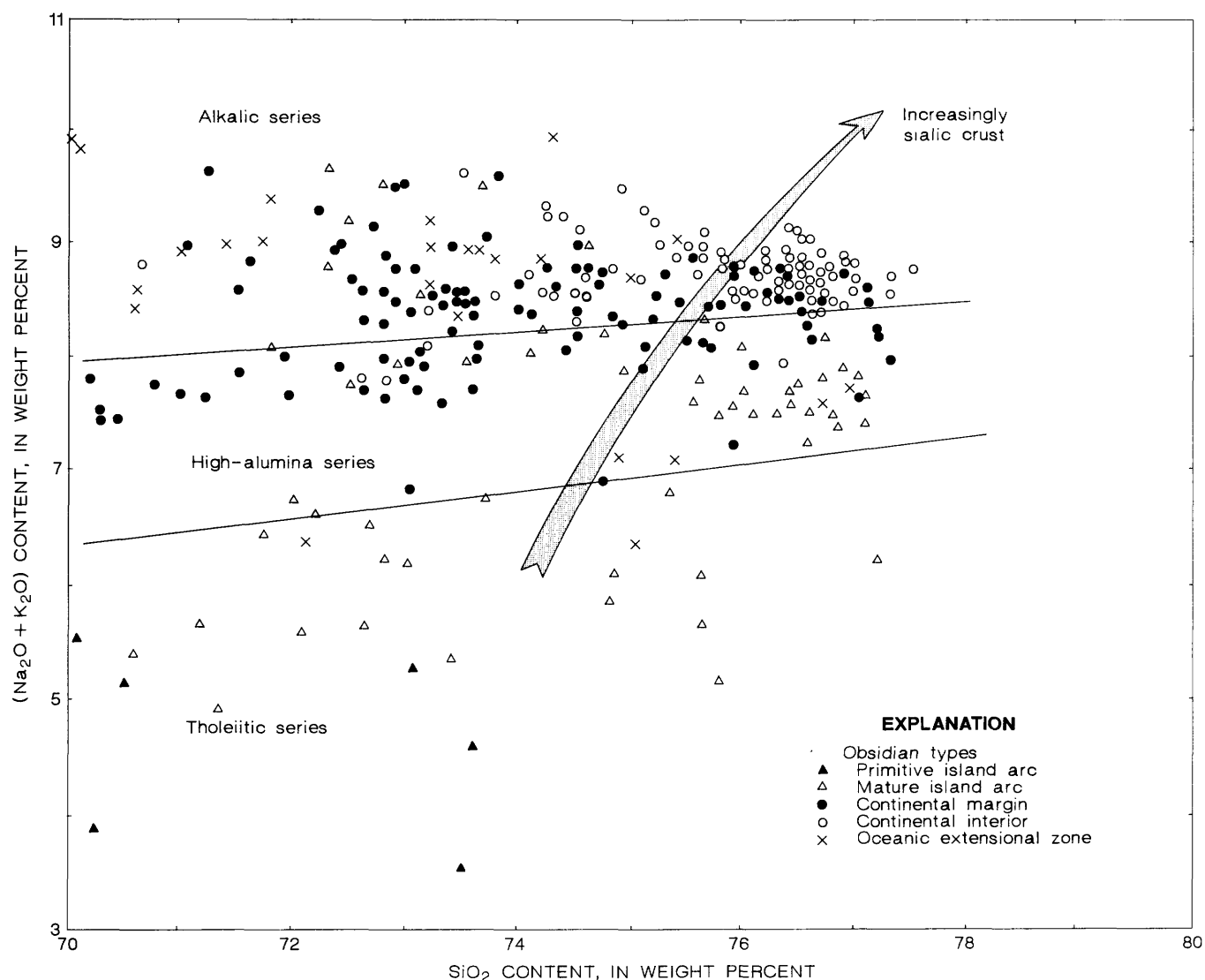


FIGURE 10.— $\text{SiO}_2$  content versus  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  content showing distribution of obsidians in fields of tholeiitic, high-alumina, and alkalic basalt series of Kuno (1966). Data from appendixes I, III, and V (samples A, C-G).

Obsidian group	Low-K	Calc-alkalic	High-K
Primitive islands arc (I) -----	4	2	—
Mature island arc (II) -----	3	21	36
Continental margins (III) ---	—	19	94
Continental interiors (IV) ---	—	—	93
Oceanic extensional zones (V) -----	—	10	14
Percent of total -----	2.4	17.6	80.0

The data broadly confirm Ewart's (1979) conclusions, namely, that with increasingly mature crustal type, the ratios of the number of samples of high-K to calc-alkalic and of calc-alkalic to low-K rhyolites increase. The  $K_2O$  versus  $SiO_2$  plot is useful as a very general indication of crustal type, though it has severe limitations; for example, the extensive overlap of continental-margin and continental-interior rocks.

As a classification scheme for silicic rocks, the plot is less satisfactory for two main reasons. First,

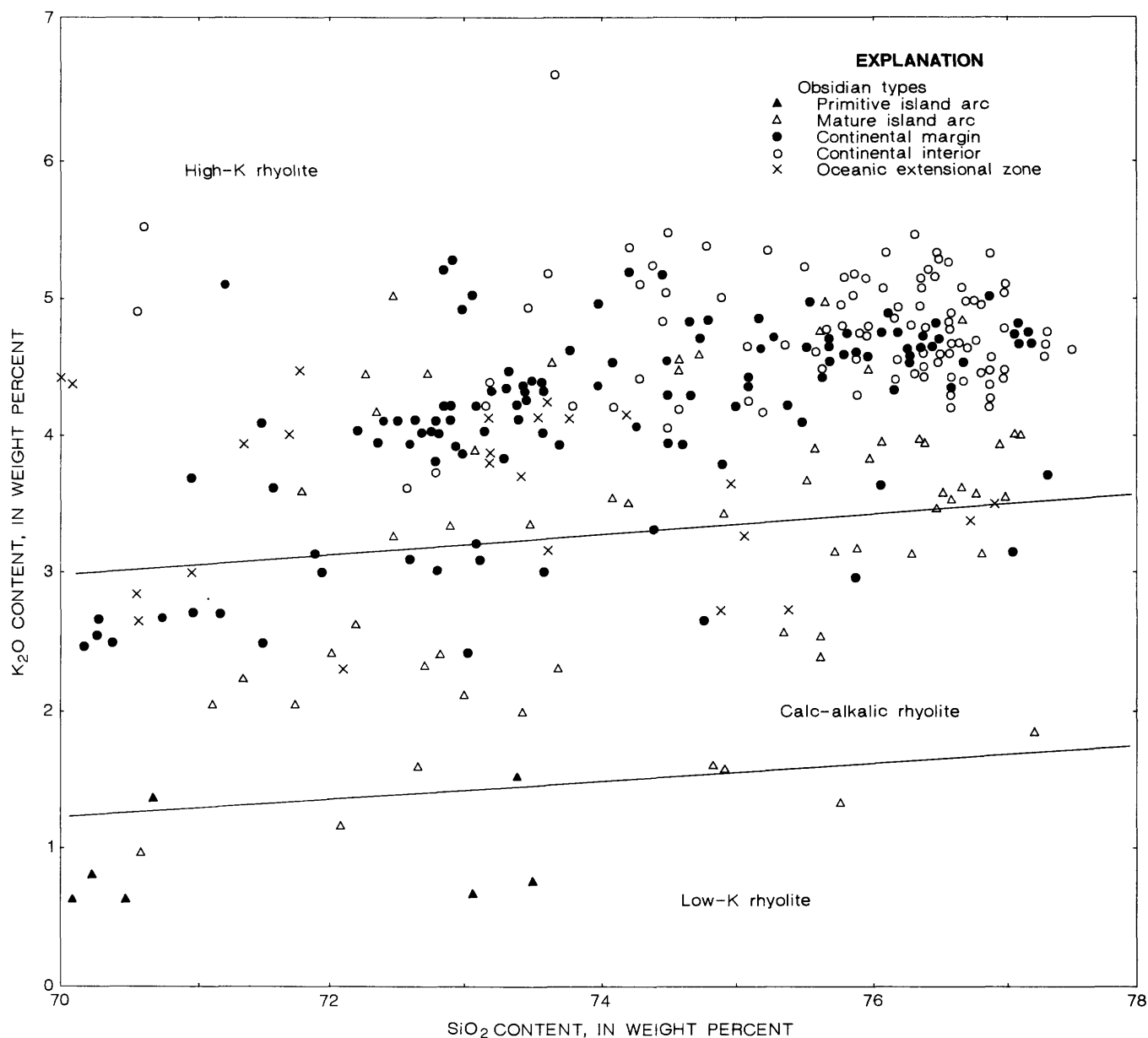


FIGURE 11.— $SiO_2$  content versus  $K_2O$  content of obsidians in fields of high-potassium, calc-alkalic, and low-potassium rhyolites of Ewart (1979). Data from appendixes I, III, and V (samples A-G).



it may produce ambiguities with existing terminologies. Most obsidians from the continental margin of the Western United States plot in the high-K field, whereas others, such as Crater Lake and South Sister, plot in the calc-alkalic field. Yet, in Peacock's (1931) scheme, the former rocks are calc-alkalic and the latter calcic. Second, and more importantly, the plot brings together rhyolites of quite different character, although they were generated in different settings. Thus, the term high-K rhyolite would be applicable to an Icelandic rhyolite and to one from the Yellowstone complex, rocks which are totally dissimilar in terms of trace-element chemistry. More generally, the mobility of alkalis during low-temperature alteration processes renders this plot possibly misleading for older, crystalline rocks and hydrated glasses.

In view of these restrictions, we prefer not to use the  $K_2O-SiO_2$  plot for classificatory purposes, even on an informal basis.

A plot of  $\log_{10} CaO/(Na_2O+K_2O)$  versus  $SiO_2$  (fig. 12) uses as its basis Peacock's (1931) method for classifying igneous rock suites. It has been employed in various forms by Christiansen and Lipman (1972), Petro and others (1979), and Brown (1979, 1982) mainly to classify igneous rocks and to identify tectonic environment. Brown (1982) presents the plot to show that with increasing maturity of arc systems, the  $CaO/(Na_2O+K_2O)$  ratio of the volcanic suites becomes lower, at given  $SiO_2$  content, as the proportions of calcic to calc-alkalic and calc-alkalic to alkali-calcic suites become smaller. The averages for each of the main rhyolite groups show this overall trend very clearly. There is, however, considerable overlap between groups, and the diagram is not an entirely successful indicator of tectonic setting. Again, concentrations of alkalis may also be disturbed in ancient rocks and hydrated glasses. Trace-element or combined trace- and major-element plots are more reliable discriminators.

#### TRACE-ELEMENT DISCRIMINATION PLOTS

Trace elements show much greater variations in abundance than major elements in obsidians from different tectonic settings (table 7) and thus provide better discrimination. The use of stable trace elements, that is, those believed to be immobile during metamorphism and (or) low-temperature alteration (Pearce and others, 1984), would make such discriminants particularly applicable to ancient silicic rocks.

A Th-Hf-Ta ternary plot (fig. 13), originally presented by Wood and others (1979), and later slightly modified by Wood (1980), was proposed as a means of tectonomagmatic discrimination. Though much of the discussion in those papers concerned mafic rocks, the diagram was also considered applicable to silicic rocks. Limited data on silicic rocks were available to Wood and his colleagues, however, and here we employ the obsidian data bank to evaluate the diagram's usefulness.

A diagram such as this, based on relative concentrations of elements, is potentially more useful than those using absolute concentrations, for example, Nb versus Ta or Nb versus  $FeO_4$  graphs (see figs. 17, 18), in that the relative amounts are unlikely to change significantly over relatively small  $SiO_2$  intervals. Thus, it is not critical to know the original absolute, magmatic  $SiO_2$  content before plotting data, a point of much value in the discrimination of altered silicic rocks.

Wood (1980) discriminates rocks from the following tectonomagmatic environments:

- A ----- N-type MORB (common or normal MORB)
- B ----- E-type MORB (enriched MORB) and tholeiitic within-plate basalts and differentiates.
- C ----- Alkaline within-plate basalts and differentiates.
- D ----- Destructive plate-margin basalts and differentiates.

The relations among these groups and the obsidian terminology of this paper are as follows:

- I ----- Obsidians of primitive island arcs:  
D ( $Hf/Th \geq 3$ ).
- II ----- Obsidians of immature and mature island arcs:  
D ( $Hf/Th \geq 3$ ).
- III ----- Obsidians of continental margins:  
D ( $Hf/Th \leq 3$ ).
- IV ----- Obsidians of continental interiors:  
?
- V ----- Obsidians of oceanic extensional zones:  
B or C, depending on affinity of volcanic center.

Group IV obsidians are the most difficult to fit into Wood's (1980) groups. They are "within-plate" and commonly associated with tholeiitic or alkaline basalts, in which case fields B and C might seem appropriate. However, it is by no means certain that they are differentiates of the associated basalts. In fact, these rhyolites occupy their own field on the Th-Hf-Ta diagram.

The subduction-related rhyolites mostly fall within field D (fig. 13A), except for some continental-margin rocks whose plotted position might justify a slight adjustment of Wood's (1980) field. Relatively calcic samples plot in more Hf-rich positions, as Wood predicts, and although data are too scarce to be sure, it appears likely that the subdivision of field D marked as "primitive arc tholeiites (and differentiates)" at  $Hf/Th=3$  is also justifiable.

Several of the rhyolites from oceanic spreading zones plot within fields B and C, as expected, but others lie to the left of field C. These points may be encompassed by expanding field C, as suggested in figure 13B; this adjusted field, showing little overlap with adjacent fields, defines tectonic setting rather accurately. Important exceptions are the Salton Sea obsidians, noted earlier as having chemical features transitional between oceanic extensional zones and continental margin. The relatively high Th contents of these rocks result in their plotting in the continental-margin field.

Apart from an important overlap with field D, it is notable that the obsidians from continental interiors occupy a field on the Hf-Th-Ta diagram, not included by Wood (1980), reflecting the lack of relevant trace-element data prior to the present study.

It is possible, therefore, to modify Wood's diagram to produce three tectonomagmatic fields: subduction-related, oceanic extensional, and continental interior, with an area of overlap between the subduction-related and continental interior fields (fig. 13B). The distribution of the obsidian groups within each field is as follows:

Obsidian group	Tectonomagmatic field			
	Subduction-related	Zone of overlap between subduction-related and continental interior fields	Continental interior	Oceanic extensional zones
Primitive island arcs -----	4	0	0	0
Mature island arcs -----	22	4	0	0
Continental margins -----	24	40	0	0
Continental interiors -----	0	45	33	0
Oceanic extensional zones -----	1	1	0	1

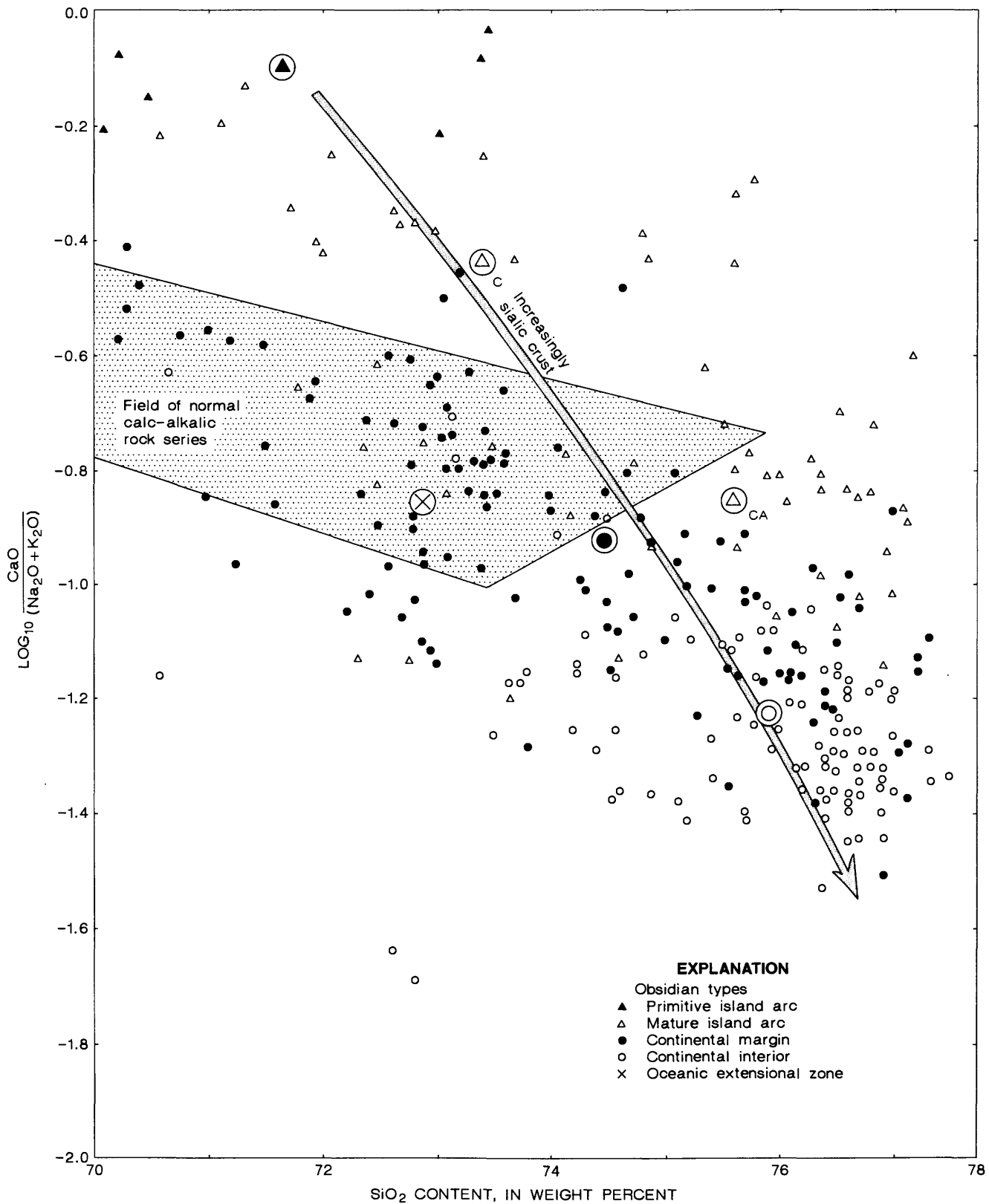
Compared to the Nb-Ta and Nb-FeO<sub>4</sub> diagrams (see figs. 17, 18), the Hf-Th-Ta diagram has the disadvantages of being less able to distinguish mature-arc from continental-margin rhyolites and of there being an overlap between subduction-related and continental-interior types. On the other hand, it is less sensitive to major-element variations, especially SiO<sub>2</sub> content, and, thus, is applicable to a wider range of altered rocks.

A plot of log Rb/Zr versus Nb content (fig. 14) was used by Brown and others (1984) in their discussion of the geochemical characteristics of granites from various subduction-related settings. It utilizes the fact that though Rb and Nb both show striking increases in silicic rocks emplaced in increasingly sialic crust, Zr is less variable (table 7). The plot of obsidian data in figure 14, showing arbitrary field boundaries, is only partially successful as a discrimination diagram. There is almost complete overlap of mature-island-arc and continental-margin rocks and substantial overlap of continental-margin and continental interior rocks. Eighteen specimens are incorrectly classified on the plot.

A possible problem regarding application to granites and crystallized and hydrated rhyolites is that Rb can be a mobile element, thus affecting the Rb/Zr ratio.

Pearce and others (1984) have used various combinations of the elements Rb, Y, Yb, Ta, and Nb for tectonic discrimination of granites. Here we plot the obsidian data on two of their diagrams: Rb versus (Y+Nb) (fig. 15) and Ta versus Yb (fig. 16). The Rb-(Y+Nb) plot (fig. 15) is moderately successful at discriminating subduction-related obsidians from continental-interior and oceanic-extensional-zone obsidians, chiefly a result of the higher Nb values in the latter two groups. Higher Rb concentrations in continental-interior rocks effectively separate them from those of the oceanic extensional zones. However, there is considerable overlap between the subduction-related and continental-interior data;

FIGURE 12.—SiO<sub>2</sub> content versus log<sub>10</sub> CaO/(Na<sub>2</sub>O+K<sub>2</sub>O) for obsidians, showing changes associated with generation in increasingly sialic crust. Large circled symbols are averages for each rhyolite group; rhyolites of mature island arcs are subdivided into calcic (subscript C) and calc-alkalic (subscript CA) varieties. Field of normal calc-alkalic rock series is from Brown (1982, fig. 2). Data from appendixes I, III, and V (samples A–G). For simplicity, individual data points for obsidians of oceanic extensional zones are not shown.



27 specimens plot in inappropriate fields using Pearce and others' (1984) boundaries. The applicability of this plot to crystalline silicic rocks is also limited by possible mobility of Rb.

The Ta-Yb plot (fig. 16) is of limited value, mainly because Yb abundances show similar ranges in all the obsidian groups. Subduction-related obsidians

plot in all four fields on the diagram and obsidians from the continental interiors and oceanic extensional zones are poorly discriminated. A total of 34 specimens are inappropriately classified.

Nb and Ta contents are particularly useful indicators of the tectonic setting of rhyolitic rocks (fig. 17; compare with Pearce and Gale, 1977). Values of

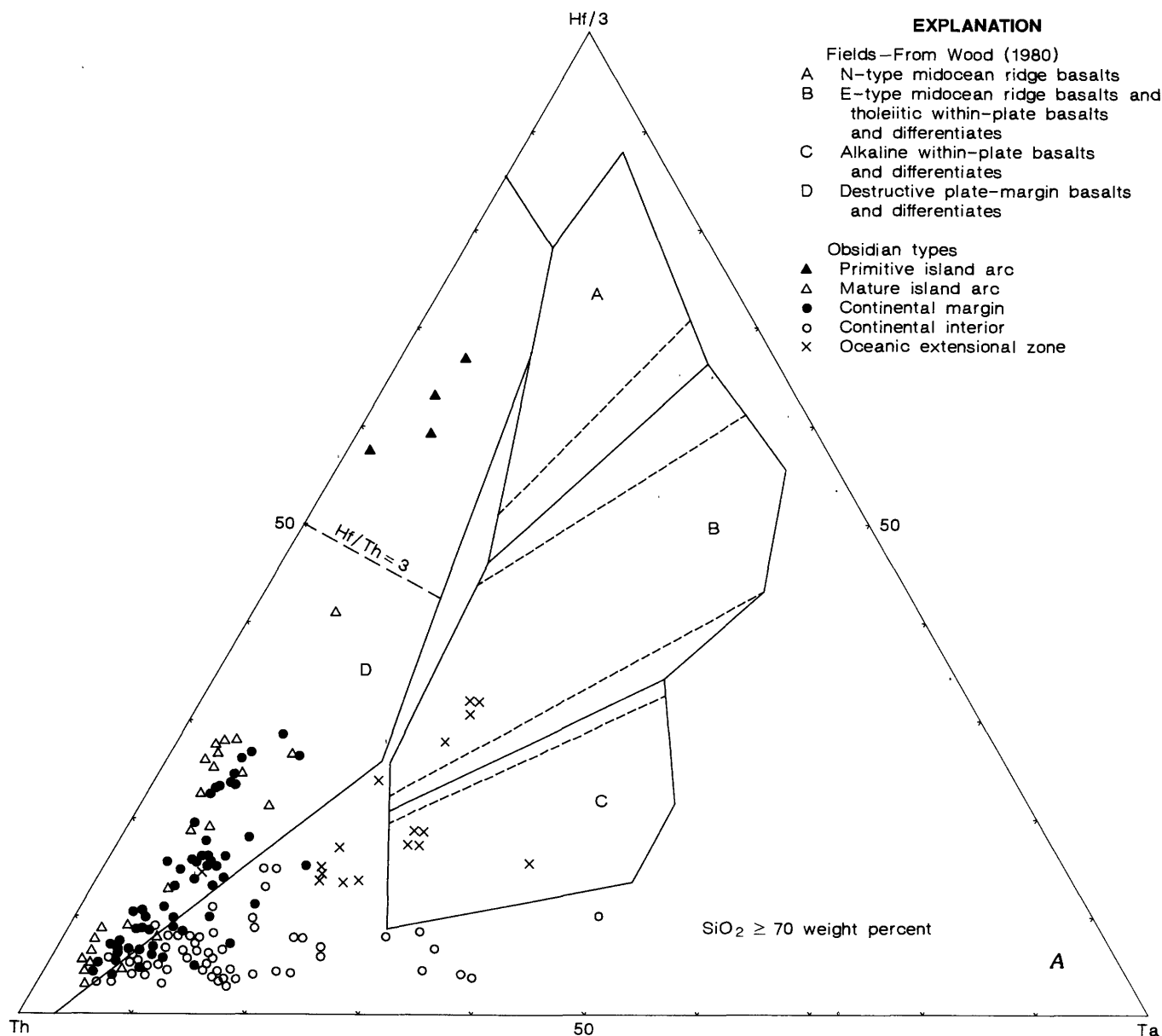


FIGURE 13.—Obsidian data plotted on (A) hafnium (Hf)-thorium (Th)-tantalum (Ta) discrimination diagram of Wood (1980). Short-dashed lines indicate areas of overlap between fields A and B and fields B and C noted by Wood. Hf/Th ratio of 3 (long-dashed lines) separates rocks of primitive island arcs

from those of more mature arcs. Data for primitive island arc rocks from appendix V (samples F, H, I, and J). Ta values were not reported for these specimens and are calculated for this plot by assuming Nb/Ta ratio of 15. B, Data plotted as in A, but with fields redefined for obsidian group classification used herein.

Ta=1.5 ppm and Nb=19 ppm have been selected to separate rhyolites of subduction-related settings (lower) from extensional types (higher). Using these values, 161 specimens are, and 9 are not, assigned to the correct category, whereas 8 lie in an overlap zone where the concentration of either Nb or Ta is too high or too low for the rock category. We suggest, therefore, that this plot is a useful guide to the tectonic setting of ancient volcanic rocks, in that both elements are unaffected

by either low-temperature alteration processes or by low-grade metamorphism. Its application to altered rocks is, of course, dependent on such rocks having magmatic  $\text{SiO}_2 \geq 70$  weight percent, which may not be easily assessed. Its main disadvantage in obsidian studies is that it cannot distinguish continental-interior from oceanic-extensional-zone rhyolites. The latter are, however, notably higher in  $\text{FeO}$ ; an Nb-FeO<sub>x</sub> plot can be used to separate the two groups.

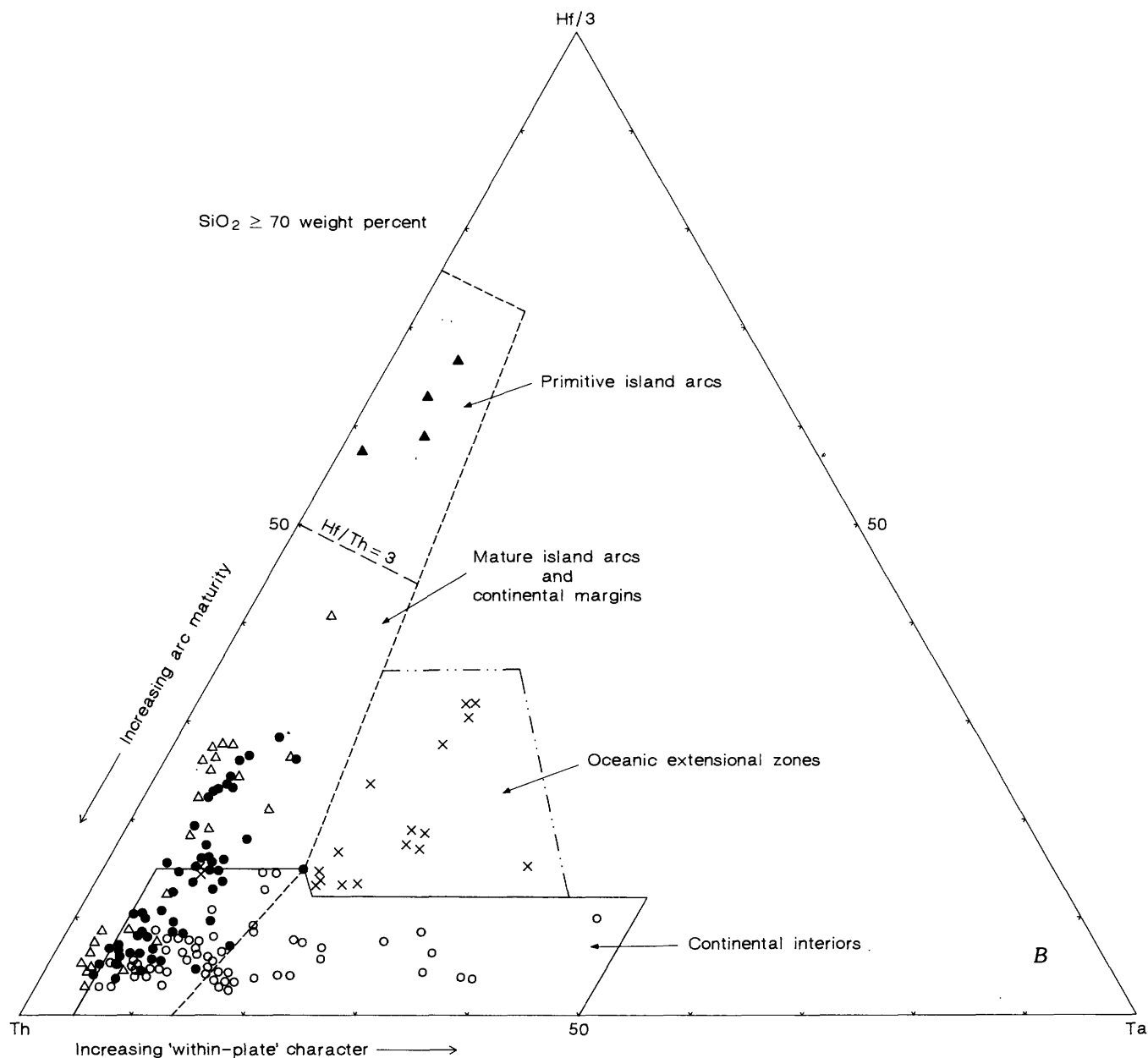


FIGURE 13.—Continued

By plotting Nb versus  $\text{FeO}_t$  (fig. 18) the boundaries between the obsidian fields can be estimated. There is a large overlap between the mature-island-arc and continental-margin types and between the continental-margin and continental-interior types, as shown on the Nb- $\text{FeO}_t$  plot. Allowing for that overlap, only four obsidians (two from the continental margin and one each from the continental interior and the oceanic extensional zone) plot outside their respective fields.

The combined use of the Nb-Ta, Nb- $\text{FeO}_t$ , Nb-Rb/Zr, and Th-Hf-Ta plots allows an accurate classification of the subalkaline rhyolitic obsidians

in terms of tectonic setting. The least satisfactory discrimination is between continental-margin and mature-island-arc obsidians, but, considering the similarity of the crustal materials, this is probably unavoidable in almost any chemical classification.

The plots may also be used to give a clearer indication of crustal type. It was noted earlier that rhyolites of the Brothers fault zone, Oregon, are chemically transitional between continental-margin and oceanic-extensional-zone types. We suggest that the underlying sialic crust might be substantially

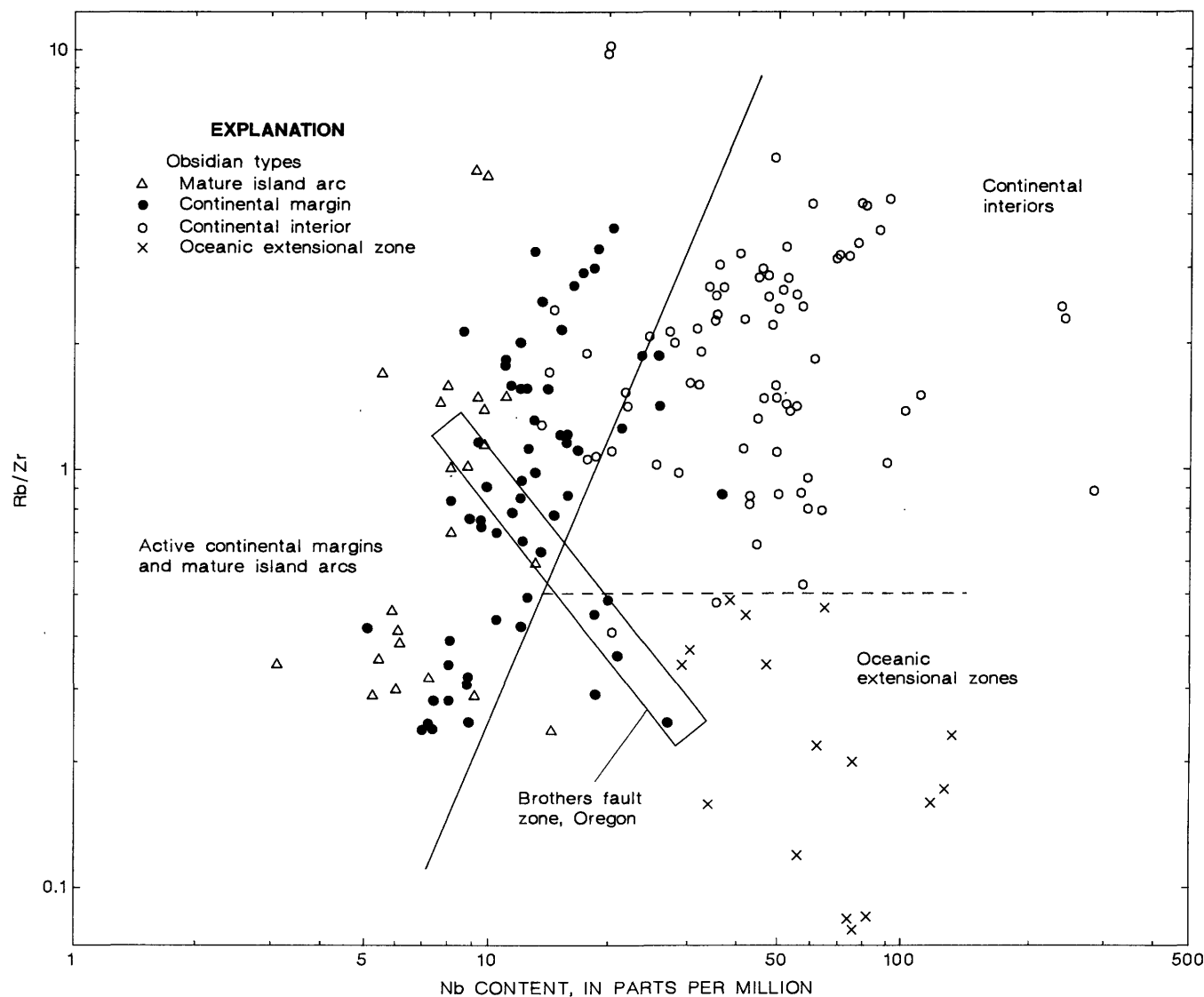


FIGURE 14.—Nb content versus ratio of Rb/Zr showing compositional fields of obsidians. Boundaries are arbitrary. Data from appendix I; sample 160 is omitted to preserve scale. Rectangle encloses obsidians of Brothers fault zone, Oregon. Rocks from primitive island arcs are omitted because of uncertainties of some Rb values.



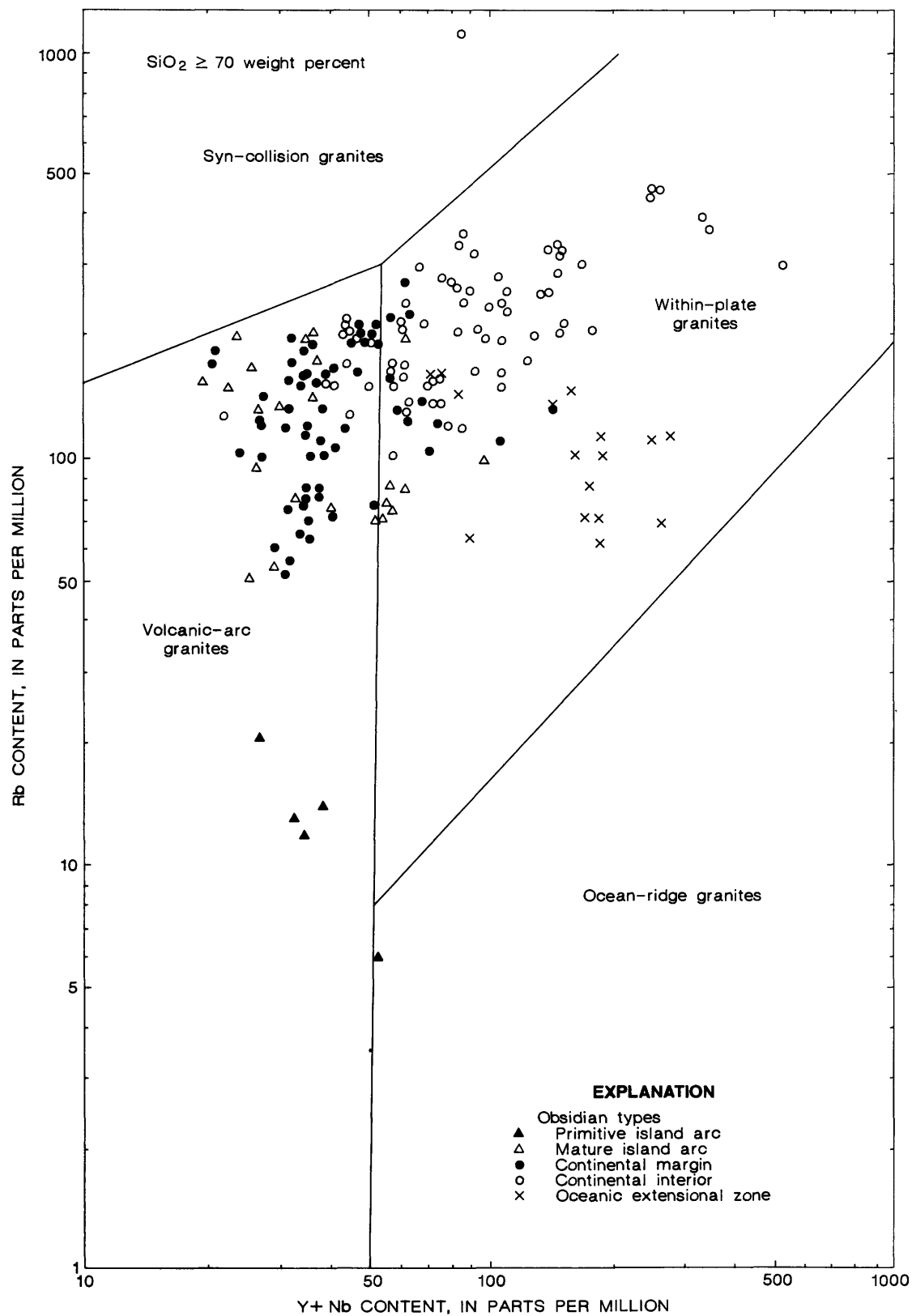


FIGURE 15.—Y+Nb content versus Rb content for obsidian groups on discriminant plot devised by Pearce and others (1984) for granites. Data from appendix I.

modified by the intrusion of mafic magmas. The multi-component nature of the obsidians is well shown on the Nb-Rb/Zr plot (fig. 14). Using the obsidian field boundaries from figure 18, a Nb-FeO<sub>t</sub> plot (fig. 19) shows that Salton Sea obsidians straddle the boundary between the oceanic-extensional-zone and continental-margin/continental-interior fields, consistent with their tectonic setting. The three Nevada specimens classified as continental-margin types (based on their location west of the craton and

affinity to Oregon subprovince types), although geographically in the continental interior, plot in the continental-margin field.

Rocks from the island of Mull in the British Tertiary province are used (fig. 19) to show the potential application to granites. The igneous centers of this province lie on mafic dike swarms, the activity possibly representing continental attenuation during aborted attempts to open the Atlantic Ocean. Many of the mafic rocks have been shown on isotopic

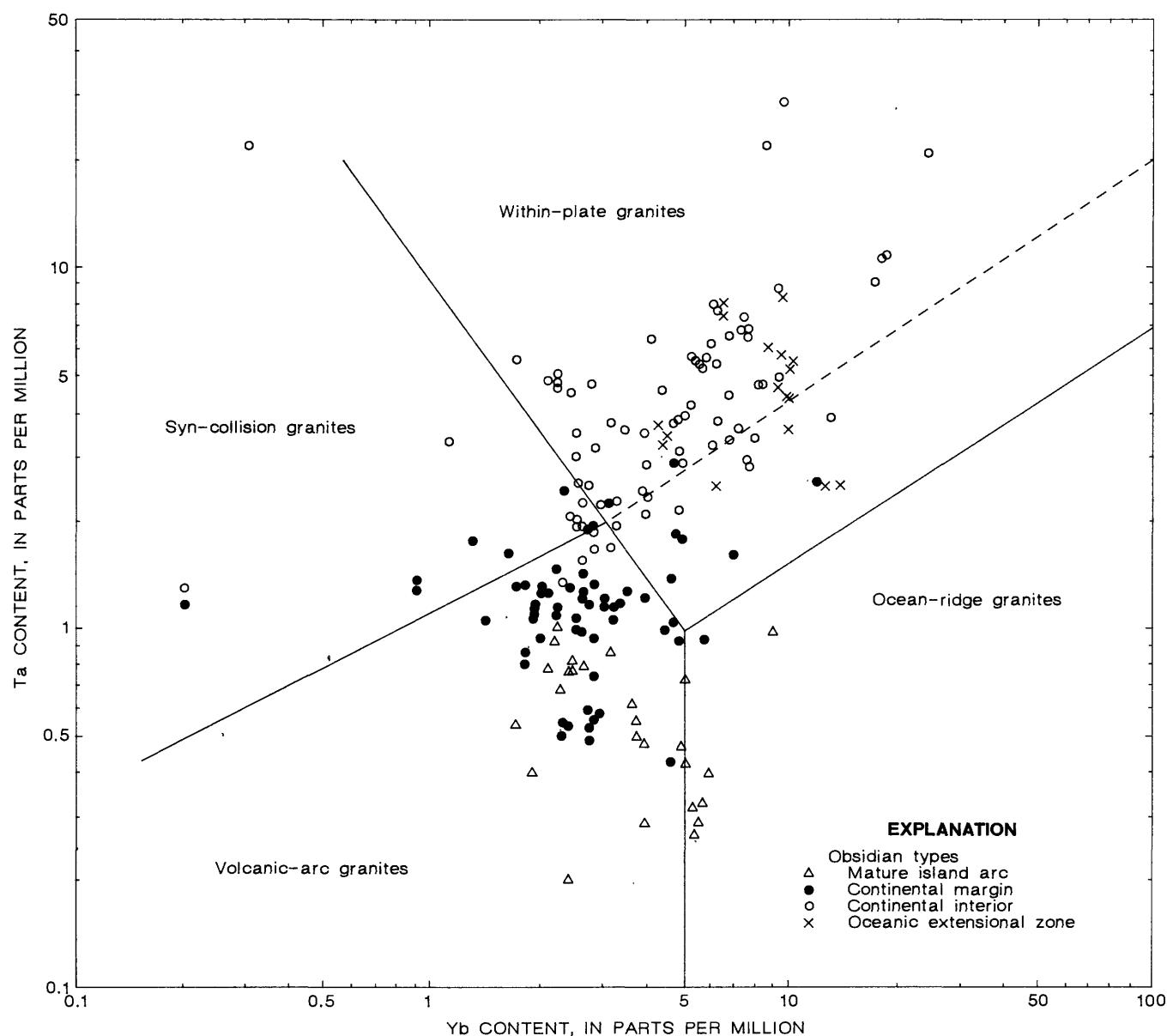


FIGURE 16.—Yb content versus Ta content for obsidian types. Fields were determined by Pearce and others (1984) for granites. Dashed line is upper compositional boundary for ocean-ridge granites from anomalous ridge segments. Data from appendix I.

and trace-element grounds to have been contaminated with Nb-poor, granulitic-facies rocks. The Mull granites straddle the oceanic-extensional-zone continental-margin boundary, consistent with derivation from mantle- and crustal-derived components.

The geological potential of these tectonomagmatic discrimination plots is considerable. For example, they

might be used to trace, via the silicic igneous rocks, the development of cratonic areas from island-arc terrains and to record periods of crustal attenuation and fracturing which may not be decipherable from structural, stratigraphic, or geophysical evidence. Such studies are complementary to isotopic studies, for example DePaolo and Farmer's (1984) regional survey

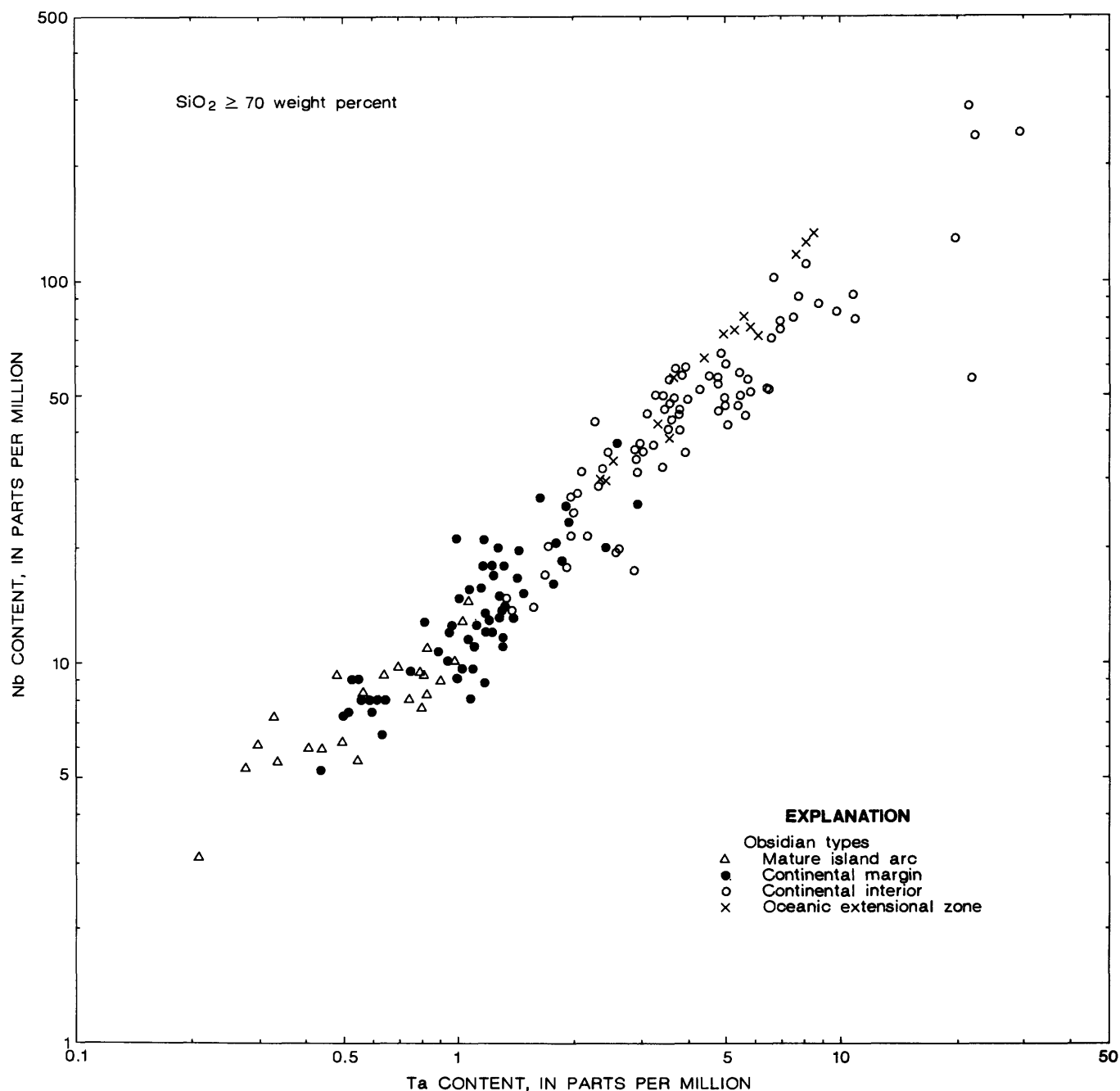


FIGURE 17.—Ta content versus Nb content in obsidians. These elements successfully distinguish subduction-related from within-plate types. Data from appendixes I and IV.

of initial Sr and Pb isotopic compositions of granitic rocks in the Western United States, which showed that magma sources can be inferred from the systematic geographical variability of the Nd data in particular.

#### GEOCHEMICAL FEATURES OF MAIN OBSIDIAN GROUPS

##### GROUP I: OBSIDIANS FROM PRIMITIVE ISLAND ARCS

There is a noticeable lack of data on obsidians from primitive island arcs. The only sample available to us was a partially hydrated pumice (No. 220, appendix II) from the South Sandwich Islands

(Gass and others, 1963). This rock is young, however, and its composition has probably been modified very little by hydration. Data are available in the literature for the residual glass of the Metis Shoal dacite (Melson and others, 1970; Ewart and others, 1973) and for recent pumices from Eua (Tonga) and Herald Cays, Queensland (Bryan, 1968, 1971). We have also made use in table 7 of apparently glassy specimens from Deception Island (Weaver and others, 1979) and Curtis Island, Kermadec Islands (Ewart and others, 1977), and of a partial analysis of an obsidian from Tafahi, Tonga (Smith and others, 1977).

To aid discussion, selected published analyses of devitrified and (or) secondarily hydrated rhyolites

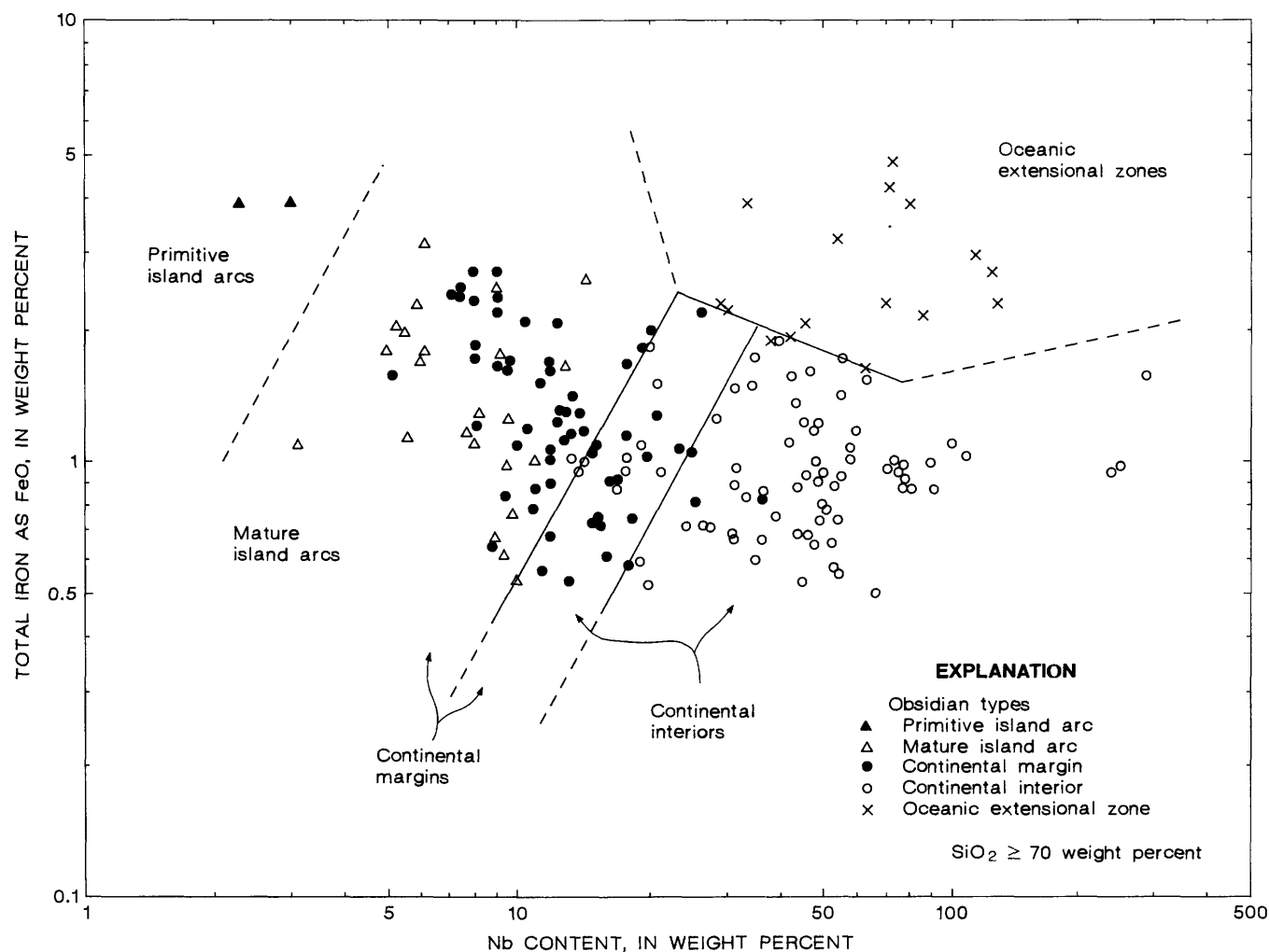


FIGURE 18.—Nb content versus total iron (as FeO) showing compositional fields of various obsidian groups. Fields were drawn by eye and dashed where uncertain. Note clear separation of continental interior from oceanic extensional zone types. Data from appendixes I and V (samples D and G).

are given in appendix V, but these have not been included in any computations or diagrams.

A further problem is that many critical elements occur in very low abundance in primitive-arc rhyolites, thus creating severe analytical problems. For example, we do not have satisfactory values for Ta in the South Sandwich pumice (No. 220).

The rhyolites share the diagnostic chemical features of the association, namely, low contents of  $K_2O$ , Nb, Rb, Ta, Th, and U. The values of 10 ppm Nb and 4 ppm Th obtained for Tafahi obsidian by Smith and others (1977) are probably too high. REE contents are low and the chondrite-normalized REE patterns are characteristically

flat, with Eu anomalies<sup>2</sup> either absent or small and negative. K/Rb ratios up to 1619 have been recorded from hydrated specimens, but such ratios almost certainly reflect Rb leaching. The relatively pristine rocks have a range of 385 to 781, which, although high in relation to other rhyolite groups, are in line with high K/Rb ratios in other members of the association (Baker, 1982). As noted by Donnelly and Rogers (1980), Th/U ratios are unusually low in these rocks, values less than 2 being common. Zr/Hf ratios are variable, four

<sup>2</sup>Eu anomalies are measured by  $Eu/Eu^*$ , where  $Eu^*$  is the chondrite-normalized Eu abundance calculated assuming a smooth REE pattern between Sm and Gd.

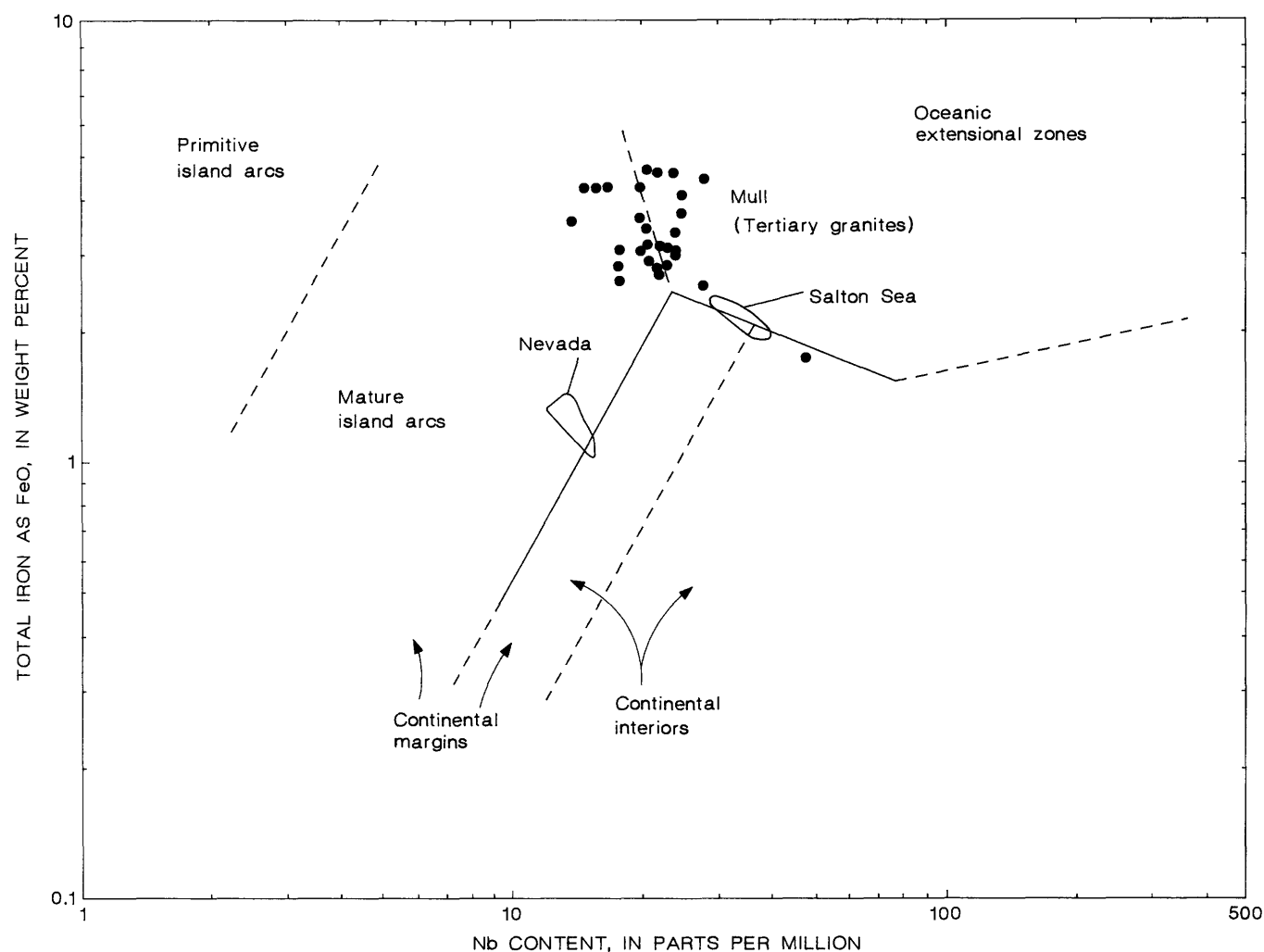


FIGURE 19.—Nb content versus total iron (as  $FeO$ ), with boundaries between obsidian fields taken from figure 18. Fields of Salton Sea and Nevada obsidian data from appendix I (samples 73–75 and 76–79, respectively).

Data for Mull granites from Walsh and others (1979). This plot illustrates the application of the Nb- $FeO$  diagram for additional insight into tectonomagmatic discrimination for specific data sets.

samples range from 36 to 68. Three of these are from Undu, Fiji, and vary from 41 to 68; however, analytical imprecision at low levels of Hf may be suspected. The values of Nb/Ta and Zr/Hf ratios in the rhyolitic magmas have not yet been established, although we have no reason to suspect that the Zr/Hf ratio (36) of our sample 220 is an abnormal ratio.

High SiO<sub>2</sub> values recorded from certain nonglassy rhyolites of this group are noteworthy; for example, on Undu, Fiji, values approaching 80 percent have been recorded (Gill and Stork, 1979). Petrographic evidence of silicification of many such specimens makes it clear that those high values are not magmatic. An upper magmatic SiO<sub>2</sub> limit for primitive-arc rhyolites has not yet been established.

Finally, an overall similarity of this group of rhyolites to oceanic plagiogranites has been recognized (Barker, 1979), though Donnelly and Rogers (1980, p. 353) claim that, in detail, there are important chemical differences between the two groups.

#### GROUP II: OBSIDIANS FROM MATURE ISLAND ARCS

Compared with primitive-arc types, the obsidians from more advanced stages of arc development have, on average, notably lower contents of CaO and FeO, and higher K<sub>2</sub>O, Ba, Cs, Hf, Nb, Rb, Ta, Th, U, and REE. Na<sub>2</sub>O/K<sub>2</sub>O and K/Rb ratios are lower and Th/U ratios higher, on average. The average Rb/Sr ratio is 0.90, seven to eight times higher than in primitive-arc rhyolites. The REE pattern shows distinct LREE enrichment, the Ce/Yb ratio averaging 11.5.

There is notable compositional diversity within the group, the most significant being the division into calcic and calc-alkalic types. The distinction is partly one of differing stages of evolution of individual suites and partly one of genuine intrasuite differences. Averages for both types of mature island-arc rhyolites are given in table 8. The lower K<sub>2</sub>O, Ba, Cs, Rb, Ta, Th, U, Zr, and LREE contents of the calcic varieties are noteworthy, and these rocks form a chemical, as well as spatial and time, transition between primitive-arc rhyolites and the calc-alkalic rhyolites of the mature-arc systems.

Another notable variant is the high-alkali type of island-arc rhyolite, such as those recorded from the Moresby Strait area, Papua New Guinea, by Smith and Johnson (1981). These have sufficiently high (Na<sub>2</sub>O+K<sub>2</sub>O) contents that they plot in the alkalic field of Kuno's (1966) alkali-silica diagram and are, in fact, broadly associated with peralkaline varieties.

Their trace-element chemistry unequivocally characterizes them as of mature island-arc type. Consider-

TABLE 8.—Average compositions of calcic and calc-alkalic obsidians from mature island arcs

[First figures in each column calculated using new data only (appendix I); second column using all data (appendices I, III), —, not determined]

	Calcic		Calc-alkalic	
	X	X <sub>T</sub>	X	X <sub>T</sub>
SiO <sub>2</sub> .....	73.4	73.4	75.6	75.3
Al <sub>2</sub> O <sub>3</sub> .....	13.54	13.55	13.04	13.10
Fe <sub>2</sub> O <sub>3</sub> .....	.59	.80	.40	.42
FeO .....	1.83	1.48	.99	1.00
MgO .....	.61	.64	.16	.20
CaO .....	2.38	2.63	1.10	1.09
Na <sub>2</sub> O .....	4.24	4.09	4.10	4.17
K <sub>2</sub> O .....	2.25	2.05	3.75	3.87
H <sub>2</sub> O <sup>+</sup> .....	.16	.41	.17	.27
TiO <sub>2</sub> .....	.39	.42	.18	.19
P <sub>2</sub> O <sub>5</sub> .....	.07	.11	.02	.05
MnO .....	.10	.09	.08	.07
Cl .....	.10	—	.11	—
F .....	.05	—	.05	—
FeO <sub>t</sub> <sup>1</sup> .....	2.37	2.55	1.35	1.38
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> .....	.76	.65	.71	.70
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> .....	2.15	2.27	1.13	1.11
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> .....	.70	.66	.83	.84
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> .....	1.01	1.01	.98	.99
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> .....	.37	.43	.14	.14
Cl/F <sup>1</sup> .....	2.0	—	2.2	—
Ba .....	521	—	664	—
Be .....	1.3	—	1.6	—
Co .....	3.2	—	.7	—
Cr .....	2.1	—	1.1	—
Cs .....	2.8	—	7.0	—
Hf .....	4.7	—	4.8	—
Li .....	27	—	27	—
Mo .....	2.4	—	2.3	—
Nb .....	7.0	—	8.4	—
Pb .....	16	—	21	—
Rb .....	50	—	127	—
Sb .....	.6	—	.8	—
Sc .....	12.5	—	5.0	—
Sn .....	1.4	—	2.0	—
Sr .....	183	—	111	—
Ta .....	.41	—	.65	—
Th .....	4.2	—	12.1	—
U .....	1.5	—	3.3	—
W .....	1.1	—	1.8	—
Y .....	35	—	30	—
Zn .....	41	—	38	—
Zr .....	139	—	169	—
La .....	15	—	23	—
Ce .....	32	—	46	—
Nd .....	19	—	22	—
Sm .....	4.5	—	5.1	—
Eu .....	.88	—	.73	—
Gd .....	4.1	—	4.8	—
Tb .....	.75	—	.84	—
Tm .....	.52	—	.55	—
Yb .....	3.7	—	3.8	—
Lu .....	.55	—	.56	—
Nb/Ta .....	17.1	—	12.9	—
K/Rb .....	374	—	245	—
Rb/Sr .....	.3	—	1.1	—
Ca/Sr .....	93	—	71	—
Th/U .....	2.8	—	3.7	—
Zr/Hf .....	30	—	35	—
Ce/Yb .....	8.6	—	12.1	—
Eu/Eu* .....	.62	—	.46	—
Maximum number of determinations	5	21	21	38

<sup>1</sup>By weight.

<sup>2</sup>Molecular.



able variations also exist in trace-element abundances in arc obsidians from different areas; for example, the Javan samples (Nos. 198–202) are relatively Cs-, Th-, and U-rich. Such features may be either source- or process-controlled and will be explained only after detailed future study of individual suites.

#### GROUP III: OBSIDIANS FROM THE CONTINENTAL MARGINS

Although obsidians of the continental margins are very similar to mature-island-arc obsidians, they do have somewhat higher average contents of  $K_2O$ , Ba, Li, Mo, Nb, Rb, Sn, Ta, Th, and U and lower Sc and Zn. K/Rb and Zr/Hf ratios are about the same, Nb/Ta, Ca/Sr, and Th/U ratios are lower, and Rb/Sr ratios higher. The REE patterns are also very similar but, on average, are more LREE-enriched and have a more pronounced negative Eu anomaly.

The continental-margin obsidians contain several chemically distinct subtypes. In the Western United States, for example, at least three such subtypes can be distinguished: (1) Cascades, (2) southeastern Oregon (east of the Cascade Range), and (3) Clear Lake. On a Sr-Th plot (fig. 20), they occupy minimally

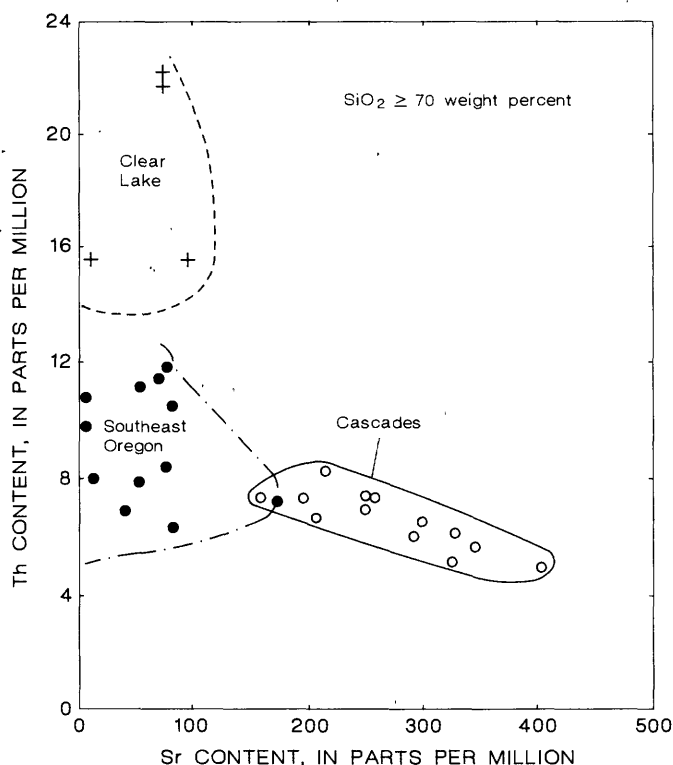


FIGURE 20.—Sr content versus Th content showing fields occupied by selected subgroups of obsidians of the Western United States continental margin. Data from appendix I. Specimens: Clear Lake, 45–48; southeastern Oregon, 22–28 and 30–34; Cascades, 8–10 and 12–21.

overlapping fields. Other distinguishing features include the higher Cs contents of the Clear Lake rocks and the relatively high Nb and Ta contents of many of the Oregon subtype specimens.

These differences are partly  $SiO_2$ -dependent; the chemical distinctions would be minimized at equivalent  $SiO_2$  contents. Partly also, they are related to tectonic setting. The Cascades volcanoes are genuinely subduction-related types, variably developing on thick prisms of Mesozoic geosynclinal sedimentary and volcanic rocks (for example, Lassen and Shasta) or on crust which is possibly partly of oceanic type (for example, Crater Lake and South Sister). The Oregon subtype rocks were erupted in extensional settings within the continental margin, in areas of thinned lithosphere which may be at least partly of oceanic type. Compositionally, they are a disparate set of rocks which contrast with other margin systems in having peralkaline associates. The Clear Lake complex is unique, situated on a transform fault within the continental margin; its relation between chemistry and tectonics, however, is obscure.

Minor- and trace-element compositions, with complementary Nd-Sr-Pb isotopic studies, of rhyolites within the continental margins will undoubtedly prove to be important tracers of crustal type and structure, but a full understanding of the mechanisms producing the chemical variations is not yet possible.

#### GROUP IV: OBSIDIANS FROM THE CONTINENTAL INTERIORS

Compared to the margin obsidians, the continental-interior rocks have markedly higher F, Be, Li, Mo, Nb, Rb, Sn, Ta, Th, U, W, Zn, and REE contents and FeO/MgO ratios and lower contents of MgO, CaO, Ba, Co, Sc, Sr, and Zr. This is the only group to have average  $Na_2O/K_2O$  and Cl/F ratios  $<1$ . The average Rb/Sr ratio is high (10), K/Rb ratio low (165), and the Zr/Hf, Th/U, and Nb/Ta ratios are lower than in continental-margin obsidians, indicating relative enrichment of the lower abundance element in each ratio. Though both LREE and HREE are higher than in margin types, the interior rhyolite pattern indicates considerably less LREE enrichment and a more pronounced negative Eu anomaly.

#### GROUP V: OBSIDIANS FROM OCEANIC EXTENSIONAL SETTINGS

Certain features of the oceanic-extensional zone obsidians are distinctive. The combination of high ( $Na_2O+K_2O$ ) and high CaO contents shown by

many specimens is rare among the other rhyolite groups. Values of molecular  $(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})/\text{Al}_2\text{O}_3$  (1.05–1.20) are among the highest in the data bank, and many rhyolites from this setting are actually peralkaline.

Notable also (table 7) is the combination of high Hf, Nb, REE, Ta, Y, and Zr with low abundances of Cs, Th, and U; the Cs values, in particular, are among the lowest in the data bank (fig. 21). Such ratios as Nb/Th and K/Cs also display these characteristics particularly well. In a gross way, the oceanic extensional rhyolites show low ratios of LIL/HFS (Large Ion Lithophile/High Field Strength) elements (Saunders and others, 1980), the main exception being that the LREE are relatively enriched, rather than depleted, in these rocks compared to other rhyolite groups.

Within the group, Johnson and others (1978) recognized that many of the geochemical features of the Icelandic rhyolites are shared by obsidians from St. Andrew Strait, Papua New Guinea. Certain differences also exist.  $\text{Al}_2\text{O}_3$  concentrations are generally not as low as in the Icelandic specimens, Cl contents are notably higher, REE are less enriched, and K/Rb ratios are higher.

Johnson and others (1978) also alluded to the similarities between the Icelandic and Salton Sea

rhyolites. There are new analyses of only three of the five small domes in the geothermal field, but the rapid-rock analyses of Robinson and others (1976) suggest that variation within the domes is small and that the new analyses are typical.

The major-element chemistry of the Salton Sea rocks is typically of group V type, but the trace elements are less similar. The Zr group of elements does not show the very high values, or the Rb group the low values, of the Icelandic rocks. The trace-element proportions are in many respects transitional between Icelandic and continental-margin types.

It is tempting to see the Icelandic-St. Andrew Strait-Salton Sea rocks as a sequence, where a "primitive" magma of Icelandic type becomes progressively contaminated with sialic crust, the amount of contamination approximately reflecting the proportion of continental crust in the tectonic setting. Such a mechanism would not by itself explain the lower HFS element concentrations in combination with increased contents of K-related elements, and more complex petrogeneses are indicated.

#### UNCLASSIFIED OBSIDIANS

Certain obsidians are sufficiently distinctive chemically to not readily fit into the classification scheme used in this paper. In terms of numbers of analyses, the most important of these occur in the Eolian arc, Italy. The arc has been interpreted (Barberi and others, 1974) as a complex zone of interaction between a marginal basin (Tyrrhenian abyssal plain) and a west-northwest-dipping subduction zone under the arc. The volcanoes are apparently developed on thin continental crust, itself perhaps underlain by a wedge of oceanic crust (Keller, 1982, fig. 2).

Obsidians from Lipari and Vulcano (Nos. 180–182) have distinctive compositions, notably extremely high concentrations of K-group elements (Rb, Cs, U, Th) in combination with high LREE, Nb, and Ta. The average Ce/Yb ratio is the highest of any of the rhyolite groups.

In terms of the classification of this paper, these Eolian rocks plot close to the boundary of the oceanic-extensional and continental-interior fields on critical compositional diagrams. Their chemistry seems, therefore, to reflect their transitional tectonic affinity between continental and oceanic settings, but superimposed on this is the regional effect of high K-group elements.

Obsidians collected from Monte Lentia, Vulcano (Nos. 322–325) also have unusual chemistry. The low

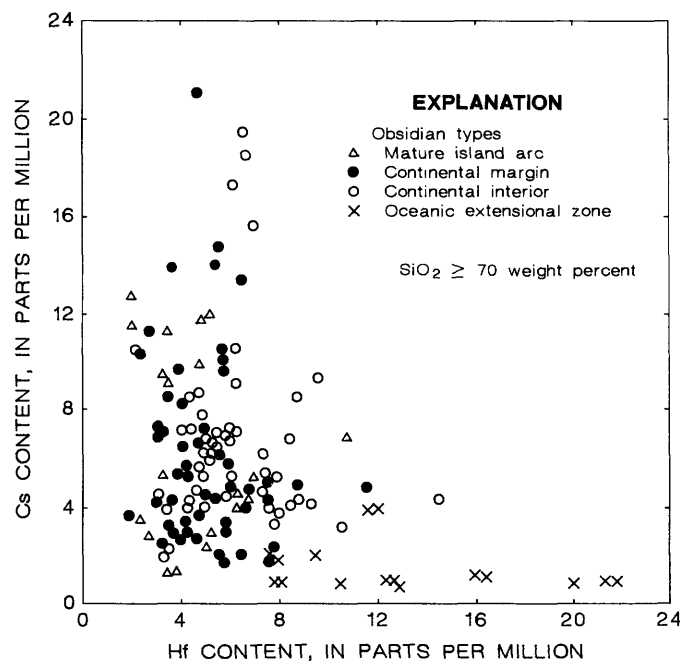


FIGURE 21.—Hf content versus Cs content showing Cs-poor (and relatively Hf-rich) character of obsidians of oceanic extensional zones. Data from appendix I.

abundances of  $\text{SiO}_2$  and high  $\text{FeO}$ ,  $\text{MgO}$ , and  $\text{CaO}$  are comparable to the calcic obsidians of mature island arcs, but the high  $(\text{Na}_2\text{O}+\text{K}_2\text{O})$  content and low  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratio are not. The low  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratios and high  $\text{MgO}$  contents distinguish them from rhyolites of oceanic extensional zones. Unfortunately, trace-element data are unavailable to allow a full characterization of these interesting rocks.

Obsidian blocks of uncertain derivation found on Mont Manengouba, Cameroon (Tchoua, 1970) also have a unique chemistry (No. 337); low total alkalis relative to  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  yield the highest value of normative corundum in the data bank, and this sample has a high normative ratio of quartz: (orthoclase+albite). This unusual rock clearly has an unusual petrogenesis, and trace-element and isotopic study would be meaningful. An obsidian from Garove Island in the Bismark Sea (No. 364) has "mixed" chemical features. The low concentrations of Ba, Cs, Pb, Rb, and Th, the high  $\text{FeO}$ , and  $\text{CaO}$  contents and K/Rb ratios, and the relatively unfractionated REE pattern ( $\text{Ce}_N/\text{Yb}_N=1.57$ ;  $\text{Eu}/\text{Eu}^*=0.76$ ) resemble features of rhyolites from primitive island arcs (app. V).  $\text{Na}_2\text{O}$  content (5.7 percent), however, is very near the maximum (5.93 percent) recorded in the data bank; Nb, Zr, and Hf concentrations are higher than in other primitive-arc rocks.

## MAGMATIC DIFFERENTIATION PROCESSES IN SILICIC SYSTEMS

### INTRODUCTION

No single differentiation mechanism can be generally applicable over the whole evolutionary history of a silicic complex; different mechanisms probably dominate at different stages. Hildreth (1977) and Pitcher (1979, p. 638) provide the following summary of mechanisms effective at different stages: (1) During partial melting and coalescence: establishment of crystal-liquid equilibrium; (2) during ascent and high-level emplacement: re-equilibration between liquid and crystal fractions and the removal of the Ca, Fe, and Mg in mafic mineral clots; (3) in the resulting high-silica caps to plutons (the potentially caldera-forming magma chambers): diffusive exchange during roofward concentration of dissolved volatiles presumably by coupled convective-diffusive internal transport; and (4) during consolidation: re-establishment of crystal-liquid equilibria, effected both by convection-aided marginal accretion of phenocrysts and by diffusion,

with vapor-transport becoming significant in the latest stages.

To these may be added the effects of wall-rock contamination before and after magma emplacement, and of the possibility of magma mixing during any except the latest stages of pluton consolidation. It should also be stressed that the above mechanisms are not exclusive to any particular evolutionary stage, nor are they mutually exclusive.

Obsidians represent melts expelled from magma chambers at different stages of evolution and undergoing different genetic mechanisms. The relative importance of such mechanisms varies, not only with evolutionary stage, but with the type of system (Smith, 1979; Hildreth, 1981). The chemistry of the rhyolites is the only means by which the evolutionary stage of the magma reservoir in many volcanic fields may be judged. This in turn determines our ability to predict the reservoir's future development. An important goal, therefore, is to link rhyolite chemistry to genetic mechanism. In this section, brief notes are made of the types of chemical evidence used to fingerprint the effects of the major differentiation mechanisms.

The processes believed operative in silicic magma chambers are crystal-liquid fractionation, magma mixing, wall-rock reaction, vapor-phase transfer, and thermogravitational diffusion. The last process was proposed, and briefly discussed, by Shaw and others (1976) as an alternative to crystal fractionation to explain the strong trace-element gradients that sometimes occur in the tops of magma chambers, usually with rather limited variations in major-element compositions. The development of the concept as it applies to silicic magmas is due mainly to Hildreth (1979, 1981) and Mahood (1981a, b). This process, popularly known as TGD, is still not well understood, a point acknowledged by Mahood and Hildreth (1983, p. 11). It involves not only convection-aided diffusion within magmatic liquids but also volatile complexing under volatile oversaturated and undersaturated conditions.

The TGD concept has been criticized by several workers. Michael (1983), Miller and Mittlefehldt (1984), and Baker and McBirney (1985) argue that compositional zonation of the type seen in the Bishop Tuff can be generated by fractionation of crystals at the sidewalls of magma chambers, with convective uprise of the lower density, residual liquids toward the roof zone of the chamber. Walker and others (1981) and Leshner and others (1982) present experimental evidence to show that Soret diffusional gradients for many elements run

counter to those ascribed to TGD in the natural magma chambers.

The fact that some process, or combination of processes, other than crystal fractionation has acted to differentiate the upper parts of many silicic systems can hardly be doubted (Smith, 1979; Hildreth, 1979, 1981; Bacon and others, 1981; Mahood, 1981a, b; Crecraft and others, 1981). However, it is premature in a descriptive geochemistry paper to classify all highly fractionated obsidians as solely the products of TGD, as presently understood, or of any other single genetic mechanism.

We distinguish chemically two broad groups of obsidians. One group has compositional variations which are judged on the basis of comparison with whole rock-separated glass pairs and trends in granitoid plutons to have been generated dominantly by crystal-liquid processes, such as crystal fractionation, restite separation, and partial melting of source rocks and chamber walls under conditions of low halogen activity. Magma mixing is a minor but common differentiation mechanism also. We refer to these rocks as CLPD compositions (that is, formed where crystal-liquid processes dominated).

The second group is systematically different, chemically, from the first and shows chemical variations comparable to those recorded in some voluminous, silicic ash-flow tuffs. The petrogenesis of these rocks has not been fully resolved but probably involves interplays of crystal fractionation, wall rock reactions, vapor-phase transfer, magma mixing, and various liquid-state differentiation mechanisms, such as volatile complexing. Although such compositions may be generated in the uppermost parts of large magma chambers, they may also result from the direct partial melting of crustal rocks under conditions of high halogen fugacities, a process probably akin to the volatile fluxing mechanism of Bailey (1970, 1974, 1980), Bailey and Macdonald (1970, 1975), and Macdonald and others (1970). We refer to such rocks as the result of a complex interaction of petrogenetic processes (CIPP).

We shall show below that it is not possible to define precisely CLPD and CIPP compositions. These vary between systems and with time within the same system. Some experience with the data base is required to appreciate fully the systematics of rhyolite geochemistry and to apply the terms CLPD and CIPP to individual specimens. Much of the following discussion is preliminary, but it is felt to be an important step toward maximizing the usefulness of the systematic, element-by-element treatment of the final section.

## RELATIVE ROLES OF CLPD AND CIPP

### SOME TERMS

Our usage of the terms "base-level magmas," "base-level liquids," and "real, total, and apparent fractionation factors" may be described with reference to an evolving silicic magma chamber, where a high-silica cap differentiating by CIPP lies above a dominant magma volume, of quartz latitic or rhyodacitic composition. Nb is used as a monitor element to describe the system's chemical evolution and is assumed to have a solid-liquid partition coefficient of zero.

Note that there is no specific composition, volume, or degree of crystallinity of base-level magmas: these vary between magmatic systems and with time in single systems. They can be defined only rather vaguely as the magmatic condition immediately prior to onset of CIPP. The hypothetical system is assumed to have evolved by CLPD to a state where the magma is substantially crystallized, in this case 50 percent (fig. 22). This magma is the *base-level magma* (with a given Nb content of 10 ppm).

As the base-level magma fractionated, a cap of nonporphyritic liquid overlying a crystal-rich bed was produced. As the result of 50 percent crystallization of base-level magma (and the zero solid-liquid partition coefficient for Nb), the nonporphyritic cap contained 20 ppm Nb presumably formed by CLPD. This nonporphyritic magma is the *base-level liquid* which existed in the magma chamber at time  $t_1$ . (The interface between the crystal-rich layer and the base-level liquid is variably sharp: in some systems, a sharp interface will be shown as a notable composition gap (Smith, 1979) in the erupted products; in some others, a transitional passage will reveal no compositional hiatus. In CLPD systems, notable  $\text{SiO}_2$  gaps are common, whereas in CIPP systems, with high-silica magma, minor element gaps are more likely to be observed.)

Subsequent CIPP differentiation builds up the concentration of Nb in the most fractionated top of the silicic cap to 60 ppm (point X at time  $t_2$ , fig. 22). Eruption occurs, tapping the magma chamber along the path X-Y. As recorded in the eruptive products, the Nb fractionation factor is 2. However, this is an *apparent fractionation factor* because the full compositional range for CIPP fractionation (20–60 ppm Nb) was not tapped during the eruption. The *real fractionation factor* relative to the base-level liquid, between times  $t_1$  and  $t_2$ , is 3, whereas the *total fractionation factor* relative to the base-level magma is 6.

Along path Y-Z, the system regenerates the compositional gradients, reaching a maximum Nb of 55 ppm. A second eruption occurs, this time tapping deeper in the chamber into the crystal-rich layer (Z-P). The apparent fractionation factor is now 3.7, higher than that in the first cycle, despite the lower real fractionation factor. These factors are therefore critically dependent on the balance between the extent of drawdown and the concentration gradients established between eruptive episodes.

Determining base-level liquid and base-level magma compositions may be exceedingly difficult. Multicyclic systems may or may not tap base levels.

A further complication is that in multicyclic systems, removal of high-silica fractions must inevitably result in up-element<sup>3</sup> depletions at or near the liquid crystal-rich layer interface, such that base-level compositions change with time.

In general, only detailed reconstruction of the histories of individual systems will allow the recognition

<sup>3</sup>Studies of compositionally zoned ash-flow sheets have shown that during differentiation of the roof zone magmas, some elements (for example, Rb, Ta) concentrated upwards into lower temperature melts, while others (for example, Ba, Sr) concentrated in higher temperature liquids of deeper levels. They are conveniently referred to as up-elements and down-elements, with no implication as to the genetic mechanism. Note that some elements (for example, Mn, Sc) can be either up- or down-elements, depending on the affinity of the magmatic system.

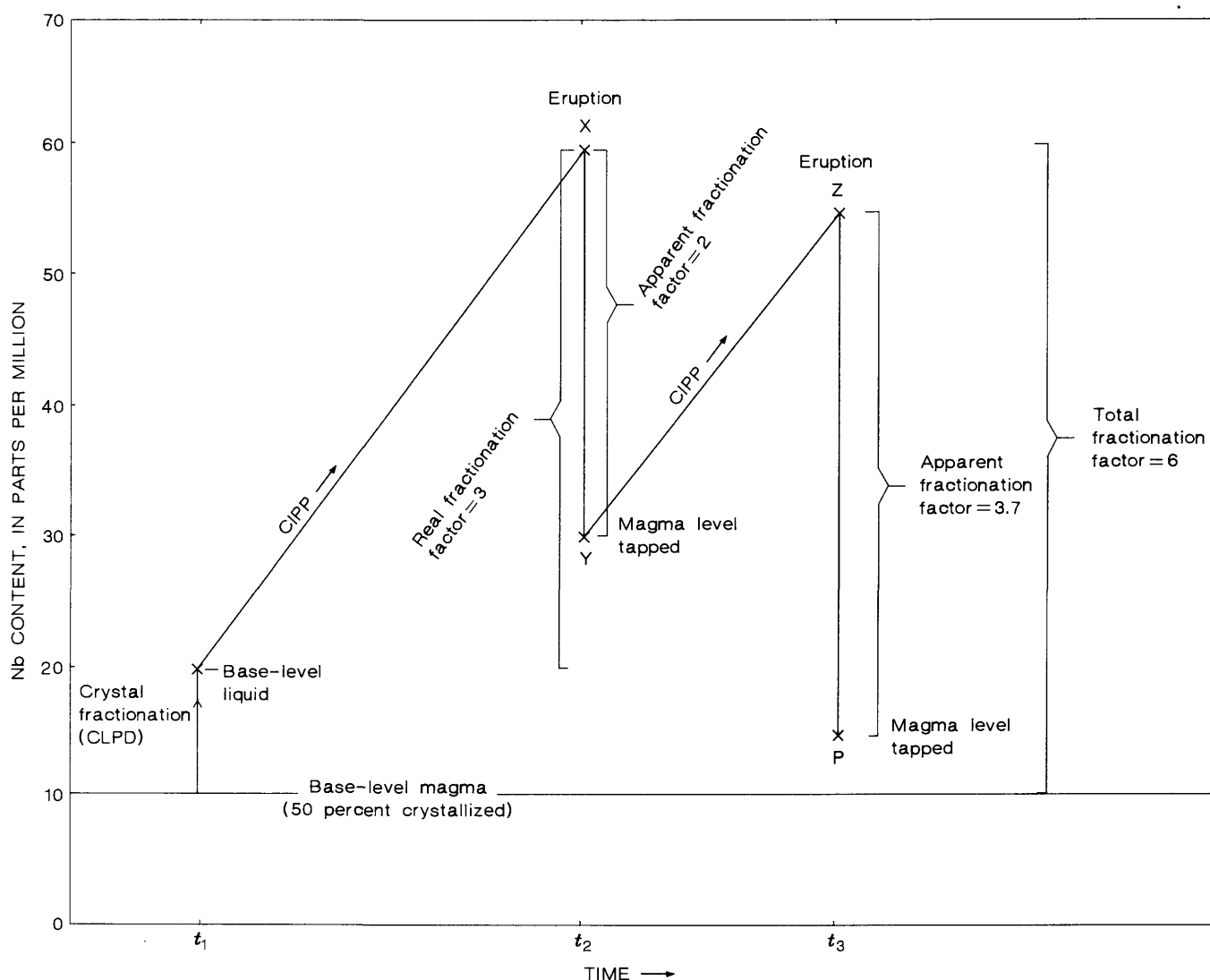


FIGURE 22.—Nb evolution, by CLPD and CIPP, in upper part of silicic magma chamber, showing base-level liquid and real, total, and apparent fractionation factors. See text for discussion of system along path denoted by arrow and at points X, Y, Z, and P.

of base-level compositions. Such an approach is clearly impossible in volcanic fields of isolated rhyolitic domes or of bimodal basalt-rhyolite systems. For many, probably most, silicic systems, base-level liquid and base-level magma compositions lie variably within the field of crystal-liquid processes. In others, base-level liquids, in the sense of being the most primitive in the system, may actually have CIPP compositions.

It is relevant to note, at this point, certain other factors which bear on the determination of enrichment factors in CIPP systems. First, they are very dependent on the quality of the analytical data. As an example, consider a system in which Sn abundances for top and bottom magmas are 12 ppm and 1 ppm, respectively, but which are reported as 10 ppm and 1.5 ppm, respectively—deviations from the true values not atypical in our experience. The real enrichment factor for the system is 12 ( $12/1=12$ ), the reported factor 6.7 ( $10/1.5=6.7$ ).

For certain elements, particularly those prone to secondary hydration, the problems of establishing real enrichment factors may be related not only to possible analytical imprecision but to sample quality also. Consider a zoned magma, erupted as an air-fall ash-flow sequence, which originally had top and bottom F abundances of 2,000 and 200 ppm, respectively (real enrichment factor=10). The sequence becomes hydrated after eruption, such that the most differentiated sample available is an air-fall pumice which loses 50 percent F (1,000 ppm). The "bottom" sample is a hydrated glass which loses only 20 percent F (160 ppm). Although F variation in the sequence appears to be systematic, the observed enrichment factor (6.3) is much lower than the real factor (10).

Considering all the problems, we urge great caution in the establishment and interpretation of enrichment factors in zoned systems. In particular, any petrogenetic conclusions based on the similarity or dissimilarity of elemental enrichments must be based on data known to be highly precise and on elements known to have preserved original magmatic abundances.

#### DIFFICULTIES OF RECOGNIZING CIPP MAGMA COMPOSITIONS

The steep trace-element gradients which characterize CIPP are normally found when  $\text{SiO}_2$  contents exceed 74 percent (Hildreth, 1979). It is tempting to suppose that these systems are approaching a natural minimum melting composition, where differentiation by crystal-liquid processes is inefficient, and other mechanisms become predominant. However, the rec-

ognition of probable CIPP effects in peralkaline magmas (Noble and others, 1979; Mahood, 1981a, b) indicates that no single minimum composition can be applicable over the whole spectrum of rhyolite chemistries. In fact, CIPP may not be restricted to silicic systems. Detailed search may reveal its operation in intermediate or even mafic magmas.

The critical factors determining the composition at which the dominant fractionation process changes are not known but may include any or all of the following: Bulk composition of the system, melt structure, volatile species and their activities, and magma dynamics. Detailed studies of many more relevant systems are required to assess the importance of each variable and, in particular, the CLPD compositions in each system must be identifiable.

CLPD compositions differ in magmas of different affinity. Thus, a CLPD liquid at 76 percent  $\text{SiO}_2$  in an island-arc volcano may contain 10 ppm Nb, in a continental-interior volcano 3 times as much. Even though both systems may subsequently experience similar CIPP fractionation histories, the factor of 3 difference in absolute Nb abundances will be maintained. Note that in figure 23 the Nb content of the

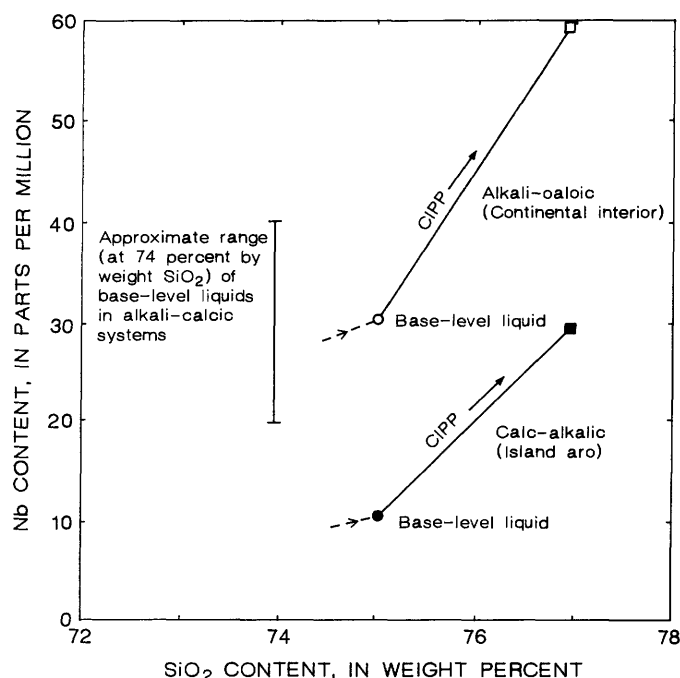


FIGURE 23.— $\text{SiO}_2$  content versus Nb content showing relation between fractionation (enrichment) factors and magmatic affinity of system for proposed CIPP fractionation. Arrows indicate direction of enrichment; squares indicate maximum enrichment for given systems.



most strongly differentiated arc rock equals that of the CLPD continental-interior liquid. *It must be emphasized that the arc system has become more evolved than the interior and that the absolute concentration of an element in silicic systems is a function of both the degree of evolution and the base-level compositions. A rock with low concentrations of lithophilic elements may be quite highly evolved.*

A further complication is imposed by variable source rock compositions. There are real variations in minor- and trace-element chemistry resulting from geographical location even within systems of equivalent major-element chemistry in the same tectonic setting. Thus, in the continental interior of the United States, CLPD silicic magmas may show, at equal  $\text{SiO}_2$  contents, variations of more than a factor of 2 in Th and U abundances.

#### CRITERIA FOR THE IDENTIFICATION OF CIPP COMPOSITIONS

A critical problem is how to distinguish chemically those rocks which have evolved dominantly by crystal-liquid processes from those which are CIPP controlled. Though end-member compositions are fairly easily recognized, it may, in fact, be difficult to distinguish mildly fractionated compositions unless they are part of a suite of compositions where the chemical trends and gradients support the CIPP concept.

Hildreth (1979, p. 71) suggests: "The most easily obtained indications that the thermogravitational process has become dominant in a rhyolitic chamber are increases in the Na/K ratio and the Mn concentration of successive eruptive products, and impoverishment of Ba, Sr, P, and Mg to levels lower than 100 ppm each."

Such an approach is less viable in areas of isolated rhyolitic extrusive rocks where sequences of composition are unknown. Here an absolute indicator of CIPP is required. It follows from the foregoing discussion that absolute concentrations of elements are not entirely satisfactory because of intersuite variability and the consequent overlapping of base-level compositions. Elemental ratios and REE characteristics prove to be more useful. Hildreth's (1979) criteria for thermogravitational processes (TGD) can be expanded to suggest, therefore, that subalkalic rocks fractionated by CIPP will have, among other things, very low Ba, Sr, P, and Mg contents, gentle to flat REE patterns with prominent Eu anomalies, low K/Rb and Zr/Nb ratios, and relatively high  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratios. Some of these features may be combined to provide a fingerprint of the process.

One attempt to define the relevant compositions of CIPP rock is shown in figure 24. It utilizes the observation that extreme depletion of Eu and the development of low K/Rb ratios characterize the CIPP process. A rather arbitrarily defined band separates rocks suspected of having been part of a CIPP system at some stage in their evolution from those for which a crystal-liquid control only is more tenable. The trend lines for the Bandelier and Bishop Tuffs cross the boundary and serve to stress that this diagram is, in reality, defining a compositional limit for crystal-liquid only processes. Rocks from the higher temperature parts of certain CIPP systems overlap CLPD rocks compositionally; definitive criteria to separate these are not yet available.

#### APPLICATION TO THE WHOLE BODY OF OBSIDIAN DATA

If crystal-liquid processes alone cannot adequately explain the chemical variations in the Bandelier and Bishop Tuffs, then it may be assumed that they are equally untenable for any comparable silicic magmas. Consider the data for the Quaternary rhyolite domes of the Coso Range, California (Bacon and others, 1981). On a K-Rb diagram (fig. 25), averaged compositions for groups 3 to 7 of the domes form a trend parallel to, and intermediate between, the generalized Bandelier and Bishop trends,<sup>4</sup> a position consistent with their intermediate magmatic affinity and intermediate tectonic setting at the epicontinental margin. The other chemical data, for the Coso rocks, show trends and gradients closely comparable to those in the Bandelier and Bishop sheets, and the differentiation processes were probably similar. Bacon and others (1981) concluded that the Coso rhyolites represent episodic leaks from a magma chamber (or chambers) evolving by thermogravitational diffusion, a conclusion we now would cautiously change to control by CIPP.

The analogy may be extended to all the obsidians. Those plotting close to the CIPP trends on a K-Rb diagram and having the other relevant chemical characteristics are considered to represent CIPP magmas. Those plotting in the CLPD field have evolved either by crystal fractionation of a more mafic parent or by crustal anatexis. Magma mixing,

<sup>4</sup>In this and subsequent plots, these trends are taken to be linear between the end-member compositions. In detail, for many elements, the trends are not truly linear. This simplification does not affect the main purpose of employing the trends—to show the compositional ranges and gradients of established CIPP systems.

vapor-phase transport, and contamination by wall rock may proceed in either field.

There is considerable overlap between the two main fields not only on a K-Rb diagram but using any chemical parameters. Experience can commonly tell whether rocks in the area of overlap are CIPP or CLPD compositions, but only detailed knowledge of the evolution of the relevant magmatic system can provide a more objective assessment.

The compositional ranges and averages for CLPD and CIPP obsidians of the continental margins and interiors are presented in table 9, and specimens being classified are listed in table 10. Important features of the averages include the following.

1. Average abundances are higher in CIPP than in CLPD rocks for F, Be, Cs, Li, Nb, Pb, Rb, Sb, Sn, Ta, Th, U, W, Y, Zn, and HREE and for  $\text{SiO}_2$  in the continental-margin group.

2. Average abundances are lower in CIPP than in CLPD rocks for  $\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{TiO}_2$ ,  $\text{P}_2\text{O}_5$ , Ba, Co,

Sc, Sr, Zr, LREE, and Eu, and for  $\text{Al}_2\text{O}_3$  in the continental-margin group.

3. Average abundances are about the same in CLPD and CIPP rocks for MnO, Cl, Hf, Mo, and for  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{K}_2\text{O}$  in the continental-interior group.

4. The element behavior indicated by the averages may not reflect that, in individual silicic CIPP systems, elements including Fe, Sc, and Zr may behave as upward-concentrating elements.

5. Average ratios of Zr/Hf, K/Rb, Ce/Yb, and Eu/Eu\* are lower and Ca/Sr and Rb/Sr ratios higher in CIPP compared to CLPD rocks for both groups.

6. The higher  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratio in CIPP continental-interior obsidians compared to CLPD types from the same group mirrors the behavior of the ratio in individual CIPP systems. The lower ratio in CIPP margin rocks relative to equivalent CLPD rocks is probably anomalous, due to the relatively potassic nature of certain of the available CIPP systems (for example, Nos. 33, 48, 49, 50).

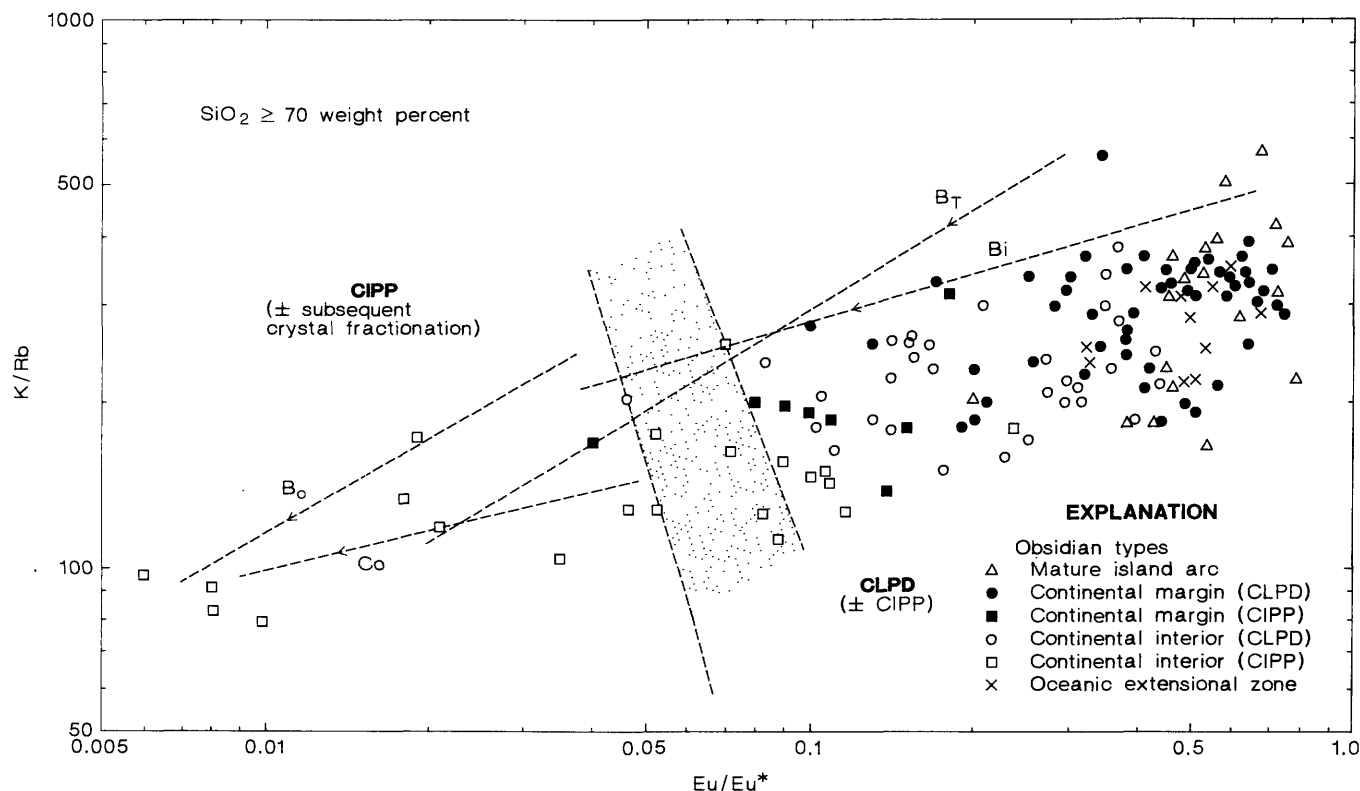


FIGURE 24.—Ratio of Eu/Eu\* versus ratio of K/Rb showing relation between composition and dominant genetic processes. Data from appendix I. Positions of the Bishop Tuff (Bi) and Coso rhyolite (Co) trends at lower values of Eu/Eu\* are estimated due to uncertainties in Eu determinations. B<sub>T</sub> and

B<sub>o</sub> are generalized trends for the Tshirege and Otowi Members of the Bandelier Tuff, respectively (R.L. Smith, unpub. data). Arrows indicate direction of liquid fractionation. Shaded band designates arbitrary and flexible field boundary. See text for discussion.

7. The lower average Nb/Ta and Th/U ratios in CIPP interior obsidians again match behavior in individual systems. When more data are available, similar lower averages will probably be found for CIPP margin rocks.

#### MAGMA MIXING AND ASSIMILATION

Well-known examples of magma mixing in silicic systems include Novarupta, Valley of Ten Thousand Smokes (Fenner, 1923), the composite rhyolite-dacite flow on Big Glass Mountain, Medicine Lake Highlands (Anderson, 1933), the obsidian flow at Borax Lake, Clear Lake (Anderson, 1936; Bowman and others, 1973), and the Inyo Craters (Bailey and others, 1976). It is being increasingly recognized, however, that magma mixing is probably ubiquitous in silicic systems (Smith, 1979). For example, casual examination of Western United States obsidian flows reveals

the almost universal presence of mafic inclusions, some of which represent quenched basaltic or andesitic magmas (R. Smith, personal observation). Such inclusions are also commonplace in the silicic members of island-arc volcanoes.

They are not, however, restricted to subduction-related systems. Mafic inclusions have been reported from the Mineral Mountains, Utah (Lipman and others, 1978), and the Coso Range, California (Bacon and Metz, 1984). Magma mixing is also an important function of Icelandic systems (Sparks and others, 1977; Sigurdsson and Sparks, 1981).

Other silicic flows may carry xenoliths of mafic to intermediate rocks which represent fragments of preexisting flows. These occur in varying stages of disaggregation and have had the potential to contaminate the silicic host to varying degrees.

Several samples analyzed in this report carry megascopically or microscopically recognizable xenoliths of basalt, andesite, or dacite. Listed by

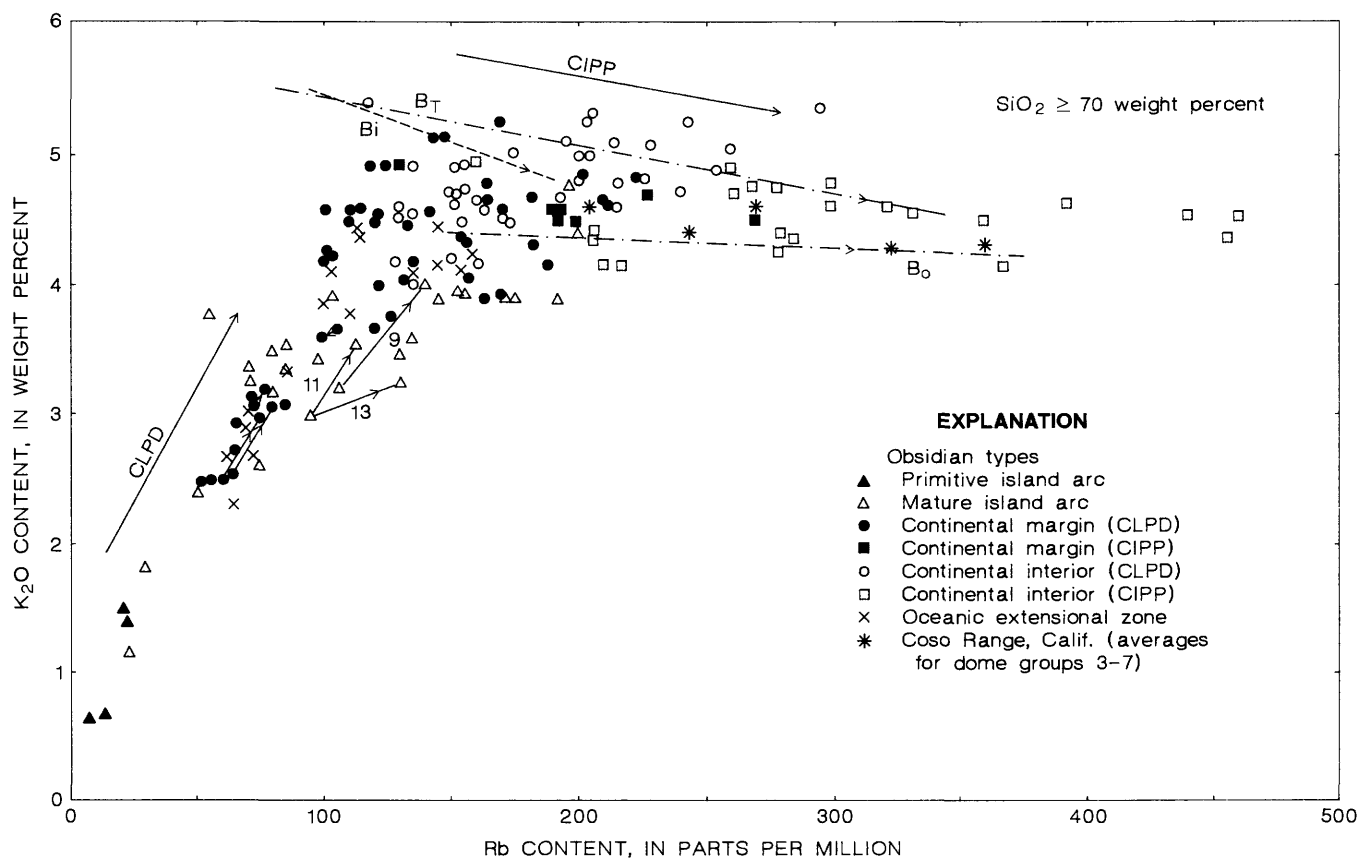


FIGURE 25.—Rb content versus  $K_2O$  content showing fields occupied by CLPD and CIPP silicic obsidians.  $B_T$  and  $B_o$  are generalized trends for the Tshirege and Otowi Members of the Bander Tuff, Valles Mountains, New Mexico, respectively (R.L. Smith, unpub. data);  $B_i$ , Bishop Tuff, California (Hildreth, 1979,

1981). Data from appendixes I and V (samples A, B, D, F, and G). Specimen 160 has been omitted to preserve the scale. Coso Range data from Bacon and others (1981). Solid tielines connect bulk rock-glass pairs; arrows point toward glass separate. Numbered tielines are data for Taupo, New Zealand (Ewart and others, 1968).

tectonic setting, they are (sample number in parentheses):

Mature island arcs

Umnak, Alaska (2, 242)

Nagrek, Java (199)

Mount Toduku and Mount Alon, Halmahera (205, 208)

Continental margins

Novarupta, Alaska (3, 243, 244)

Big Glass Mountain, Medicine Lake (42, 43, 269–273)

Orijana Canyon, Oregon (33)

Borax Lake, California (48, 281)

Inyo Craters, California (51, 283, 284)

Wadatoge, Japan (188, 346)

Continental interiors

Huckleberry Ridge Tuff, Yellowstone (89)

Ammon Tuff, Idaho (84)

Walcott Tuff, Idaho (85)

Oceanic extensional zones

Askja, Iceland (176)

Vatnajökull, Iceland (319)

Domadalshraun, Iceland (174)

Alcedo, Galapagos (158)

The specimen from Vulcano, Italy (182), also carries xenolithic fragments.

Samples 33, 84, 85, and 89 are welded tuffs, and the inclusions they carry are almost certainly accidental. Using data for the other rocks and for the mixed-magma series noted above, it is possible to examine the role of contamination in causing chemical diversity in the silicic obsidians.

Magma-mixing series will give straight-line trends on a two-axis, linear graph, whose slope and position are dependent on end-member compositions. Data for three mixed series are shown in figure 26. The nonlinearity of the Novarupta and Glass Mountain trends indicates either analytical error or the presence of a differentiation factor other than mixing; for example, phenocryst and (or) xenocryst redistribution. Nevertheless, the trends show that magma mixing can produce variations of similar magnitude to crystal-liquid effects, at least in terms of major elements.

Because rhyolitic magmas will, in general, mix with higher temperature magmas of the same series, the chemical variations produced will tend to mimic crystal-liquid trends. Recognition of the operation of magma mixing in single obsidian samples on purely chemical grounds is thus extremely difficult. One rock in which it may have occurred is an obsidian from White Mountain, Utah (No. 96, app. I). This rock has the chemical characteristics

of a CIPP, continental-interior rhyolite, except for high MgO, CaO, Co, and Cr, consistent with contamination by mafic material. We have not identified such material in thin section, but the mode of occurrence of the rock, as a small isolated dome in a basaltic field, makes it a prime candidate for mixing with basalt, and basaltic inclusions do locally occur in the rhyolite.

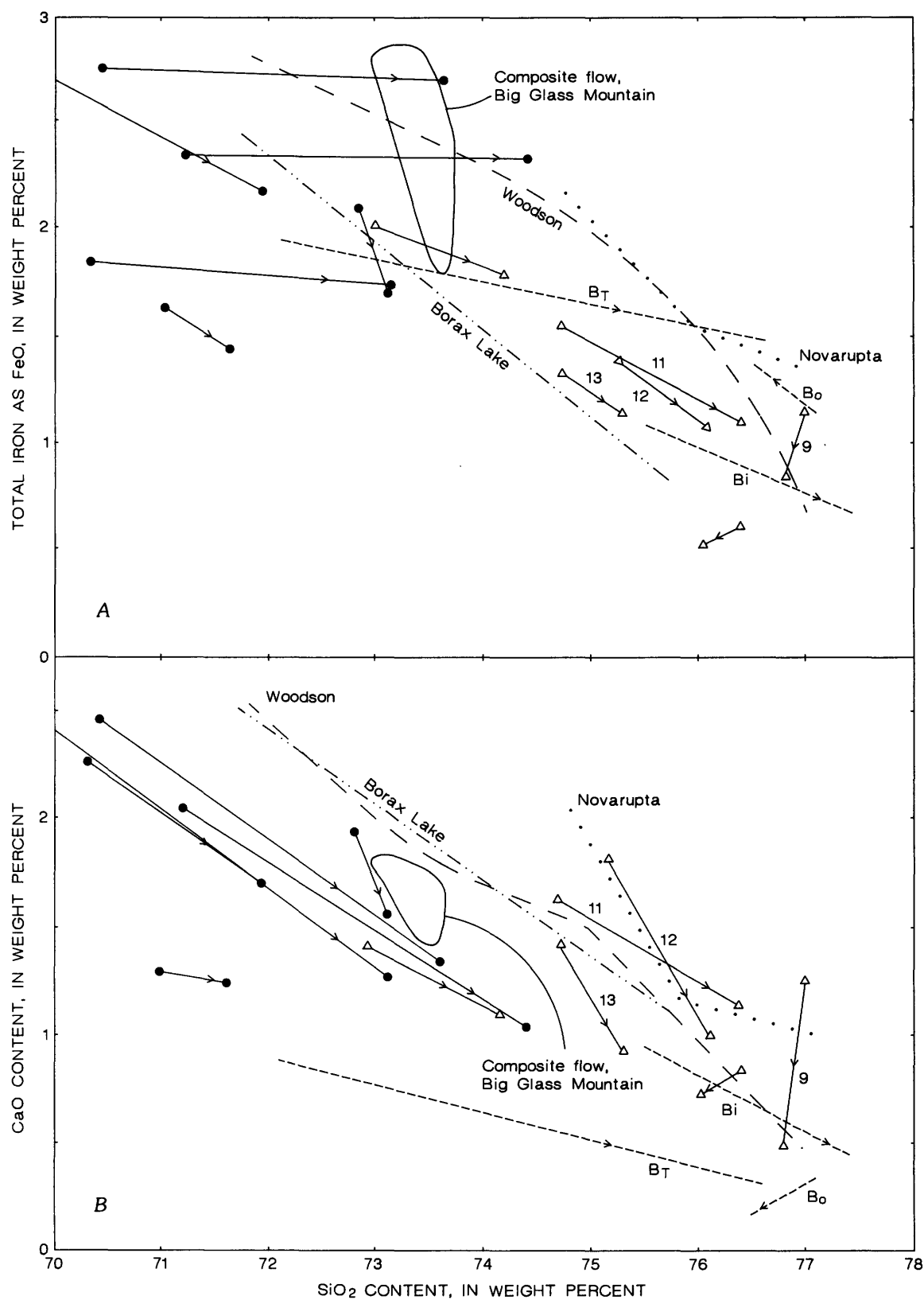
A crude estimate of the amount of possible contamination of the obsidians by mafic magmas or xenoliths may be made using Cr concentrations. Though our Cr data are limited by poor precision at low abundance levels, virtually all the obsidians have Cr < 4 ppm. The average Cr content in basalts is 162 ppm (Prinz, 1968), suggesting that the maximum basaltic component in the rhyolites is much less than 5 percent. Correspondingly larger components are possible when the lower silica member is andesitic or dacitic, but it may be significant that only six obsidian samples have Cr contents as high ( $\geq 9$  ppm) as those from the Borax Lake mixed rhyolite-dacite obsidian flow (Bowman and others, 1973), and three of those probably reflect analytical error.

It is concluded that although magma mixing and assimilation of mafic rocks may affect significant chemical variations in silicic systems, there is no convincing evidence that those processes have been other than minor differentiation mechanisms in the obsidians.

#### VAPOR-PHASE TRANSPORT

An integral part of the thermogravitational diffusion model (Shaw and others, 1976; Hildreth, 1979) and accepted here as a likely CIPP component is the roofward migration and concentration of trace elements as hydroxyl, halide, or carbonate complexes. Hildreth (1981) has noted that thermogravitational diffusion may also include chemical exchange between liquid and a transient vapor phase. If, in silicic systems, the roof zone becomes saturated with

FIGURE 26.—SiO<sub>2</sub> content versus total iron as FeO (A) and CaO (B) content for various rock-glass pairs (solid tielines; appendix I; Ewart and others, 1968, pairs 9, 11, 12, 13); Borax Lake (Bowman and others, 1973), Novarupta (specimens 3, 243, 244), and Big Glass Mountain (specimens 264–268) mixed flows; Bishop Tuff, Bi (Hildreth, 1981); Bandelier Tuff, Otowi, B<sub>o</sub>, and Tshirege, B<sub>t</sub>, Members (R.L. Smith, unpub. data); and Woodson granodiorite stock (Tilling and Gottfried, 1969; David Gottfried, unpub. data). Arrows indicate direction of liquid fractionation.



volatiles prior to eruption, with the evolution of a discrete vapor phase, partitioning of elements into this potentially fugitive volatile phase may be an important differentiation mechanism.

Unfortunately, there is no general agreement as to whether volatile saturation actually occurs in CIPP systems. Hildreth (1981, p. 10175), for example, argues from a review of pertinent petrographic and geochemical evidence that "the weight of evidence is against preeruptive water and halogen saturation in explosive rhyolitic magmas, but the transient effects of  $\text{CO}_2$ -bearing vapor might be important to transport of some trace components." Similarly, Mahood (1981a, b) finds little evidence that the Tala Tuff magma chamber became saturated with volatiles prior to eruption.

Nevertheless, there is a natural progression during the plutonic stages from CLPD to liquid-vapor-crystal-controlled processes in the roof zones of silicic systems, the latter being recorded, for example, in pegmatites, greisens, and other pneumatolytic deposits. Chemically, CIPP forms a transitional stage, as shown in figure 27, in terms of K-Rb covariance. The crystal-liquid processes dominant (CLPD) field of this paper coincides with the "Main Trend" zone of Shaw (1968), whereas the complex interaction of petrogenetic processes (CIPP) field spans the composition range between the CLPD field and that defined by the pegmatite-hydrothermal trends of Shaw.

Ratios of other pairs of coherent elements may change significantly during CIPP. The effect is particularly clearly shown by the Zr/Hf ratio. Zr is a

"down" element whereas Hf concentrates "upward." Obsidians strongly fractionated by CIPP have low Zr/Hf ratios, commonly less than 20. During the pegmatitic-hydrothermal stages, Zr/Hf fractionation may be even more marked, to the extent of producing hafnon-bearing pegmatites. The Nb/Ta ratio is also decreased by CIPP, though less markedly than the Zr/Hf ratio (table 9), and again CIPP forms a bridge to the postmagmatic processes.

Although the role of vapor-phase transport in redistributing elements within silicic magma chambers cannot yet be quantified (Hildreth, 1981), one important result of the bleeding of volatile-rich solutions into the roof rocks of magma chambers would be the attainment in the magma of apparent fractionation factors lower than the real factors achieved prior to volatile evolution as shown by the Bandelier and other data.

#### SUMMARY OF PETROGENETIC PROCESSES

A summarization, in terms of K and Rb, of the compositional fields in which each petrogenetic process has played a dominant or important role is shown in figure 28. The following points may be noted:

1. The "crystal-liquid" field encloses the range of compositions of base-level magmas whose evolution has been controlled either by crystal fractionation or by crustal anatexis. The inflection in the zone is ascribed to a change either in the fractionating assemblage from mineralogies dominated by plagioclase to those dominated by plagioclase and alkali feldspar, or in the type of source rocks, for example, from one- to two-feldspar-bearing sources.

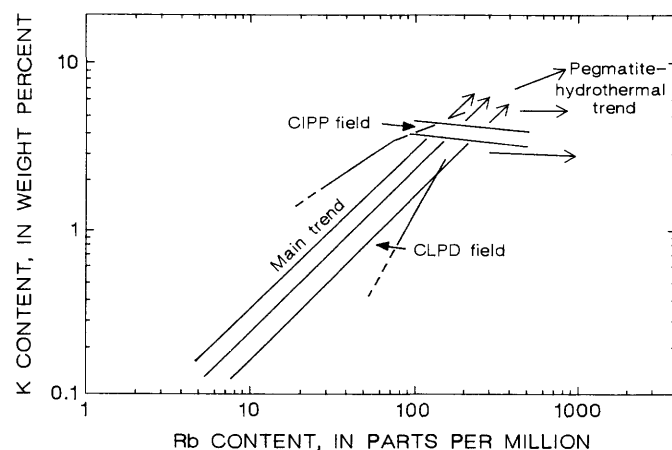


FIGURE 27.—Rb content versus K content showing that CIPP forms a link between crystal-liquid processes and hydrothermal activity. Main trend and pegmatite-hydrothermal trends are from Shaw (1968). Dashed lines express uncertainty of field boundaries.

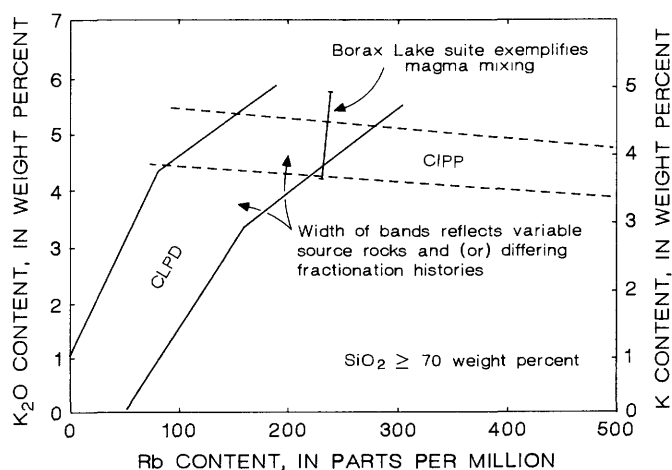


FIGURE 28.—Rb content versus  $\text{K}_2\text{O}$  content showing effects of main genetic processes affecting silicic magmas.



2. The CIPP field encompasses the range of the Bishop and Bandelier ash-flow sheets and of several obsidians inferred to have evolved dominantly by similar processes. The field overlaps that of crystal-liquid processes, such that a distinction between processes cannot be made on the basis of K and Rb contents within this field. Thus, Rb contents in the most evolved members of the Bishop system are lower than those in most CLPD continental-interior rocks. It is, of course, likely that true base levels for many interior systems probably lie below the Bishop maximum, but these values may occur in magmas having  $\text{SiO}_2 < 70$  percent (Smith, 1979, fig. 8). Subsequent crystal fractionation within diffused systems may result in extension of, and spread within, the CIPP field.

3. The width of the base-level zones reflect three factors. Most important are variations in source rock composition. Secondly, minor differences in partial melting trends and fractionation trends also exist, because the extensive parameters under which the magmas evolved must also have varied. Thirdly, some scatter has resulted from magma mixing and wall-rock contamination. Thus, the data for the mixed obsidian at Borax Lake form a crosstrend on the K/Rb diagram.

4. We stress that, at present, our understanding of the chemistry of CIPP magmas and of the process itself is heavily dependent on the studies of the Bandelier and Bishop Tuffs. As Hildreth (1979, p. 69) points out, more complete documentation is required of zoned systems of a range of bulk compositions over a spectrum of volumes, temperature ranges, and phenocryst and volatile contents.

## SYSTEMATIC GEOCHEMISTRY

In this section, the geochemistry of the subalkalic silicic obsidians is described element by element. A first aim is simply to present data in histogram form to show the elemental ranges for each rhyolite group and to indicate those elements which are most closely covariable in the obsidians. A second aim is to explain the variations in terms of the genetic mechanisms described in the previous section. The obsidian analyses are compared with data from rock-glass pairs and granitic plutons (representing crystal-liquid-controlled compositions), from compositionally zoned ash-flow tuffs thought to have evolved dominantly by CIPP and from mixed-magma series where data permit.

For purposes of discussion, the rocks are divided (table 10) into those whose evolution had been con-

trolled by CLPD or CIPP, respectively, using criteria outlined in the section entitled "Magmatic Differentiation Processes in Silicic Systems." This study represents the first detailed attempt to relate the complexities of rhyolite geochemistry to all the tectonic and genetic variables.

The elements are discussed, more or less, in the order they appear in the tables of analyses; the coherent pairs Nb-Ta, Zr-Hf, and Th-U are linked together; and the rare metals Be, Li, Mo, Sn, and W are included in appendixes I and II to make the data available in the broader context of the tabular data base. However, these data were acquired for an independent study by Smith and D. Gottfried and are not discussed in detail in this paper. The presentation varies somewhat from element to element but normally the data are given as histograms (for example, see figs. 29, 40), as  $\text{SiO}_2$ -variation diagrams (see figs. 30, 41), and as correlation matrices for relevant elements.  $\text{SiO}_2$ -variation diagrams are not suitable for trace elements which show orders-of-magnitude variations, and another element is then used as a basis of comparison.

Correlation coefficients for all pairs of the following variables have been computed (app. VI): all major and trace elements,  $\text{FeO}$ , and  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratio. In order to maximize the value of the coefficients, only rocks with both major- and trace-element data were used (app. I). Hydrated (app. II) and peralkaline samples, those samples with  $\text{SiO}_2 < 70$  percent, and the quite exceptional macusanite sample (No. 160) were also excluded from the calculations. The maximum degrees of freedom, that is, for rocks in which all elements had been satisfactorily determined, were 193; any correlation  $> 0.2$  is significant at the 1 percent level. In the following discussion, a value of  $r = \pm 0.60$  was selected to isolate the most important interelement correlations, and these are listed in the section for each element. This value means that correlations are significant at better than the 0.1 percent level even for those elements for which the fewest determinations are available.

## SILICON

The  $\text{SiO}_2$  values range from an arbitrary lower limit of 70 percent to 77.5 percent. The upper limit is almost identical to that (77.4 percent) suggested by Hildreth (1981) as a likely maximum for unaltered rhyolites, and there are sufficient obsidian analyses (11 samples) bearing  $\text{SiO}_2 > 77$  percent to be confident that such liquids do occur in nature.

TABLE 9.—*Ranges and average compositions of CLPD and CIPP obsidians of continental margins and interiors*

(First averages in each column calculated using new data only (appendix I); ranges and second averages using all data (appendices I, III); —, not determined)

	Continental margins			CIPP			Continental interiors			CIPP		
	CLPD			CLPD			CLPD			CLPD		
	Range	X	X <sub>T</sub>	Range	X	X <sub>T</sub>	Range	X	X <sub>T</sub>	Range	X	X <sub>T</sub>
Major elements (weight percent)												
SiO <sub>2</sub> .....	70.2–77.3	74.2	73.8	74.5–77.2	76.4	77.3	70.6–77.3	75.8	75.7	70.7–77.5	75.9	76.0
Al <sub>2</sub> O <sub>3</sub> .....	12.30–15.37	13.73	13.79	11.92–12.96	12.50	12.35	11.9–14.63	13.20	13.01	12.09–16.30	12.78	12.93
Fe <sub>2</sub> O <sub>3</sub> .....	.09–1.67	.51	.52	.19–.51	.36	.35	.21–1.3	.46	.47	.09–1.33	.40	.42
FeO .....	.32–2.62	.96	1.20	.39–.93	.63	.68	.12–1.76	.64	.73	.19–1.31	.53	.52
MgO .....	<.01–.93	.23	.27	.01–.27	.04	.05	.00–.66	.09	.10	.00–.44	.02	.03
CaO .....	.44–2.94	1.07	1.19	.27–.79	.48	.53	.31–1.61	.60	.59	.16–2.07	.44	.47
Na <sub>2</sub> O .....	3.40–5.38	4.35	4.32	3.52–4.38	4.08	4.07	3.00–4.98	3.96	3.90	3.30–5.07	4.31	4.28
K <sub>2</sub> O .....	2.43–5.26	4.04	4.05	4.50–4.95	4.62	4.64	4.01–6.60	4.76	4.90	3.60–5.53	4.45	4.48
H <sub>2</sub> O <sup>+</sup> .....	.04–1.10	.19	.26	.09–.71	.25	.34	.03–.68	.18	.22	.01–.98	.31	.30
TiO <sub>2</sub> .....	.03–.54	.22	.23	.05–.13	.09	.08	.02–.31	.13	.14	.00–.15	.07	.06
P <sub>2</sub> O <sub>5</sub> .....	.01–.22	.04	.05	.008–.03	.01	.01	.00–.09	.02	.02	.00–.55	.01*	.01*
MnO .....	.02–.12	.06	.05	.02–.10	.06	.05	.02–.14	.06	.05	.02–.13	.05	.05
Cl .....	.01–.17	.07	—	.03–.10	.06	—	.04–.13	.08	—	.04–.20	.09	—
F .....	.02–.11	.05	—	.05–.12	.07	—	.05–.12	.09	—	.07–.136	.20*	—
FeO <sub>t</sub> <sup>1</sup> .....	.53–2.89	1.38	1.67	.74–1.20	.95	1.00	.50–2.30	1.05	1.15	.56–1.71	.89	.90
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> .....	.35–.95	.65	.70	.45–.83	.64	.66	.08–.84	.58	.61	.24–.85	.57	.55
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> .....	.68–2.16	1.08	1.07	.74–.96	.84	.85	.61–1.13	.83	.80	.60–1.23	.97	.96
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> .....	.73–1.00	.84	.83	.86–.97	.94	.93	.80–.99	.88	.90	.66–.99	.93	.92
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> .....	.89–1.12	.98	.99	.96–1.03	1.01	1.01	.90–1.07	.97	.99	.68–1.04	.99	.98
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> .....	.05–.39	.13	.14	.03–.10	.06	.06	.03–.20	.07	.07	.02–.23	.05	.05
Cl/F <sup>1</sup> .....	15–3.94	1.5	—	.35–1.23	.9	—	.36–2.40	.90	1.19	.03–1.21	.5	—
Trace elements (parts per million)												
Ba .....	13–1440	814	—	13–415	121	—	6–1040	287	—	1–70	16	—
Be .....	1.3–3.4	2.5	—	3.1–5.5	3.9	—	18–7.3	3.8	—	4.6–32	11	—
Co .....	.1–4.5	1.1	—	<.2–.4	.3	—	.1–3.7	.5	—	.1–3.1	.4	—
Cr .....	1.1–10.7	2.3	—	1.7–3.5	2.4	—	1.0–13.2	3.1	—	1.3–9.0	1.6	—
Cs .....	1.8–14.8	5.1	—	4.7–21.1	10	—	2.0–15.7	5.3	—	3.7–503	7.6*	—
Hf .....	1.9–11.5	5.0	—	2.7–6.7	4.7	—	2.3–10.6	5.3	—	1.3–14.5	5.8	—
Li .....	28–81	45	—	42–110	68	—	32–170	56	—	36–3400	116*	—
Mo .....	.58–6.5	3.2	—	.96–8.1	3.4	—	1.6–9	4.5	—	.26–9.9	3.6	—
Nb .....	5.2–27	13	—	14.5–37	23	—	14–65	37	—	20–288	77	—
Pb .....	9–34	21	—	17–49	25	—	15–50	26	—	20–101	38	—
Rb .....	52–223	126	—	130–270	202	—	103–296	179	—	160–1174	291*	—
Sb .....	.2–1.9	.8	—	.6–1.3	1.0	—	.1–1.3	.5	—	.3–2.9	.9*	—
Sc .....	1.1–8.4	3.7	—	1.57–5.15	2.8	—	1.03–4.23	2.4	—	.12–3.85	1.6	—
Sn .....	.7–6	2.2	—	3.1–7.9	4.7	—	1.3–9.4	3.4	—	2.4–250	8.2*	—
Sr .....	9–444	135	—	2–40	14	—	2–202	41	—	.3–20	4	—
Ta .....	.44–1.82	1.13	—	1.02–2.95	2.01	—	1.33–5.69	3.13	—	2.57–29.41	7.67	—
Th .....	4.9–26.6	12	—	9.8–26.4	18	—	4.2–45.6	22	—	1.3–52.7	30	—
U .....	2.9–8.3	4.7	—	4.2–13.2	6.8	—	3.5–14.4	7.2	—	5.3–35.1	12.9	—

W -----	.5-3.5	1.6	—	2.1-3.9	2.8	—	1.0-3.5	2.2	—	1.4-76	3.4*	—
Y -----	8-80	27	—	26-108	43	—	8-93	37	—	25-245	78	—
Zn -----	16-89	35	—	30-95	47	—	18-101	41	—	33-282	65	—
Zr -----	40-447	171	—	52-260	123	—	52-367	147	—	22-338	125	—
La -----	9-90	28	—	19-40	25	—	10-95	45	—	1-72	22	—
Ce -----	18-142	51	—	41-71	51	—	18-185	84	—	3-132	48	—
Nd -----	8-51	22	—	15-30	23	—	7-71	30	—	4-56.9	25	—
Sm -----	2.0-9.0	4.5	—	3.3-10.5	6.0	—	2.6-15.9	6.6	—	1.5-15.6	6.6	—
Eu -----	13-1.11	.60	—	.08-.61	.22	—	.14-.98	.41	—	.02-.31	.10	—
Gd -----	1.6-9.5	4.1	—	3.1-10.8	5.6	—	2.2-13.2	5.7	—	<2-16.6	7.8	—
Tb -----	.24-1.53	.67	—	.62-2.25	1.1	—	<.03-2.44	1.0	—	.17-4.26	1.7	—
Tm -----	<.10-1.10	.42	—	.32-1.82	.68	—	<.2-1.34	.67	—	.25-3.22	1.1	—
Yb -----	.2-6.9	2.6	—	2.3-11.7	4.6	—	1.1-8.0	3.8	—	.3-23.6	7.2	—
Lu -----	.12-.98	.39	—	.32-1.66	.65	—	.15-1.10	.54	—	.04-3.04	.99	—
<hr/>												
Nb/Ta -----	7.4-21.2	11.5	—	8.1-14.2	11.4	—	6.0-18.9	11.8	—	2.5-15.4	10.0	—
K/Rb -----	180-394	266	—	138-316	190	—	150-380	221	—	25-257	127	—
Rb/Sr -----	.1-15	.9	—	4.8-65	14.4	—	.8-1173	4.4	—	14-1533	73	—
Ca/Sr -----	35-389	57	—	107-965	245	—	38-1668	105	—	429-12863	786	—
Th/U -----	1.4-3.6	2.6	—	1.9-3.6	2.6	—	1.2-5.1	3.1	—	.1-3.9	2.3	—
Zr/Hf -----	17-48	34	—	17-41	26	—	18-43	28	—	10-36	22	—
Ce/Yb -----	7.4-230	19.6	—	4.7-18.6	11.1	—	10-120	22.1	—	2.4-21.5	6.7	—
Eu/Eu* -----	.10-.75	.43	—	.04-.18	.12	—	.05-.56	.20	—	.01-.24	.04	—
<hr/>												
Maximum number of determinations:												
major elements	105			14			64			44		
trace elements	58			8			41			39		

<sup>1</sup>By weight

<sup>2</sup>Molecular

\*Averages exclude P<sub>2</sub>O<sub>5</sub>, F, Cs, Li, Rb, Sb, Sn, and W data for sample 160.

TABLE 10.—Classification of obsidian samples used for plotting purposes

[Peralkaline and hydrated specimens, those with  $\text{SiO}_2 < 70$  weight percent and those for which only trace element data are available, are not included]

Primitive island arcs	Mature island arcs		Continental margins		Continental interiors		Oceanic extensional zones	Others
	calcic	calc-alkalic	CLPD	CIPP	CLPD	CIPP		
371	189, 193, 194, 195, 205, 335, 336, 338, 340-345, 347-352, 354	1, 2, 186, 187, 190, 192, 196, 198, 199, 200-204, 206, 208, 209, 210, 215-217, 242, 331-333, 339, 353, 357-361, 365-370	3-6, 8-10, 12-28, 30-32, 34-43, 45-47, 51-54, 76-78, 152-5, 159, 162-166, 184, 243-280, 283, 284, 289, 290, 328-330, 334, 346	33, 44, 48-50, 79, 188, 191, 281, 282, 285-288	7, 81, 82, 84, 85, 91-93, 95, 100, 101, 103, 105-107, 110, 112-116, 119-122, 124, 125, 138-145, 151, 161, 179, 183, 185, 291-300, 305-314, 355, 356	55-66, 68-72, 80, 83, 86-88, 90, 94, 96-99, 102, 104, 108, 109, 111, 117, 118, 123, 146, 147, 160, 301-304, 315, 316	73-75, 156-158, 169-178, 212-214, 317-321, 362, 363	180-182, 322-327, 337, 364

A histogram (fig. 29A) reveals increasing numbers of samples with increasing  $\text{SiO}_2$  contents. This increase presumably reflects the tendency of higher silica liquids to chill to glass.

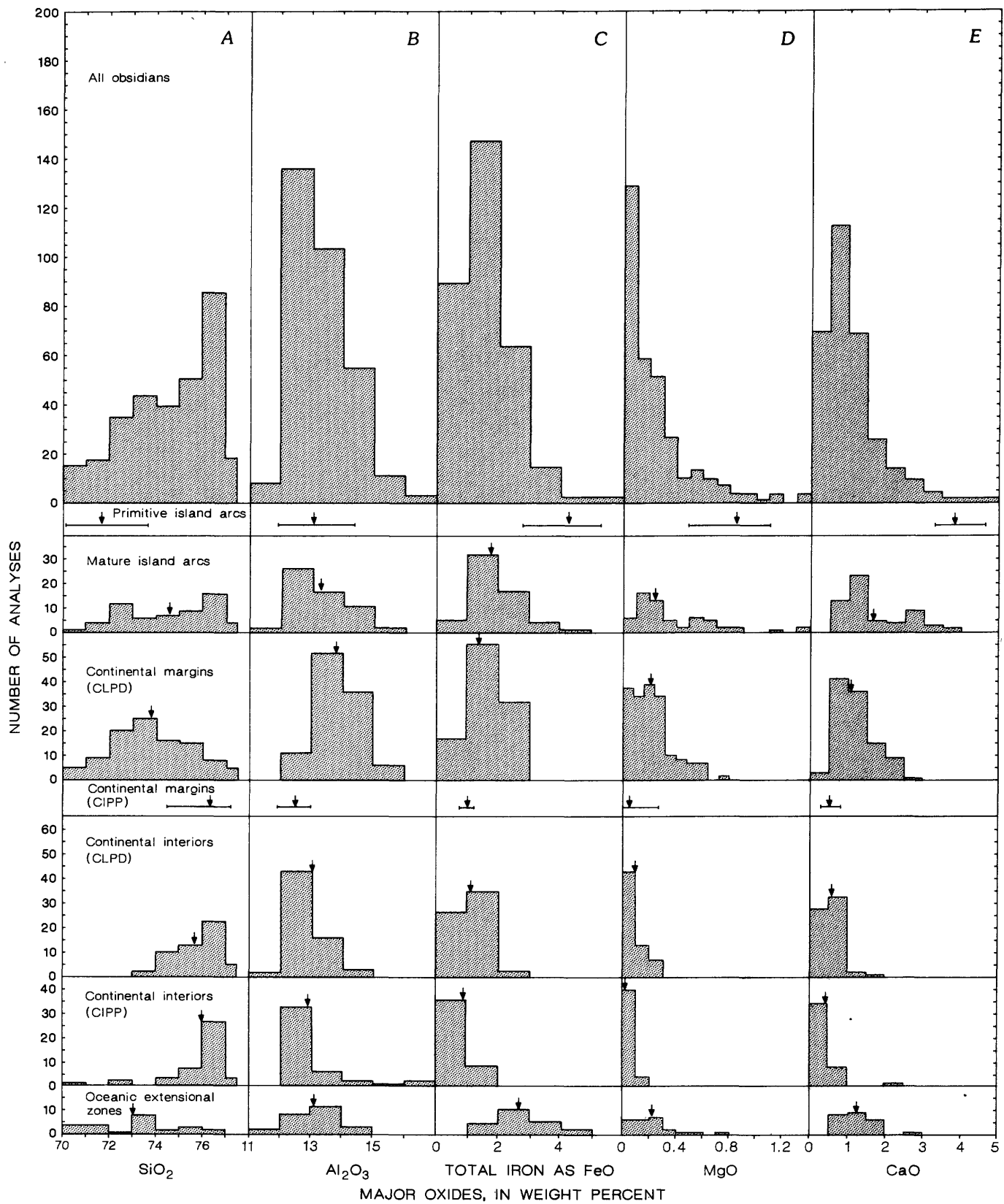
No very high silica obsidians are known from primitive island arcs, which casts doubt on the magmatic nature of the high silica content (up to 80 percent) recorded in certain devitrified and secondarily hydrated specimens in this setting (see section "Geochemical Features of Main Obsidian Groups," group I). The bimodal character of silica distribution in mature-arc obsidians probably results from two effects. The lower silica peak represents the end-member compositions of the calcic rhyolites usually associated with tholeiitic complexes, which do not generally evolve to high- $\text{SiO}_2$  compositions. The higher silica peak is formed by rocks of calc-alkalic type, the position of the peak again being determined by viscosity relations.

Base-level compositions (CLPD type) in continental-margin obsidians show an approach to a normal  $\text{SiO}_2$  distribution, which probably reflects the overall distribution of silicic magma types in such settings. Although there are few samples in the data base, CIPP types are notably more silicic, reflecting  $\text{SiO}_2$  enrichment in lower temperature magmas. The magnitude of the shift relative to base-level rocks may be exaggerated, in that the CIPP nature of the lower  $\text{SiO}_2$  range of the Bishop Tuff, for example, is 75.5-77.4 percent, and this probably does not include base-level compositions (Hildreth, 1979).

There is a distinct scarcity of obsidians with  $\text{SiO}_2$  in the range 70-74 percent in the continental interiors. This may be partly due to the fact that the base-level rocks are genuinely richer in silica, perhaps being derived by melting of more quartz-rich sources. The activity has not normally tapped deep enough levels within the relevant systems; the Bandelier Tuff, for example, ranges in composition from 72-77 percent  $\text{SiO}_2$ .

Although there are fewer samples of the obsidians of the oceanic extensional zones, specimens are probably evenly distributed over the  $\text{SiO}_2$  range, as the histogram suggests.

FIGURE 29.—Distribution of major elements in obsidians. Obsidians of primitive island arcs and continental margins (CIPP types) are shown as ranges only. Arrows indicate average values. Data from appendixes I, III, and V. A,  $\text{SiO}_2$ . B,  $\text{Al}_2\text{O}_3$ . C, Total iron as  $\text{FeO}$ . D,  $\text{MgO}$ . E,  $\text{CaO}$ . F,  $\text{Na}_2\text{O}$ . G,  $\text{K}_2\text{O}$  (sample 313 omitted to preserve scale). H,  $\text{Na}_2\text{O}+\text{K}_2\text{O}$ . I,  $\text{TiO}_2$  (sample 176 omitted to preserve scale). J,  $\text{P}_2\text{O}_5$  (samples 160, 316, 321, and 351 omitted to preserve scale). K,  $\text{MnO}$  (sample 345 omitted to preserve scale). L, Cl (sample 212 omitted to preserve scale). M, F (sample 160 omitted to preserve scale). Change of scale on  $\text{P}_2\text{O}_5$  and F axes is intentional.



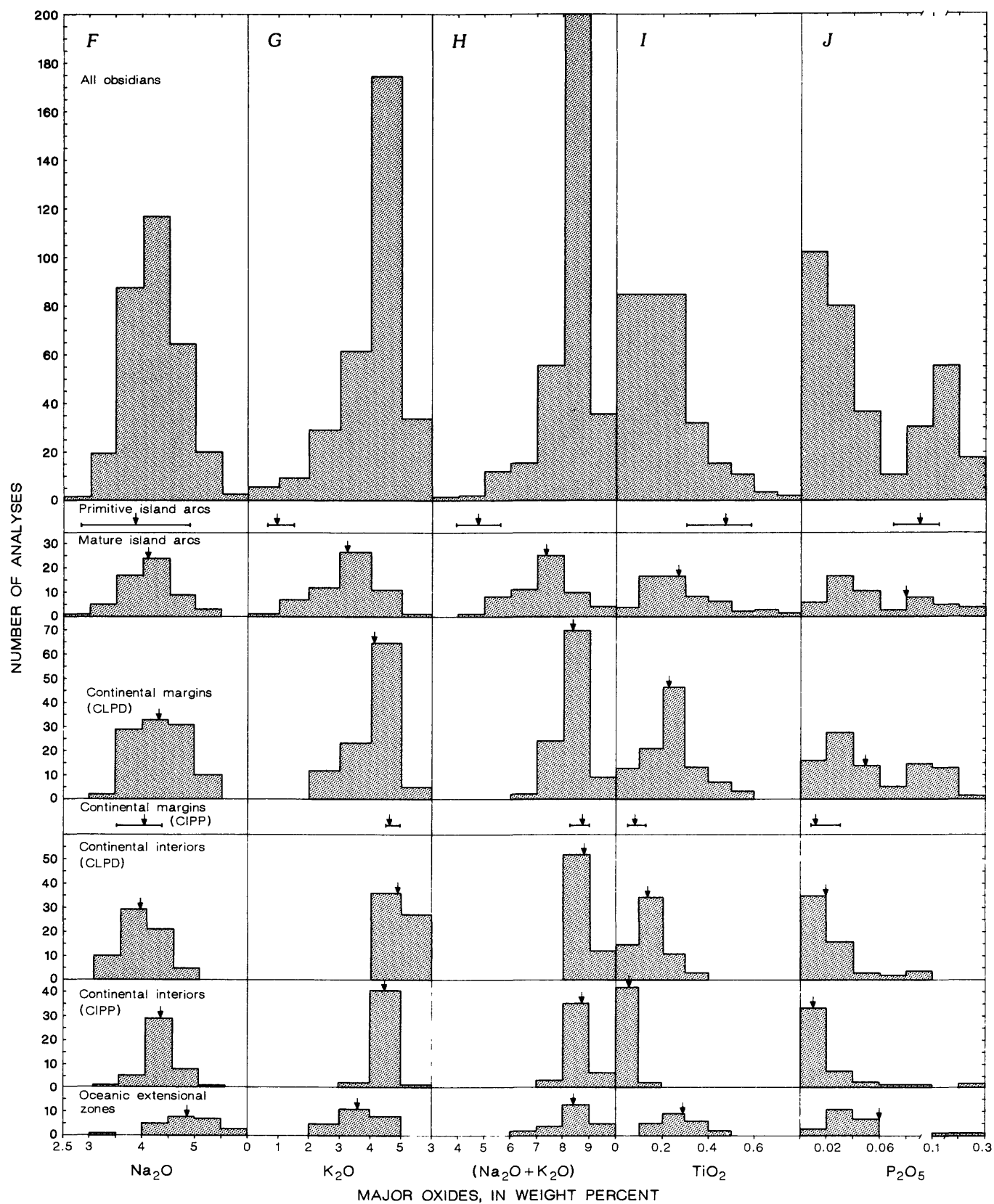


FIGURE 29.—Continued.

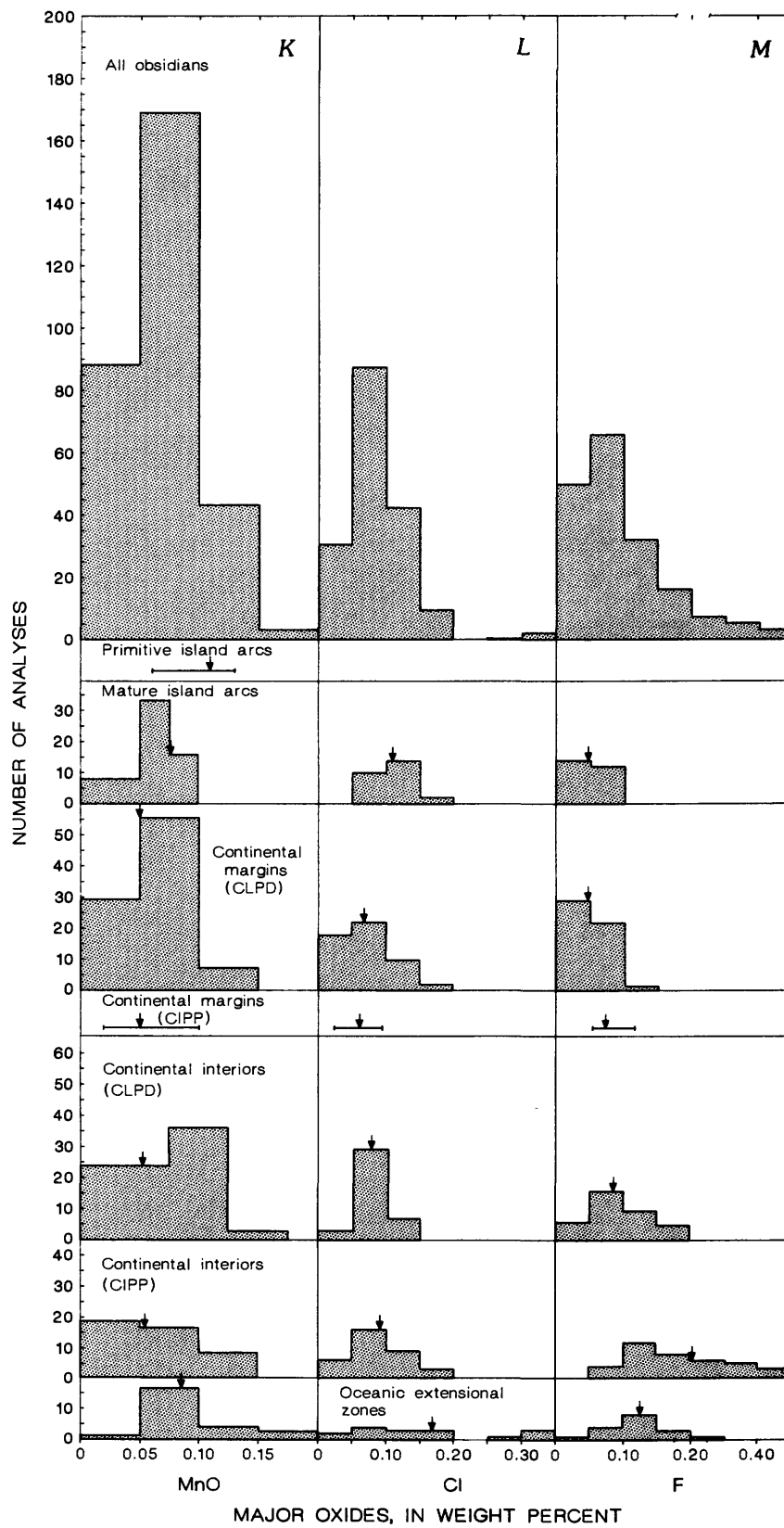


FIGURE 29.—Continued.



$r \approx 0.60$	SiO <sub>2</sub>
Al <sub>2</sub> O <sub>3</sub> -----	-0.83
FeO -----	-0.77
MgO -----	-0.74
CaO -----	-0.71
Na <sub>2</sub> O -----	-0.70
TiO <sub>2</sub> -----	-0.79
P <sub>2</sub> O <sub>5</sub> -----	-0.67
Sr -----	-0.65
Zr -----	-0.66
Eu -----	-0.61

## ALUMINUM

Al<sub>2</sub>O<sub>3</sub> shows a very scattered, but significant ( $r = -0.83$ ), negative correlation with SiO<sub>2</sub> (see fig. 30A). This imparts a skew in the Al<sub>2</sub>O<sub>3</sub> histogram toward lower Al<sub>2</sub>O<sub>3</sub> values (fig. 29B). Much of the spread at constant SiO<sub>2</sub> results from variations between rhyolite groups. Rocks from primitive island arcs and oceanic extensional zones tend to have lower Al<sub>2</sub>O<sub>3</sub> values than those of the other groups. Calcic varieties of island-arc obsidians tend to have lower Al<sub>2</sub>O<sub>3</sub> abundances than calc-alkalic types at similar SiO<sub>2</sub> contents.

Of the various rhyolite groups, continental-margin obsidians show the least scatter when plotted against SiO<sub>2</sub> (fig. 30). The spread of points is generally parallel to the rock-glass tielines and to the trend of the Woodson granodiorite stock. Though this is compatible with their compositions having been controlled by crystal-liquid processes, the CIPP trends for zoned ash-flow tuffs are also parallel, such that there is gross overlap between the fields of CLPD and CIPP rocks on this diagram.

$r \approx 0.60$	Al <sub>2</sub> O <sub>3</sub>
SiO <sub>2</sub> -----	-0.83
MgO -----	0.85
CaO -----	0.61
P <sub>2</sub> O <sub>5</sub> -----	-0.62
Sr -----	0.73

## IRON

TOTAL Fe AS FeO (FeO<sub>t</sub>)

FeO<sub>t</sub> shows an overall negative correlation with SiO<sub>2</sub> ( $r = -0.79$ ). For any given SiO<sub>2</sub> value, there is a three- to five-fold variation in FeO<sub>t</sub>, the scatter resulting from two main effects. First, important intergroup differences exist in FeO<sub>t</sub>-SiO<sub>2</sub> relations. Thus, obsidians from primitive arcs and oceanic ex-

tensional settings have higher FeO<sub>t</sub> contents than those from the other groups at equivalent SiO<sub>2</sub> values. Second, there are variations within groups, two examples of which are shown in figure 31. Within the arc setting, the calcic types (as defined in fig. 4) tend to have higher FeO<sub>t</sub> than the calc-alkalic types, again normalized to SiO<sub>2</sub>. In the continental interiors, CLPD obsidians of the Snake River Plain and Yellowstone systems have notably higher FeO<sub>t</sub> than similar rocks from Utah and New Mexico.

The behavior of Fe during CIPP is partially dependent on bulk composition. In the Bishop and Coso systems, Fe was a downward-concentrating element (Hildreth, 1979, 1981; Bacon and others, 1981); in peralkaline systems, especially Cl-rich types, it is normally an "up" element (Mahood, 1981a, b; Hildreth, 1981). Smith (1979, p. 14) omitted Fe from his list of element behavior in the Bandelier Tuff, because there is evidence of a more complex pattern, whereby Fe increased upward during CIPP episodes but was fractionated downward during intermittent periods of CLPD. As far as the body of obsidian data is concerned, CIPP has had the overall effect of lowering the mean FeO<sub>t</sub> content in CIPP as opposed to relevant base-level rocks (fig. 29C) and, as a result, increasing the SiO<sub>2</sub>/FeO<sub>t</sub> ratio (fig. 30B).

$r \approx 0.60$	FeO <sub>t</sub>
SiO <sub>2</sub> -----	-0.79
Fe <sub>2</sub> O <sub>3</sub> -----	0.73
FeO -----	0.97
MgO -----	0.63
CaO -----	0.70
Na <sub>2</sub> O -----	0.62
K <sub>2</sub> O -----	-0.62
TiO <sub>2</sub> -----	0.80
Hf -----	0.75
Sc -----	0.61
Zr -----	0.83
Eu -----	0.82

FeO/(FeO+Fe<sub>2</sub>O<sub>3</sub>) RATIOS

The iron oxidation ratio is prone to modification during even slight secondary hydration of glasses. Furthermore, analytical imprecision is probably an important problem, especially in older analyses. For example, the average FeO/(FeO+Fe<sub>2</sub>O<sub>3</sub>) ratio in published analyses of obsidians from mature island arcs, especially the calcic varieties, is lower than that in

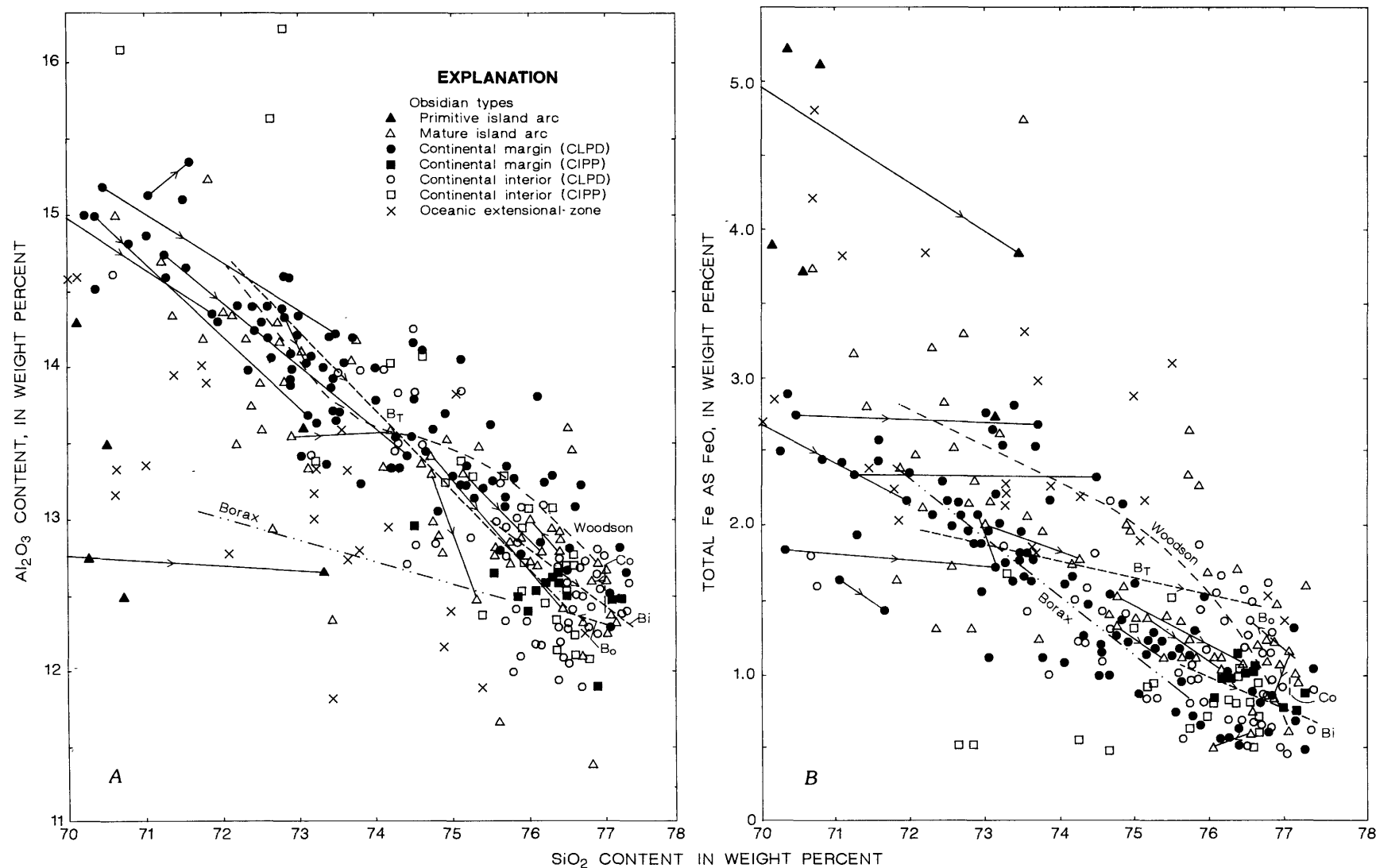


FIGURE 30.—Major-element silica-variation diagrams for obsidians and various comparative rocks. Data for obsidians from appendixes I, III, and V; others are same as for figure 5.  $\text{SiO}_2$  content versus: A,  $\text{Al}_2\text{O}_3$ . B, Total iron as FeO. C, MgO (samples 350 and 351 omitted to preserve scale). D, CaO. E,  $\text{Na}_2\text{O}$ . F,  $\text{K}_2\text{O}$  (sample 313 omitted to preserve scale). G,  $\text{Na}_2\text{O}+\text{K}_2\text{O}$ . H,  $\text{TiO}_2$ . I,  $\text{P}_2\text{O}_5$ . J, MnO

K, Cl. L, F (sample 160 omitted to preserve scale). Solid tielines indicate rock-glass pairs. Dashed lines indicate range of compositions of systems; Bishop Tuff (Bi); Bandelier Tuff (Otowi Member, B<sub>o</sub>, Tshirege Member, B<sub>t</sub>) Coso Range (Co); Borax Lake; and Woodson Granodiorite. References as in figure 5. All arrows indicate direction of fractionating liquid.

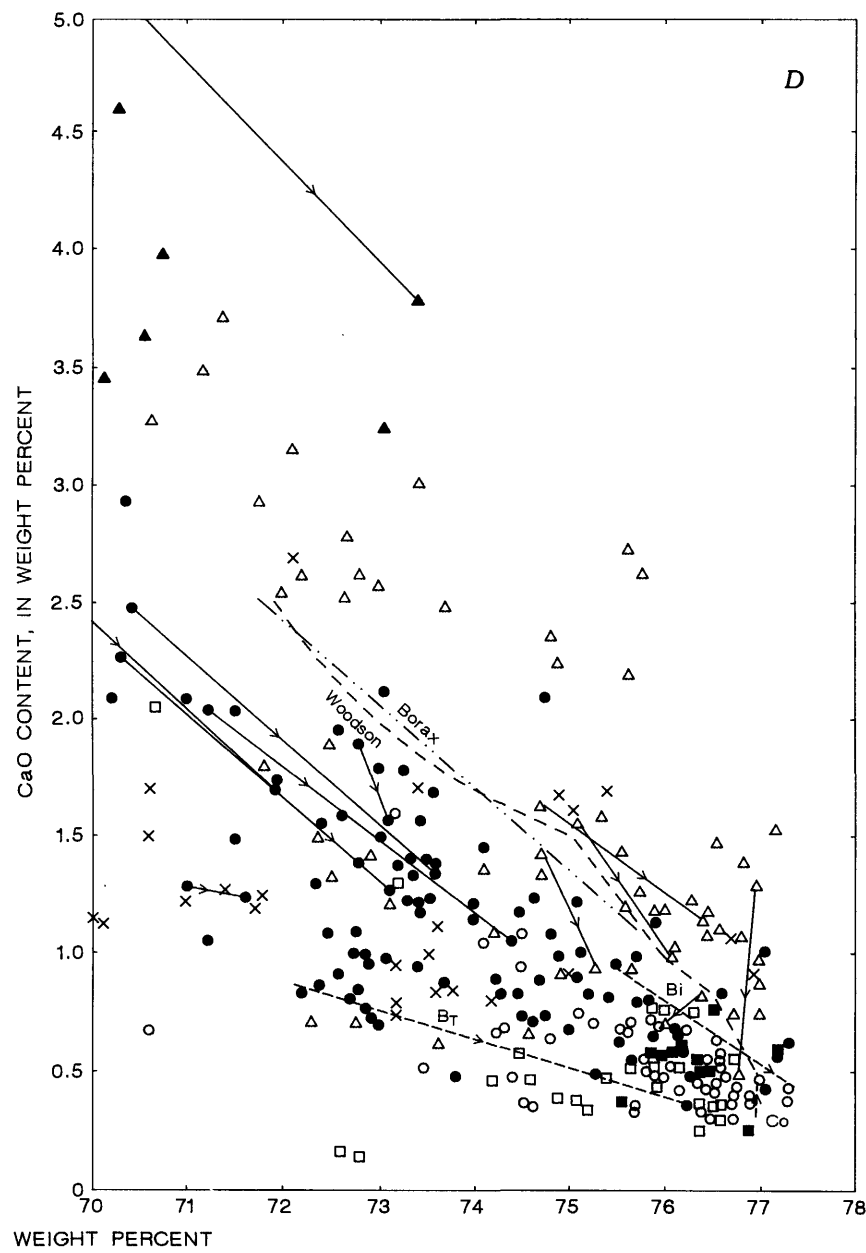
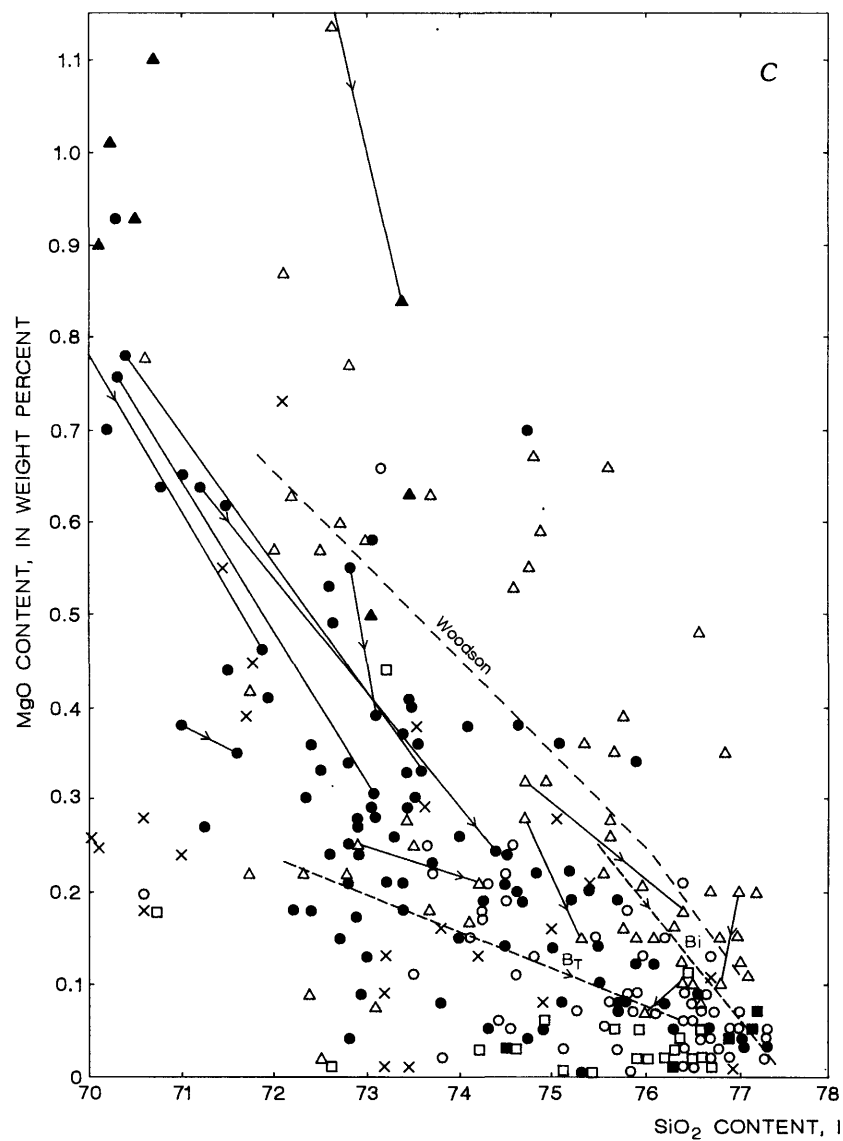


FIGURE 30.—Continued.

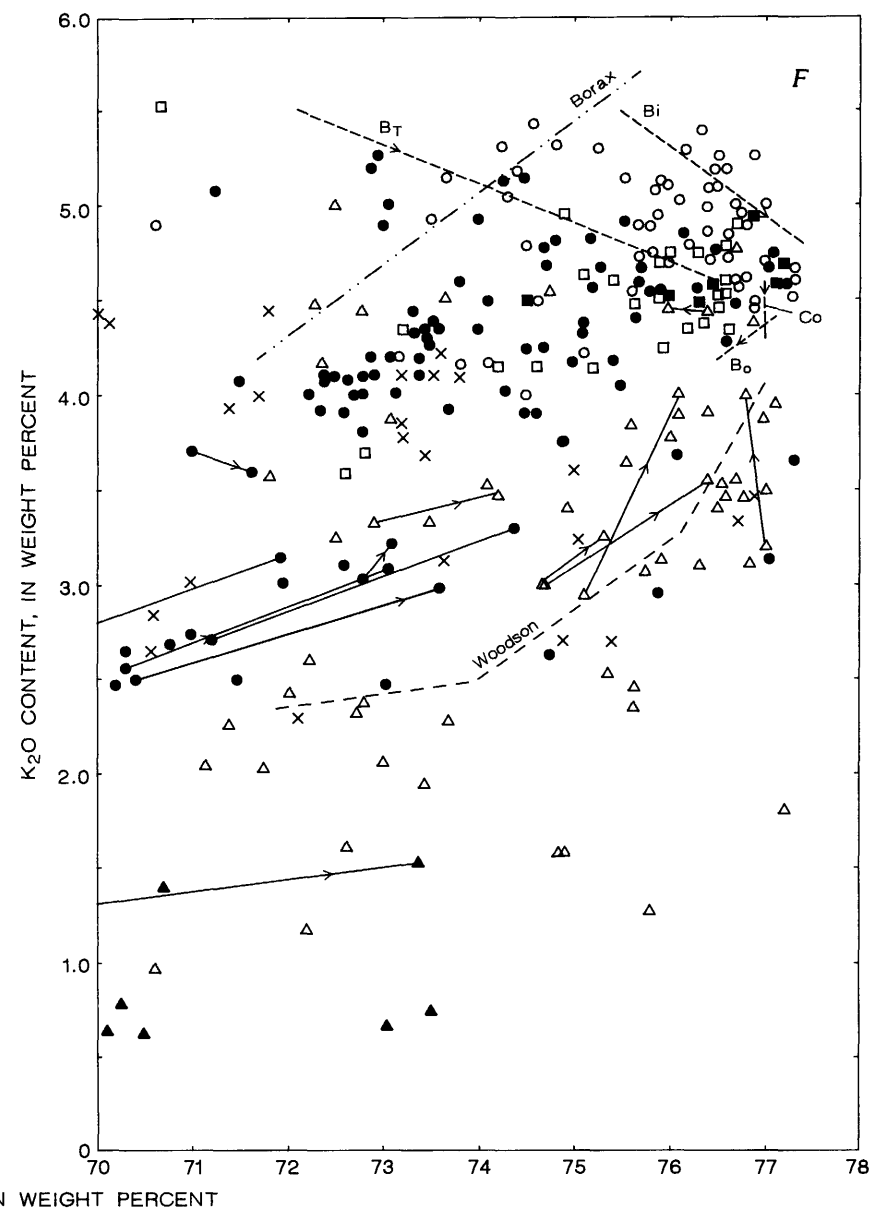
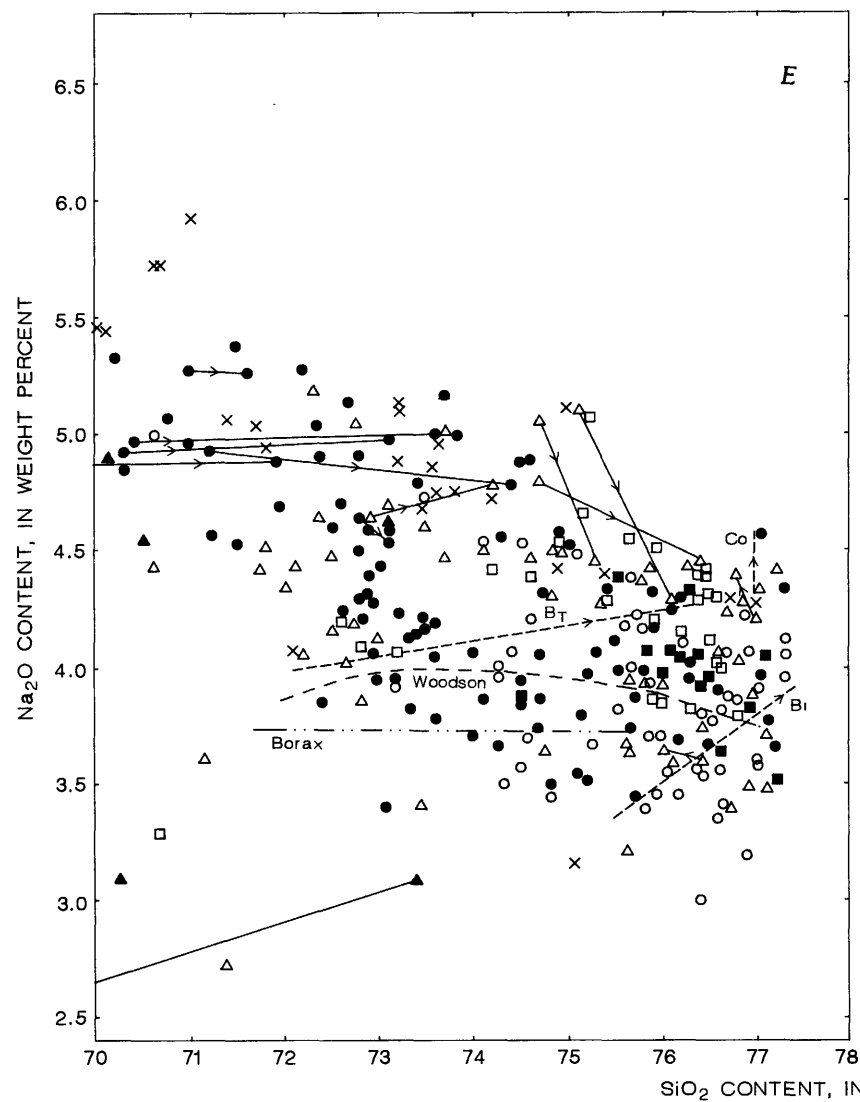


FIGURE 30.—Continued.

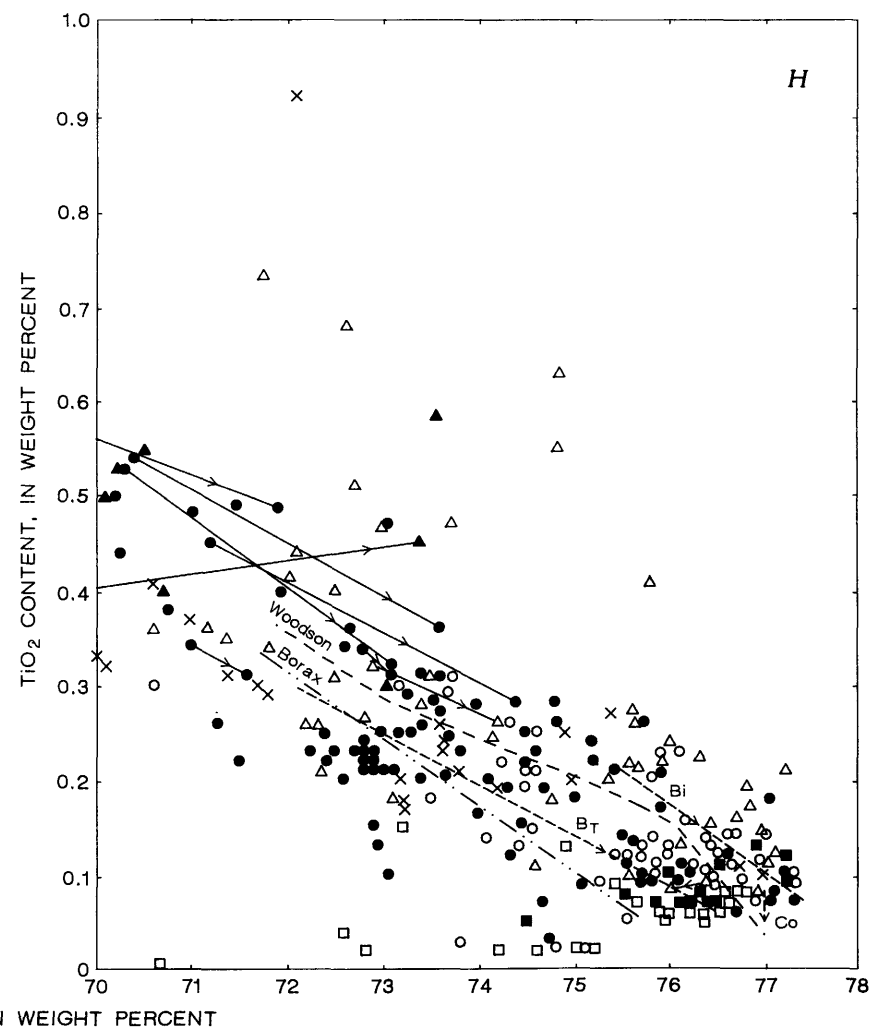
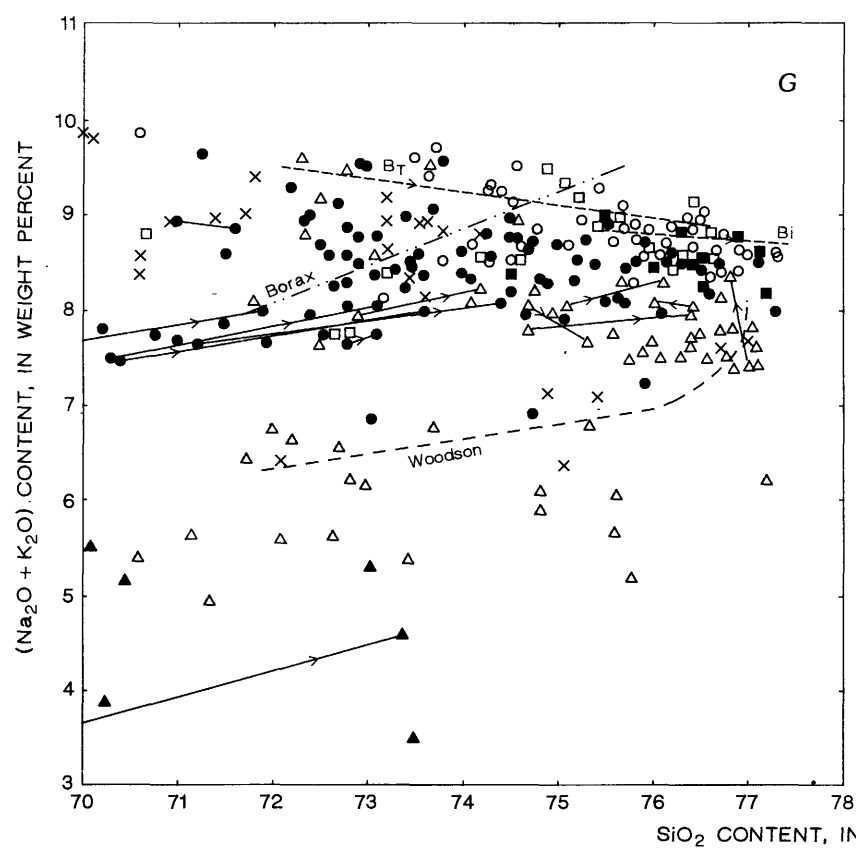


FIGURE 30.—Continued.

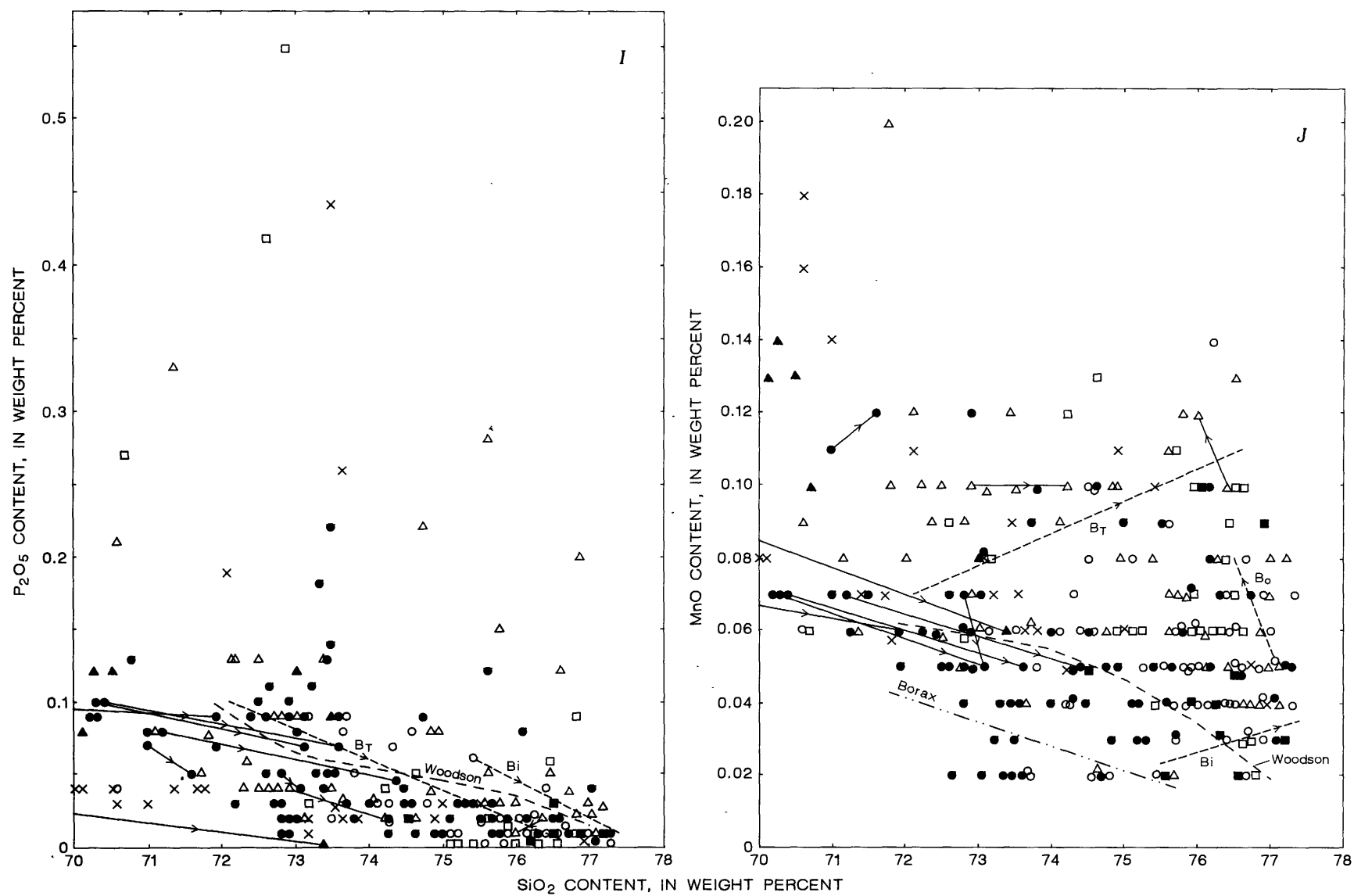


FIGURE 30.—Continued.

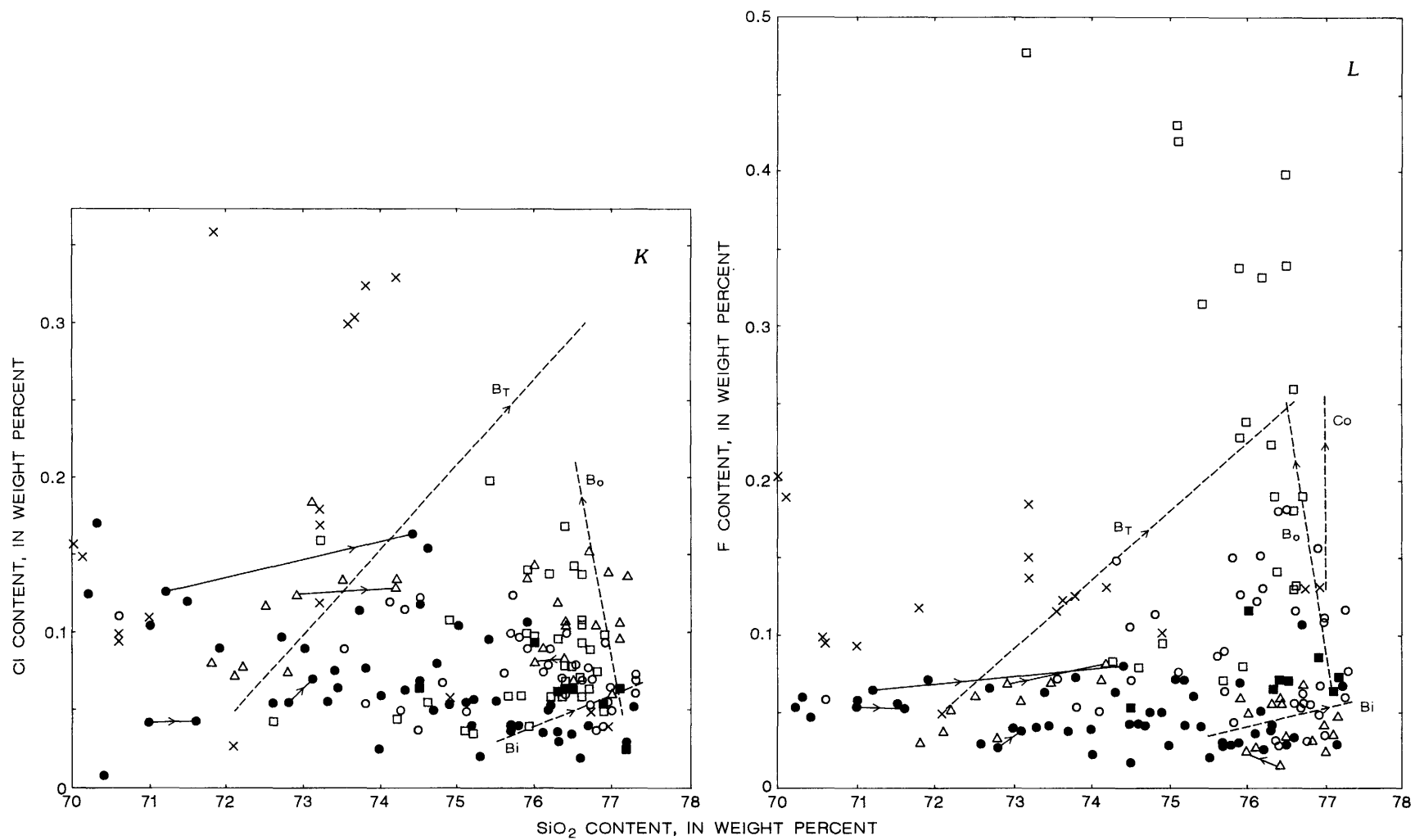


FIGURE 30.—Continued.



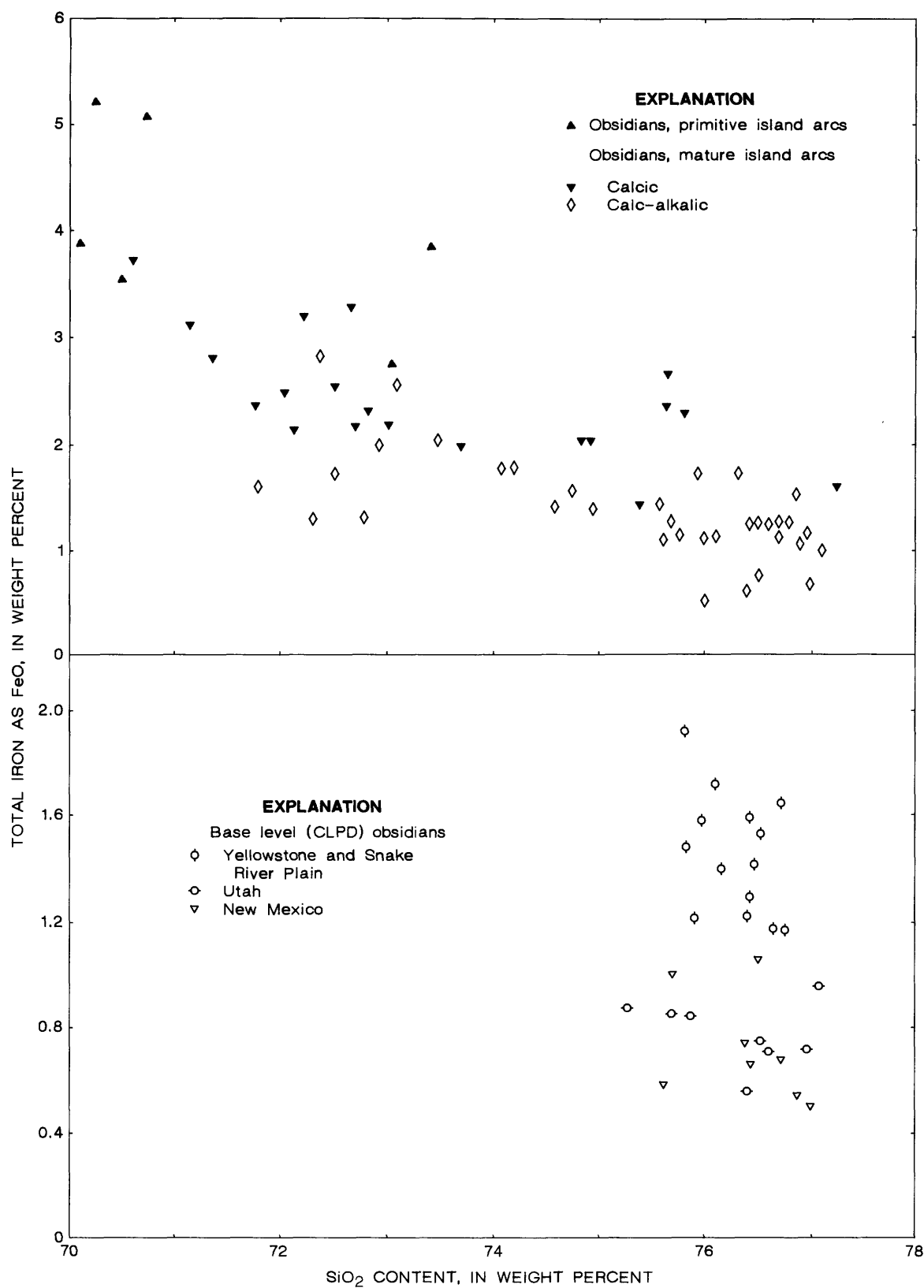
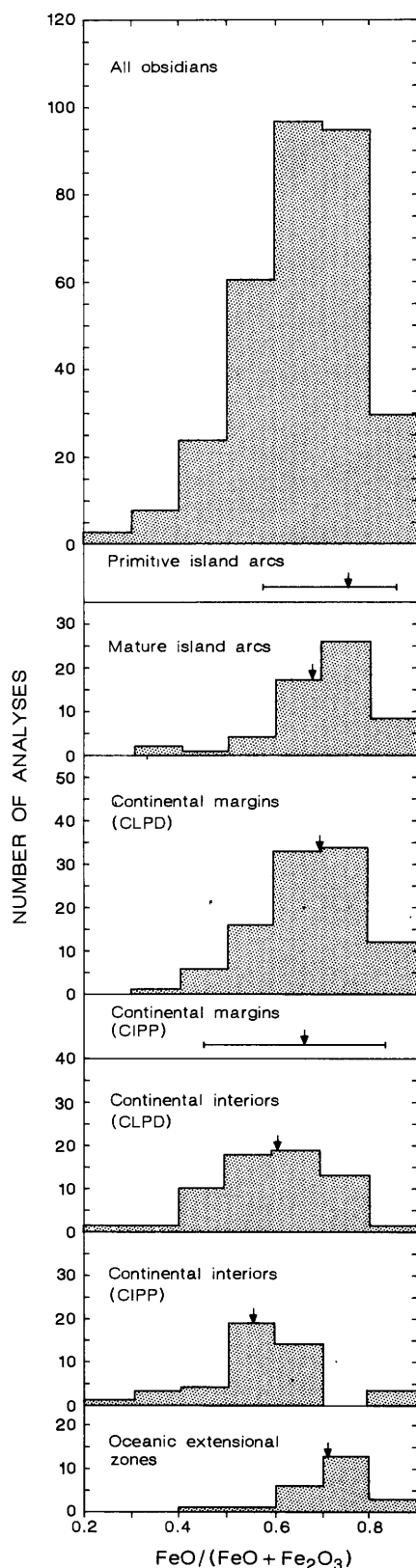


FIGURE 31.—SiO<sub>2</sub> content versus total iron as FeO for (A) obsidians of island arcs. Calcic rocks tend to have higher Fe contents, at equivalent SiO<sub>2</sub> values, than calc-alkalic types. Data from appendixes I, III, and V. B, Selected CLPD obsidians from United States continental interior. Data from appendixes I and III.



the new data (app. I). The peak of the histogram (fig. 32A) lies between 0.6 and 0.7, and the average for the magmas probably lies toward the higher end of this range. The range and average are comparable to those in peralkaline silicic glasses (Macdonald and Bailey, 1973).

Values of  $\text{FeO}/(\text{FeO} + \text{Fe}_2\text{O}_3) < 0.4$  and  $\geq 0.8$  (by weight) should be treated with caution. Many such values probably represent analytical error. Lower than average values may be determined on glasses from ash-flow tuffs, where oxidation of Fe can occur during tuff emplacement and consolidation. The average ratio for the whole-rock, welded-tuff obsidians in the compilation is 0.57, the range 0.40–0.74.

It is of interest to note that the average ratio calculated from the new analyses decreases in the sequence arc→margin→interior (table 7). Though the differences may not be significant in the light of possible hydration and analytical problems, it would be important genetically if silicic rocks from sialic areas truly were more oxidized than those from less mature crust.

#### MAGNESIUM

MgO has a compositional range of three orders of magnitude, from  $<0.005$  percent to  $>1$  percent. At the lower end of this range, analytical uncertainties are such that only broad generalizations are possible. At least some of the scatter at constant  $\text{SiO}_2$  results from intergroup differences. Obsidians from primitive arcs and calcic types from mature arcs are more magnesian than continental-margin and continental-interior rocks (fig. 29D).

Hildreth (1979, p. 71) noted that diffusion can result in impoverishment of Mg to levels below 100 ppm. The new data show that most obsidians with  $\text{MgO} < 0.05$  percent are CIPP (fig. 30C), but that CLPD magmas may also have extremely low MgO abundances (0.01 percent).

The strong positive correlations of MgO with  $\text{Al}_2\text{O}_3$ , CaO,  $\text{TiO}_2$ ,  $\text{P}_2\text{O}_5$ , Co, and Sr indicate that these oxides behave similarly in terms of both tectonic setting and genetic processes. All are depleted in lower temperature magmas. A slightly lesser correlation with Sc (0.63) results from the

FIGURE 32.—Distribution of  $\text{FeO}/(\text{FeO} + \text{Fe}_2\text{O}_3)$  ratio in obsidians. Obsidians of primitive island arcs and continental margins (CIPP types) are shown as ranges only. Arrows indicate average values. Data from appendixes I, III, and V. Samples 12, 15, 194, 266, 271, and 310 are omitted to preserve scale.

complex behavior of Sc in CIPP systems where Sc and Mg may show different senses of enrichment. Both K and Mg are down elements during CIPP. Potassium shows much greater differences in rocks from different tectonic settings (table 7), and the overall relation between K and Mg is negative.

$r \approx 0.60$	MgO
SiO <sub>2</sub> -----	-0.74
Al <sub>2</sub> O <sub>3</sub> -----	0.66
CaO -----	0.91
K <sub>2</sub> O -----	-0.71
TiO <sub>2</sub> -----	0.87
P <sub>2</sub> O <sub>5</sub> -----	0.82
Co -----	0.69
Sc -----	0.65
Sr -----	0.80

## CALCIUM

CaO shows a large variation in the obsidians, from 0.15 to 4.61 weight percent (fig. 30D). Even at constant SiO<sub>2</sub> there may be an almost order-of-magnitude variation. The scatter is related mainly to crustal type. CaO broadly decreases in the sequence obsidians of primitive island arcs→mature island arcs→continental margins→continental interiors (table 7; fig. 30D).

Within each group, there is a finer scale of variation. By definition (fig. 4), the calcic obsidians of mature arcs and margins have higher CaO/SiO<sub>2</sub> ratios than associated calc-alkalic types. Within the continental margin group, the obsidians of Medicine Lake have higher CaO, at given SiO<sub>2</sub> values, than those of the Newberry volcanic complex. Rhyolites of oceanic extensional zones break down into two subgroups: a higher CaO subgroup commonly associated with tholeiitic centers and a lower CaO subgroup of rhyolites from more alkalic centers.

CLPD and CIPP lead to very low CaO concentrations (<1 percent by weight) in high-silica rocks. Though a majority of specimens with CaO<0.5 percent are inferred to be CIPP types, many CLPD rocks from continental margins and interiors also show such low abundances (fig. 30D).

The elements which correlate most strongly with Ca are the same as those which correlate with Mg, with the addition of FeO and Rb. The strong positive correlation with Sr is predictable because they form a chemically coherent pair. Ca and Sr are, however, partitioned by CLPD and CIPP.

The average Ca/Sr ratio decreases in the sequence primitive island arc→mature island arc→continental margin (table 7), indicating relative enrichment of Sr

as the crust becomes more continental in character. The much higher ratio in continental-interior obsidians largely reflects the much stronger downward concentrating tendency of Sr in CIPP systems. In the Bishop and Coso systems, for example, the Ca/Sr ratio changed from 62 to  $\geq 322$  and 463 to 1,634, respectively, in lower temperature magmas (calculated from data in Hildreth, 1979, and Bacon and others, 1981); in the Tshirege Member of the Bandelier Tuff, the change was from 39 to  $\geq 236$  (R.L. Smith, unpublished data).

$r \approx 0.60$	CaO
SiO <sub>2</sub> -----	-0.71
Al <sub>2</sub> O <sub>3</sub> -----	0.61
FeO -----	0.72
MgO -----	0.91
K <sub>2</sub> O -----	-0.80
TiO <sub>2</sub> -----	0.85
P <sub>2</sub> O <sub>5</sub> -----	0.77
Co -----	0.66
Rb -----	-0.60
Sc -----	0.72
Sr -----	0.83

## SODIUM

Na<sub>2</sub>O shows a relatively small range, from 2.72 to 5.93 weight percent, and 86 percent of the samples falls within the more restricted range of 3.5 to 5.0 weight percent (fig. 29F). At constant SiO<sub>2</sub>, there is considerable within-group variation (fig. 30E); for example, at approximately 73 percent SiO<sub>2</sub>, continental-margin obsidians nearly cover the complete spread of Na<sub>2</sub>O values, whereas continental-interior rocks do the same at 76.5 percent SiO<sub>2</sub>. Variations within groups are therefore of the same magnitude as variations between groups.

Further spread is caused by CIPP, which tends to reverse the negative correlation between Na<sub>2</sub>O and SiO<sub>2</sub> resulting from crystal-liquid processes. Na<sub>2</sub>O is an up-element in all such systems yet described (Hildreth, 1979, 1981).

Na<sub>2</sub>O correlates strongly (that is,  $r > 0.60$ ) only with SiO<sub>2</sub>, FeO, and Zr. At a slightly lower level (0.55–0.60), it also correlates with Hf and Eu. All these elements show similar geochemical behavior during crystal-liquid processes (see section on zirconium and hafnium).

$r \approx 0.60$	Na <sub>2</sub> O
SiO <sub>2</sub> -----	-0.67
FeO -----	0.62
Zr -----	0.64

## POTASSIUM

$K_2O$  is more variable than  $Na_2O$ , the range being 0.64 to 6.60 weight percent (fig. 29G). As discussed earlier, tectonic setting plays an important role in potassium geochemistry. On a  $K_2O$  versus  $SiO_2$  plot (fig. 30F) rocks from island arcs fall, albeit with several exceptions, in a separate field from rocks of the continental margins and interiors. Within-group divisions can also be made; thus, in both margin and arc settings, calcic types are less potassic than calc-alkalic types at similar  $SiO_2$  values (table 8). The lowest  $K_2O$  values are found in obsidians from primitive island arcs (table 7), although they show some overlap with rhyolites from tholeiitic centers in more mature arcs.

Potassium is a downward-concentrating element during CIPP in contrast to sodium. Data from the rock-glass pairs and from the Woodson stock indicate K concentration in residual liquids during crystal fractionation.

It is of interest that  $K_2O$  shows only negative strong correlations ( $r > 0.60$ ). The reason is two-fold: the strong crustal control on K distribution and the fact that during CIPP, K shows different behavior to otherwise coherent elements such as Cs, Rb, Th, and U.

$r \geq 0.60$	$K_2O$
FeO-----	-0.61
FeO <sub>t</sub> -----	-0.62
MgO-----	-0.70
CaO-----	-0.80
TiO <sub>2</sub> -----	-0.67
P <sub>2</sub> O <sub>5</sub> -----	-0.61
Sc-----	-0.67
Sr-----	-0.69

 $Na_2O+K_2O$ 

The intergroup differences in  $K_2O$  are reflected in ( $Na_2O+K_2O$ ) abundances (fig. 29H). The lowest total alkali contents are found in arc (especially primitive arc) obsidians and in those from tholeiitic centers in oceanic extensional zones. As Miyashiro (1974) has stressed, however, mature-arc volcanoes can show a spectrum from low-alkali to high-alkali types, and arc rhyolites, in a few cases, may contain higher ( $Na_2O+K_2O$ ) abundances than continental-interior rocks of similar  $SiO_2$  content (fig. 30G). It is also difficult to separate continental-margin from interior rocks on the basis of alkali-silica relations.

Judging from the rock-glass pairs and the Woodson stock data, crystal fractionation more commonly produces a mild alkali enrichment in residual liquids. In the Bandelier, Bishop, and Coso CIPP systems, ( $Na_2O+K_2O$ ) values are about the

same in lowest and highest temperature eruptions, suggesting that upward concentration of  $Na_2O$  is about balanced on a weight basis by downward concentration of  $K_2O$ . On a molecular basis, however, the upward migration of Na and downward migration of K and Al results in a marked increase in the agpaitic index ( $(Na_2O+K_2O)/Al_2O_3$ ) upwards.

 $Na_2O/K_2O$  RATIOS

There is a very wide range of  $Na_2O/K_2O$  ratios, resulting mainly from variations in  $K_2O$  abundances (fig. 33). Though the ratios show an overall negative correlation with  $SiO_2$  (fig. 34), there is a great deal of scatter, resulting from several effects.

1. *Genetic processes.* Rock-glass pairs, data from zoned plutons, and the data from base level rocks indicate that crystal-liquid processes tend to produce decreasing  $Na_2O/K_2O$  ratios with increasing  $SiO_2$ . Values as low as 0.6 have been recorded in CLPD obsidians from the continental interiors.

CIPP reverses the trend, however, such that  $Na_2O/K_2O$  ratios increase in increasingly differentiated rocks. A magma series with a complex history may reach the same  $Na_2O/K_2O$  ratio twice or more during its evolution. It is worth noting that CIPP may begin to operate in different systems at different  $Na_2O/K_2O$  ratios. It is not possible to define a unique trend of base-level  $Na_2O/K_2O$  ratios against relative  $SiO_2$ , as they actually define a broad band. Some systems evolve to high-silica compositions before beginning to evolve by CIPP; for example, the Yellowstone complex magma was very rich in  $SiO_2$  and potassic at this stage. The Long Valley and Clear Lake systems may be inferred to have been undergoing CIPP at less silicic and more sodic compositions. It is tempting to suggest that this may be a general case (that is, calc-alkalic systems begin to evolve by CIPP at more "mafic" compositions than alkali-calcic systems), but there is as yet insufficient information on the true base-level compositions of most relevant systems to test this.

2. *Tectonic environment.* Clear effects of tectonic environment are related mainly to  $K_2O$  variations. At given  $SiO_2$  values,  $Na_2O/K_2O$  ratios decrease in the order of obsidians from primitive island arcs → calcic obsidians from mature island arcs → calc-alkalic obsidians from mature island arcs → calcic types from continental margins → calc-alkalic obsidians of continental margins → obsidians from continental interiors. Rhyolites from oceanic extensional zones have ratios broadly comparable to those of the continental margins.

3. *Within-group variations.* Variations within groups also exist. The Newberry obsidians have

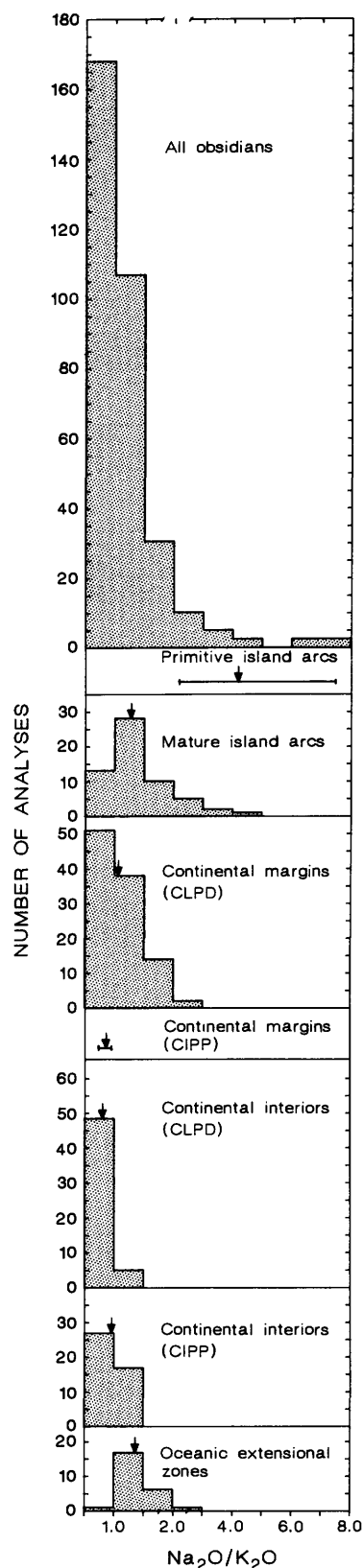


FIGURE 33.—Distribution of  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratios in obsidians. Obsidians of primitive island arcs and continental margins (CIPP types) are shown as ranges only. Arrows indicate average values. Data from appendixes I, III, and V. Note change of scale in ratio axis.

higher  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratios than rocks of comparable  $\text{SiO}_2$  content from Medicine Lake. Ratios in CLPD glasses from the American continental interior may vary by a factor of two. The Java rhyolites are more potassic than those from New Zealand.

4. *Magma mixing.* Further variation in the  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  ratio is caused by magma mixing. The Novarupta rhyolites with  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  of 1.4–1.7 (Nos. 3, 243, 244) represent somewhat more potassic rhyolites mixed with a more sodic, less silica-rich member.

$r \approx 0.60$	$\text{Na}_2\text{O}/\text{K}_2\text{O}$
$\text{SiO}_2$ -----	-0.62
$\text{FeO}$ -----	0.67
$\text{FeO}_t$ -----	0.67
$\text{MgO}$ -----	0.70
$\text{CaO}$ -----	0.73
$\text{Na}_2\text{O}$ -----	0.71
$\text{K}_2\text{O}$ -----	-0.90
$\text{TiO}_2$ -----	0.70
$\text{Sc}$ -----	0.64

#### WATER AND THE ISOTOPES OF HYDROGEN AND OXYGEN

##### WATER

Water in the obsidians ranges from 0.01 percent to approximately 1 percent by weight. Values consistently less than about 0.1 percent probably need some special explanation, either analytical or geological. Friedman and others (1963) showed from experimental work on viscosity and water content of rhyolite glass that obsidian lavas extruded at 900 °C would have no more than 0.1 percent  $\text{H}_2\text{O}$  in equilibrium at atmospheric pressure. Because the solubility of  $\text{H}_2\text{O}$  in obsidian increases with decreasing temperature at constant pressure, these authors concluded that the water content of obsidian equilibrated at 1 atm would be a function of the temperature of the obsidian. As most rhyolite obsidians are probably erupted at temperatures less than 900 °C, most will have water contents greater than 0.1 percent by weight.

Recent work by Eichelberger and Westrich (1983) on the solubility of  $\text{H}_2\text{O}$  in rhyolitic magma suggests about 0.2 percent  $\text{H}_2\text{O}$  in equilibrium with melt at 1 atm pressure. This work is essentially in agreement with that of Friedman and others (1963).

Our new data suggest that  $\text{H}_2\text{O}$  in rhyolite flows and domes rarely exceeds 0.5 percent and that higher values are found only in intrusive margins of domes, in dikes, or in clasts from pyroclastic deposits.

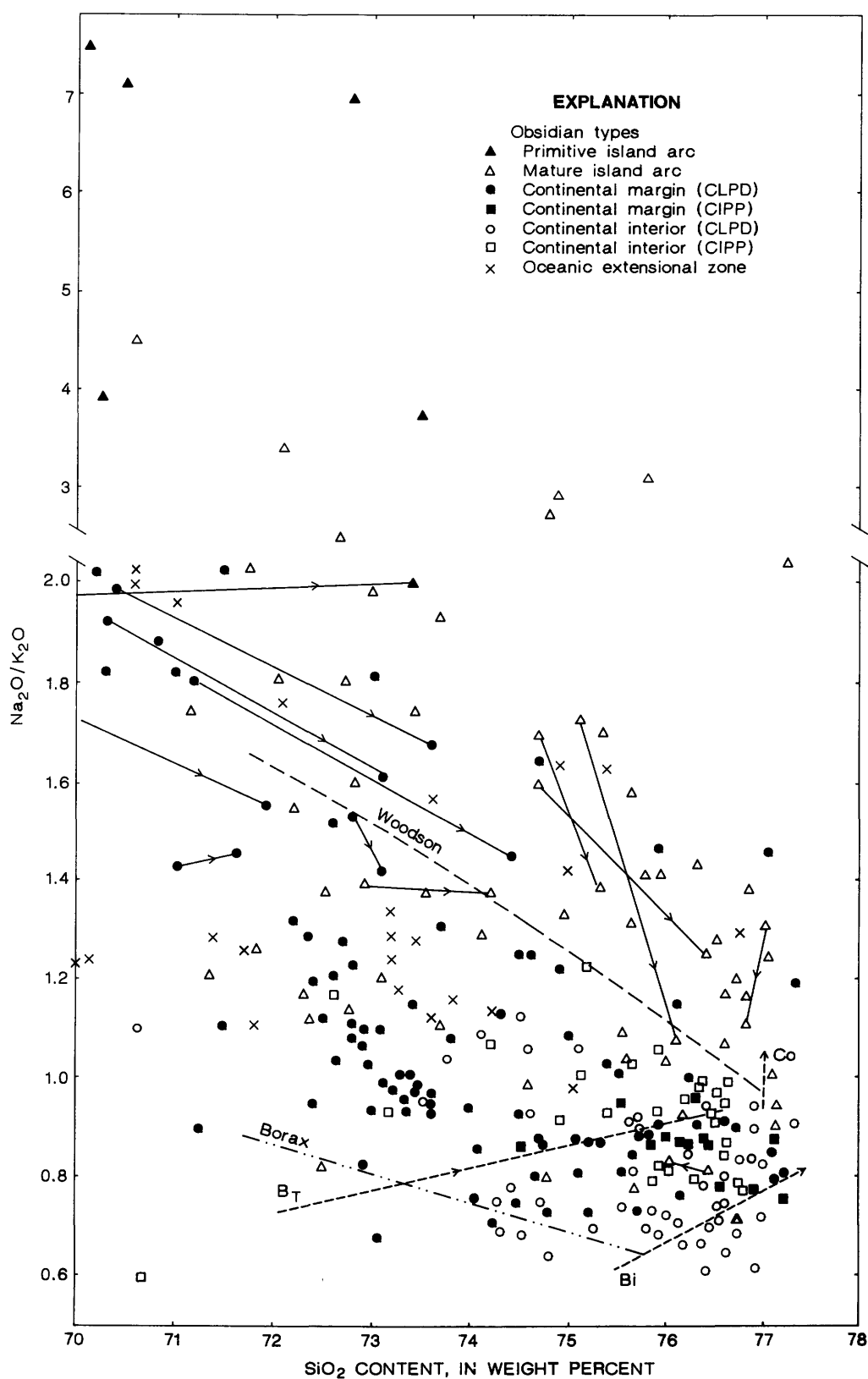


FIGURE 34.— $\text{SiO}_2$  content versus ratio of  $\text{Na}_2\text{O}/\text{K}_2\text{O}$  for obsidians and various comparative rocks. Data sources are same as for figure 5 (Bi, Bishop Tuff; Co, Coso Range;  $B_T$ ,

Tshirege Member, Bandelier Tuff). Note change of scale on y axis. Arrows on solid tielines and on dashed lines point in direction of liquid fractionation.

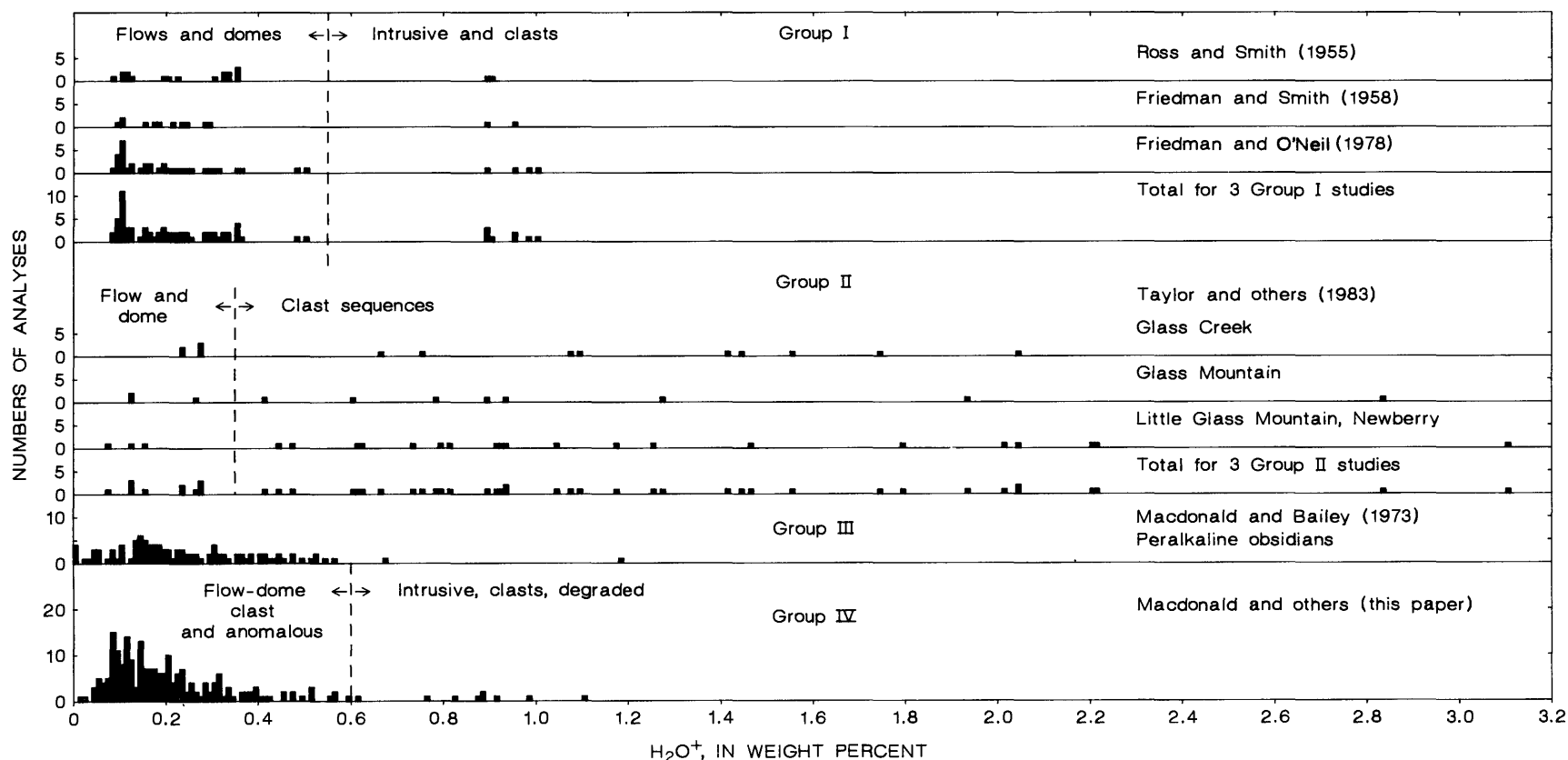


FIGURE 35.—Distribution of  $H_2O^+$  data from all major studies of  $H_2O$  in obsidians. These studies are shown as four major groups. Group I, early studies emphasizing hydration of obsidian to form perlite and studies of deuterium/hydrogen (D/H) relations. Many of the same

samples were used in all three studies. Group II, recent studies of clast sequences showing many samples of higher  $H_2O^+$  content than earlier studies. Group III, data on peralkaline obsidians. Group IV, data on subalkaline obsidians studied in this paper.

Approximately 25 percent of the obsidians in the data base contain <0.1 percent  $\text{H}_2\text{O}$ . About half of these contain between 0.08 and 0.1 percent. On the basis of a comparison of our data with other data representative of modern water analyses by vacuum extraction methods (fig. 35), our obsidians appear to differ on the low side by at least 0.02 weight percent. We think that this difference is somehow related to differences in analytical techniques and is exaggerated in the water concentration range typical of the most highly annealed obsidians. In this range, vacuum extraction is probably the more efficient method for maximum water extraction. Below about 0.08 percent, there may be other reasons for very low amounts. These reasons include, as most likely causes, superheat and devitrification. Superheat may often be suspected from the presence of basaltic or andesitic xenoliths or xenocrysts that are commonly found in rhyolites of the rhyolite-basalt association and in agglutinates of rhyolitic and dacitic composition in andesitic stratovolcanoes.

Examples of such obsidians from appendix I are specimen 2, an agglutinate from Okmok caldera, Alaska, and specimen 176, an agglutinate from the 1875 eruption of Askja, Iceland, both having 0.05 percent  $\text{H}_2\text{O}^+$ . Specimen 96 from White Mountain, Utah, with 0.01 percent  $\text{H}_2\text{O}^+$ , the lowest in the data base, is also the sample nearest to total devitrification, as it is flecked with tiny, gray spherulites. This material may also be an example of superheated obsidian, because it is from a small rhyolite dome within a field of basalts; the rhyolite locally contains basaltic xenoliths. Aspects of the chemical composition of this rock are consistent with contamination by mafic magma (see section "Magma Mixing and Assimilation"). Obsidian sample 85, with 0.04 percent  $\text{H}_2\text{O}^+$ , is a welded facies of the Walcott Tuff, Idaho, and formed in a thin unit of very high temperature, fine-grained ash. We suspect that vacuum extraction of water from these samples would yield water contents slightly higher than those cited, but probably less than 0.08 percent.

Several obsidians in the data base, from flows or domes, were received from donors who had already prepared powders for analysis. Some of these samples appear to have anomalously high water values. We suggest that these samples have been degraded by adsorption of a few tenths of a percent  $\text{H}_2\text{O}$  between sample preparation and analysis, not all the adsorbed  $\text{H}_2\text{O}$  being driven off at 110 °C. This problem is common with obsidian chemistry, especially with older published analyses. Examples of such problems may be seen with Crater Lake samples 11–18, which range from 0.14 to 1.10 percent  $\text{H}_2\text{O}^+$ ,

compared with samples 19–21, which range from 0.10 to 0.19 percent  $\text{H}_2\text{O}^+$ . Samples 19–21 were prepared directly for this study with water analyses in mind, whereas samples 11–18 were prepared some years before we analyzed them. The sample containers were not tightly sealed, allowing adsorption of water before analysis. The differences in the Llao Rock samples are particularly notable. It is doubtful that this difference is due to natural glass hydration, as the rocks are less than 7,000 years old. A similar contrast is seen in samples 110 and 111 from No Agua, New Mexico, with 0.15 and 0.91 percent  $\text{H}_2\text{O}^+$ , respectively. Sample 110 was prepared for this study, whereas 111 was from a stored tube sample.

We placed an upper limit of 1 percent  $\text{H}_2\text{O}^+$  on the data bank, because the geologic and isotopic evidence available at the time of data collection indicated that rhyolitic glasses containing more than 1 percent  $\text{H}_2\text{O}^+$  were overwhelmingly hydrated with meteoric water (Friedman and Smith, 1958; Taylor, 1968). However, Eichelberger and Westrich (1983) and Taylor and others (1983), during studies of obsidian clasts from pyroclastic deposits, have determined  $\text{H}_2\text{O}^+$  contents up to about 3 percent by weight. They interpret this water as primary, thus extending the known range of water in obsidian from 1 to 3 percent. Other, more recent, work (Newman and others, 1985; O'Neil and Taylor, 1985; Dunbar and Kyle, 1986) has extended the number of localities and samples of obsidian pyroclasts containing  $\text{H}_2\text{O}^+$  above 1 percent (table 11). More will surely be found.

Chemical changes related to low-temperature glass hydration are well covered in the literature and will not be repeated here (Truesdell, 1962, 1966; Lipman, 1965; Noble, 1967; Noble and others, 1967; Macdonald and Bailey, 1973; Stewart, 1979). To date, the variable water contents in high-water clasts have not been shown to be accompanied by any significant differences in the composition of the glass, other than the D/H relations discussed below. There is no evidence, therefore, that the highly systematic nature of obsidian chemistry based on samples with <1 percent  $\text{H}_2\text{O}^+$  would be complicated by inclusion of higher water rocks, even should they prove to be common geologically.

The discovery of high-water obsidians and the growing importance of obsidian studies for deciphering the chemistry of magmas make it mandatory that the distinction between hydrated and nonhydrated glass be fully recognized and understood. In most cases, visual examination is sufficient for the trained eye, but there are many



TABLE 11.—Range of H<sub>2</sub>O contents and  $\delta$ D values in subalkaline silicic obsidians

	H <sub>2</sub> O* (weight percent)	$\delta$ D (per mil)
Ross and Smith (1955)	0.08 – 0.9	—
Friedman and Smith (1958)	.09 – .95	–88 to –165
Friedman and O'Neil (1978)	.07 – .31	–90 to –180
*Taylor and others (1983)	.10 – 3.1	–60 to –130
O'Neil and Taylor (1985)	.23 – .64	–91 to –134
Westrich and others (1985)	.08 – .65	–104 to –119
*Newman and others (1985)	.12 – $\leq$ 2.6	–52 to –123
*Dunbar and Kyle (1986)	.23 – .64	—
Macdonald and others (this paper)	.01 – 1.1	—

\*Clast sequences

glasses, such as those found in the group generally called pitchstones, where the field distinction may be more difficult and isotopic (see the subsection, "Deuterium and Hydrogen" below) or other chemical studies may be necessary to distinguish them.

Summing up the water data after allowing for a few samples degraded by adsorption of water before analysis, it seems possible to make the following generalizations regarding thermal history and provenance of subalkaline silicic obsidians based on H<sub>2</sub>O<sup>+</sup> contents (see also fig. 36).

H <sub>2</sub> O* (weight percent)	Association
<0.1	----- Superheated at $T > 900$ °C. Equilibrated at $P < 1$ atm. Close to total devitrification. Analytical error.
–0.1 – –0.5	----- Lava flow or dome carapace.
–0.5 – –1.0	----- Dike or intrusive mar- gin of dome.
<0.1 – >1.0	----- Clasts in pyroclastic deposits.

## DEUTERIUM AND HYDROGEN

Deuterium (D)-hydrogen (H) relations in rhyolitic glasses were first studied by Friedman and Smith (1958). These authors found a significant difference in D/H ratios between obsidian and perlite in pairs from the same outcrops; tielines in figure 37 connect coexisting pairs from several localities. The D/H ratio in water extracted from perlitites was a reflection of the D/H ratio in meteoric water at that locality. The obsidians showed no such relation, and Friedman and Smith (1958) concluded that the water in obsidian was retained from the magmatic state, concurring with the ear-

lier conclusions of Ross and Smith (1955). Taylor (1968) confirmed the Friedman-Smith study and strengthened it by oxygen isotope measurements, which led to the same conclusion.

More recent work by Taylor and others (1983), Newman and others (1985), and O'Neil and Taylor (1985) has shown a positive relation between D/H ratio and total water in obsidians, with D enriched in high-water clasts (fig. 37; table 11). These authors interpret this relation as evidence of degassing of water from the magma and fractionation of D to the vapor phase from beginning to end of a rhyolitic eruption. These studies, made on series of obsidian clasts from close-spaced pyroclastic beds, record a progressive decrease of H<sub>2</sub>O in clasts from earlier erupted beds, through the pyroclastic phase, to final degassed domes and lava flows. The sequence is accompanied by progressive decrease in D/H ratios. The fractionation of D from H with decreasing water content is interpreted to be consistent with the Rayleigh distillation law.

The infrared studies of Newman and others (1985) on the OH/H<sub>2</sub>O relations suggest that this ratio increases with decreasing total water, implying a preference for OH by the lighter isotope.

## OXYGEN ISOTOPES

Taylor (1968) noted that, with respect to mafic, ultramafic, and many intermediate rocks, granites and rhyolites exhibit a very large range in  $\delta^{18}\text{O}$  values, the range being from –6.3 to +17.0 per mil. He arbitrarily divided the granitic rocks into five groups on the basis of  $\delta^{18}\text{O}$  contents and showed that, compared to the total range of values, nonhydrated obsidians show a rather restricted range, the majority of rocks falling between 5.5 and 7.7 per mil (fig. 38; table 12).

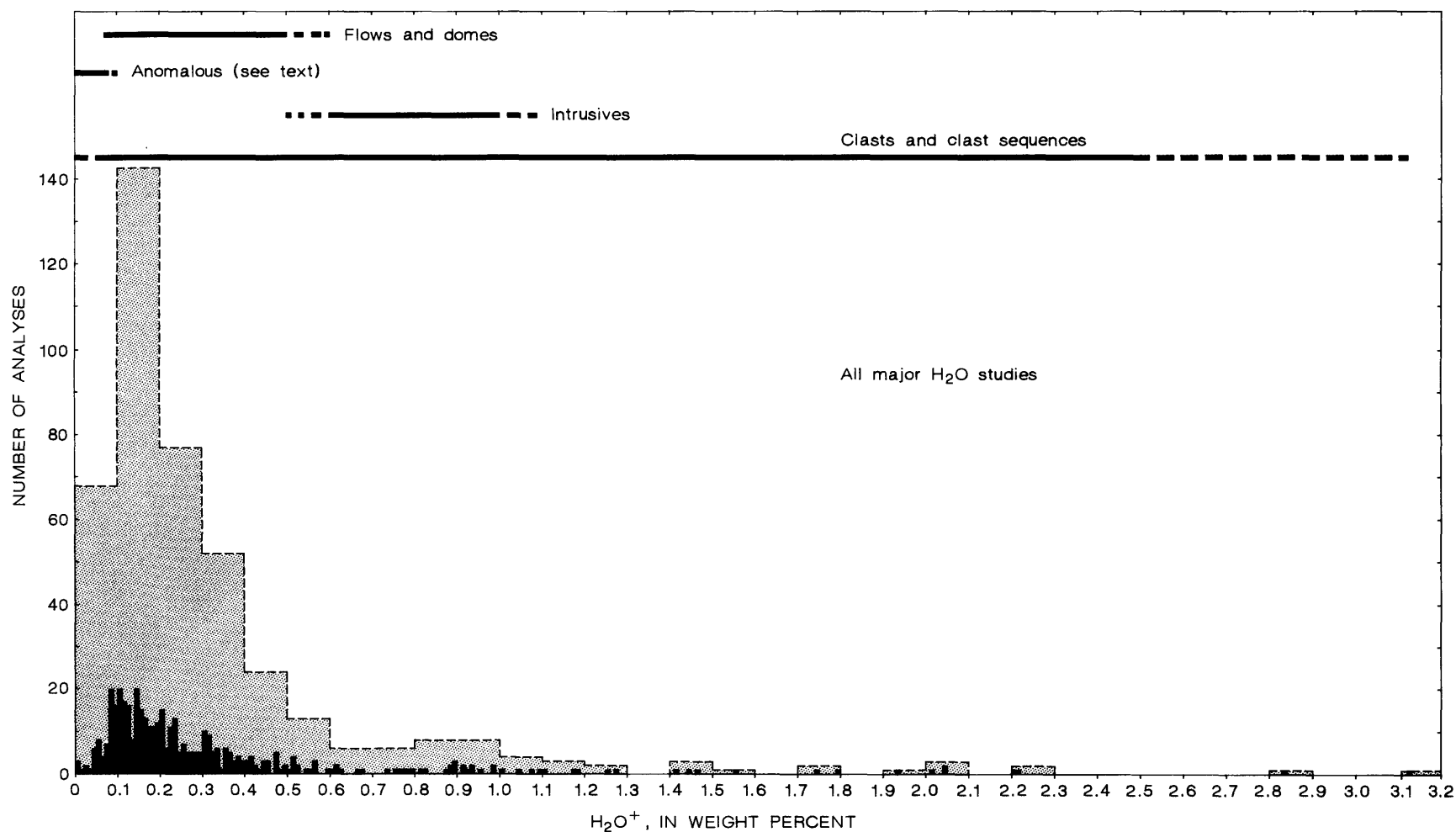


FIGURE 36.—Distribution of total  $H_2O^+$  data from four groups of obsidians shown in figure 35. Total data are shown in increments of 0.01 (solid bars) and 0.1 light shaded bars) weight percent  $H_2O$ , respectively. Horizontal bars show ranges (dashed where uncertain) of  $H_2O$  by obsidian provenance: flows and domes, intrusives, clasts and clast sequences, anomalously low  $H_2O$ , and overlaps as suggested by total data base.

In a later study, Muehlenbachs (1973) recorded the occurrence in Iceland of low  $^{18}\text{O}/^{16}\text{O}$  rhyolitic obsidians. These have values from 2.8 to 4.4 per mil and belong to Taylor's (1968) LL group (see fig. 38), thus expanding the known compositional spectrum in obsidians.

Taylor (1968) suggested that silicic obsidians demonstrate a geographic distribution of  $^{18}\text{O}/^{16}\text{O}$  ratios. L-group obsidians tend to be from either oceanic areas or continental-margin settings, whereas H-group glasses are from continental-interior areas (fig. 38). He noted some exceptions: two samples from the Jemez

Mountains, N. Mex., belong to the L group, and the Clear Lake, Calif., obsidians are peculiar in having  $\delta^{18}\text{O}$  values not only higher than other margin types but in fact higher than any other rhyolite obsidian.

Broadly speaking, this distribution was attributed to differing modes of evolution for the interior- and margin-type magmas (Taylor, 1968). The continental-margin varieties formed by differentiation of basaltic magma, whereas contamination by  $^{18}\text{O}$ -rich crustal material has played some role in the evolution of the interior-type magmas. However, on the basis of available data (fig. 38),

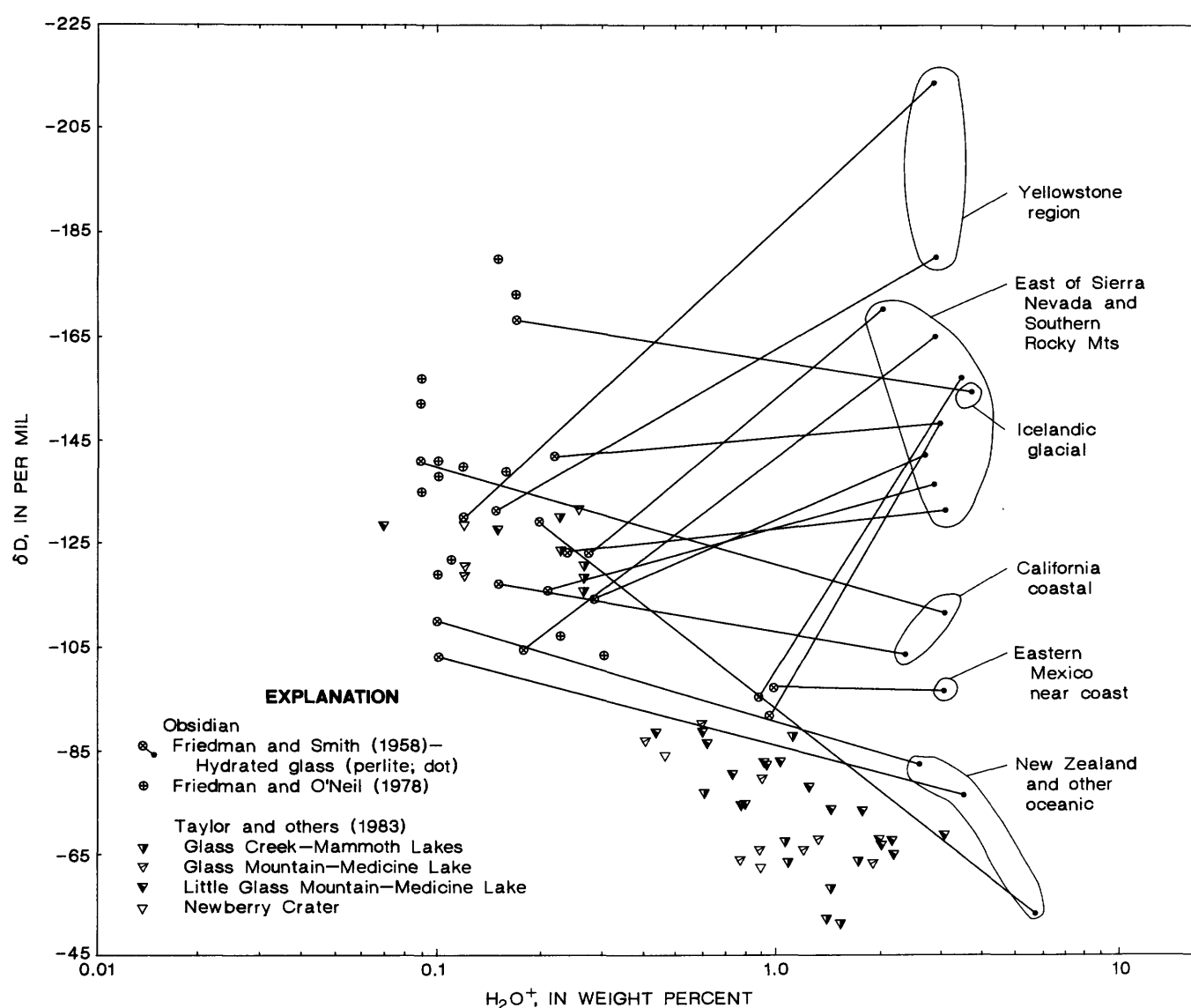


FIGURE 37.— $\text{H}_2\text{O}^+$  content versus  $\delta\text{D}$  for obsidian and obsidian-hydrated glass (perlite) pairs. Obsidian data show strong positive correlation between increasing  $\text{H}_2\text{O}^+$  and decreasing  $\delta\text{D}$ . Hydrated glass data are shown to reaffirm that there is a real

difference between  $\delta\text{D}$  in most hydrated glass and  $\delta\text{D}$  in high-water obsidians, and that  $\delta\text{D}$  in obsidian appears to relate to  $\text{H}_2\text{O}$  content, whereas  $\text{H}_2\text{O}$  in hydrated glass appears to relate to deuterium/hydrogen (D/H) composition of local meteoric waters.

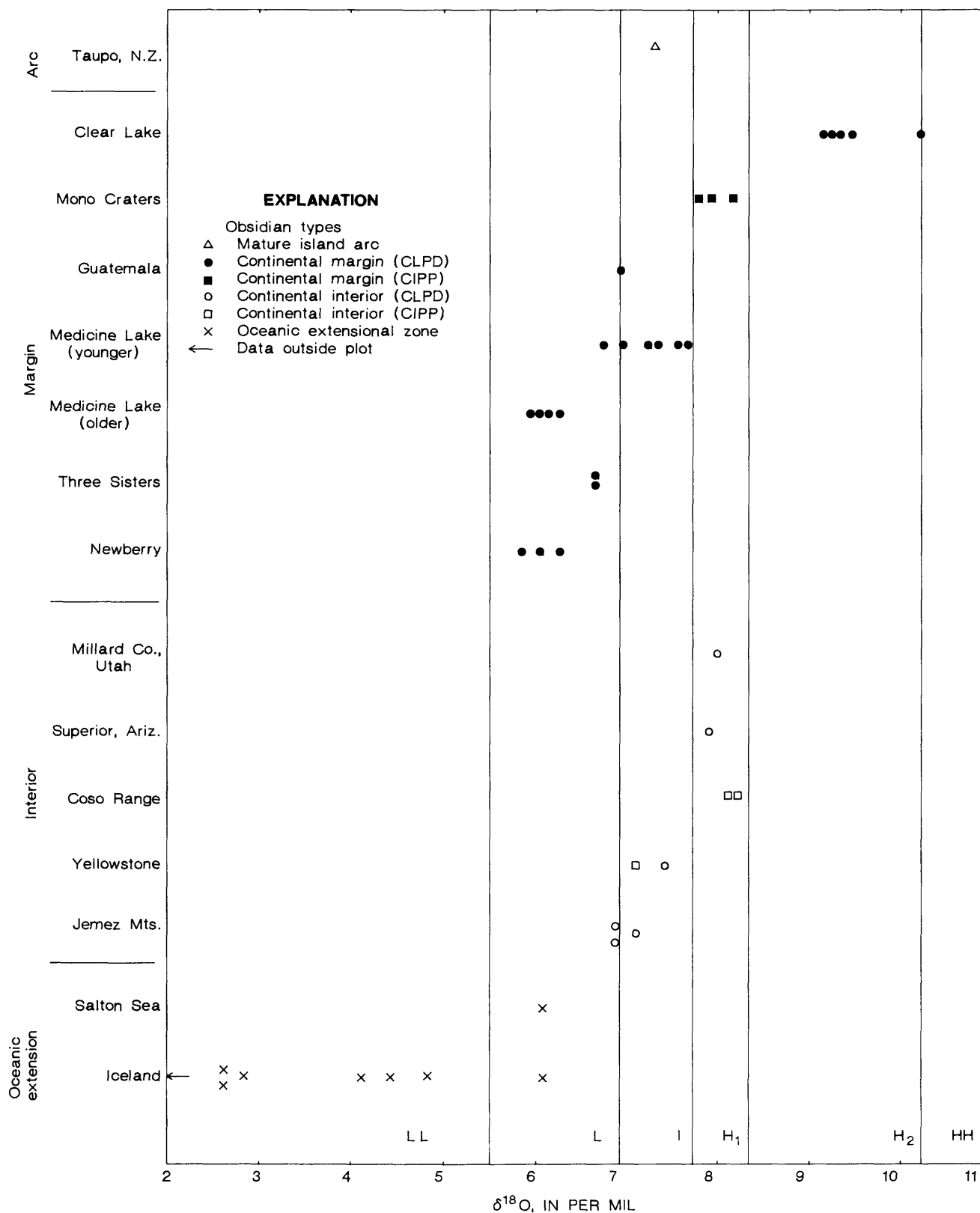


FIGURE 38.— $\delta^{18}\text{O}$  of whole rock and glass samples of obsidians. Vertical lines separate arbitrary groups distinguished by Taylor (1968); limits are: LL,  $\delta < 5.5$ ; L,  $5.5 < \delta < 7.0$ ; I,  $7.0 < \delta < 7.8$ ; H<sub>1</sub>,  $7.8 < \delta < 8.4$ ; H<sub>2</sub>,  $8.4 < \delta < 10.2$ ; HH,  $\delta > 10.2$ . Data from appendix I.

TABLE 12.—Oxygen isotope analyses of silicic obsidians

Locality	Published specimen number	Material analyzed	$\delta^{18}\text{O}$ (per mil)	Reference
<b>Newberry Volcano, Oregon</b>				
Rhyolite dome, due S. of East Lake -----	PL-5-3	Whole rock	6.3	(1)
Younger obsidian flow, SE. corner of East Lake -----	PL-6-3	Whole rock	6.1±0.0	(1)
Youngest obsidian flow in caldera -----	PL-4-3	Whole rock	5.9±0.2	(1)
<b>Medicine Lake Highlands, Calif.</b>				
Rhyolite-dacite composite flow -----	ML-55	Whole rock	7.4±0.2	(1)
Older rhyolite obsidian, 5 mi NE. of Glass Mountain -----	ML-59	Whole rock	6.2±0.1	(1)
Older rhyolite obsidian, 3.5 mi S. of Little Glass Mountain -----	ML-65	Whole rock	6.1±0.1	(1)
Older rhyolite obsidian, 7 mi S. of Little Glass Mountain -----	ML-66	Whole rock	6.3±0.1	(1)
Perlitic rhyolite, 1.5 mi SW. of Mt. Hoffmann -----	ML-17	Whole rock	6.0±0.2	(1)
Big Glass Mountain flow, 2 mi NE. of Glass Mountain -----	ML-57	Whole rock	7.3±0.1	(1)
	ML-57a	Black glass	7.3	(1)
	ML-57a	Gray glass	7.0	(1)
Little Glass Mountain flow, 1 mi -----	ML-63	Whole rock	7.7±0.2	(1)
N. of Little Glass Mountain -----	ML-23	Whole rock	7.6±0.1	(1)
Little Glass Mountain flow -----	Doe-8	Whole rock	6.8±0.2	(1)
<b>Clear Lake volcanic field, Calif.</b>				
Older rhyolite obsidian, 2.7 mi S. of Mt. Konocti -----	CL-20-3	Whole rock	9.4	(1)
Older rhyolite obsidian, E. side of Konocti Bay road -----	CL-9-3	Whole rock	9.3	(1)
Older rhyolite obsidian, W. side of Konocti Bay road -----	CL-10-3	Black glass	9.3	(1)
	CL-10-3	Gray glass	9.5	(1)
Older rhyolite obsidian, E. side of Konocti Bay road -----	CL-19-3	Black glass	9.2	(1)
Recent flow, 1 mi SE. of Borax Lake -----	Doe-5	Whole rock	10.2±0.1	(1)
<b>Mono Craters, Calif.</b>				
Panum Crater -----	T-807	Whole rock	8.0	(1)
Dome, 7 mi SE. of Lee Vining -----	Mono-2	Whole rock	7.9±0.2	(1)
Flow, 2 mi E. of June Lake -----	Mono-7	Whole rock	8.2	(1)
<b>Coso volcanic field, Calif.</b>				
Coso Hot Springs -----	T-341d	Whole rock	8.2	(1)
	Coso-2	Whole rock	8.1	(1)
Salton Sea, Calif., Obsidian Butte -----	W-772	Whole rock	6.1±0.2	(1)
<b>Yellowstone volcanic field, Wyo.</b>				
Cougar Creek vent dome -----	Doe-40	Whole rock	7.4±0.1	(1)
Obsidian Cliff -----	YNP-3	Whole rock	7.1	(1)
Near Black Rock, Millard Co., Utah -----	Ward-obs.	Whole rock	8.0±0.0	(1)
Superior, Ariz., Marekanite nodules -----	Ariz-5	Black obs.	7.9±0.1	(1)
<b>Jemez Mountains volcanic field, N. Mex.</b>				
Nodule in perlite, Arroyo Hondo -----	Doe-28	Whole rock	7.1±0.2	(1)
Obsidian, Los Posos -----	Doe-29	Whole rock	6.9±0.1	(1)
Jemez Creek Canyon, S. of Rio San Antonio -----	NM-4-4	Whole rock	6.9±0.1	(1)
Guatemala Ixtepeque flow, Obrajuelo complex -----	G-664	Whole rock	6.9±0.1	(1)
<b>Iceland</b>				
Hrafninnuhryggur -----	—	Whole rock	2.8±0.13	(2)
Kerlingarfjöll -----	—	Glass	4.8±0.13	(2)
Prestahnukur -----	—	Glass	4.4±0.13	(2)
Landmannalaugar -----	BMR	Whole rock	2.8±0.13	(2)
Oraefajökull -----	SAL-74	Whole rock	6.11	(3)
Krafla -----	KK-26	Whole rock	2.88	(3)
Askja, 1875 eruption -----	A-1875	Whole rock	1.37	(3)
Taupo, New Zealand -----	JH-515	Whole rock	7.4±0.1	(4)

## References:

- (1) Taylor (1968)
- (2) Muehlenbachs (1973)
- (3) Condomines and others (1983)
- (4) Blattner and Reid (1982)

we feel that Taylor (1968) perhaps overemphasized the geographical control over  $^{18}\text{O}/^{16}\text{O}$  ratios, and that no distinction can yet be made between obsidians of the continental margin and continental interiors.

Studies of individual volcanic centers reveal rather more complex petrogenetic relations. Thus, in the Medicine Lake Highlands, Taylor (1968, p. 44–47) showed that there is a general order of increasing  $^{18}\text{O}/^{16}\text{O}$  ratios in the sequence andesite→basalt→rhyolite→dacite; that is, there is no simple relation between the ratio and  $\text{SiO}_2$  content. There is, however, a general increase in  $\delta^{18}\text{O}$  values of each rock type with decreasing age. Older, pre-Modoc, flows tend to belong to the L group while younger, recent flows are of I type (fig. 38).

These observations militate against any simple process of magmatic differentiation connecting the major rock types at Medicine Lake; at least two different mechanisms were operative. Taylor (1968, p. 47) specifically excludes the involvement of silicic crustal rock in the generation of the magma but allows the possibility of magma mixing as a partial cause of the isotope variations.

The  $\delta^{18}\text{O}$  data for the Newberry volcano also preclude crustal contamination with sedimentary rocks and (or) granites as an important mechanism in the formation of the rhyolites (Taylor, 1968, p. 48).

As well as being higher in  $\delta^{18}\text{O}$  than any other obsidians yet analyzed, the Clear Lake rocks also show a progression in  $^{18}\text{O}$  content with decreasing age, from 8.8 per mil in a Pleistocene rhyodacite to 10.2 per mil in a younger obsidian. Again, no simple explanation of either observation can yet be offered. Closed-system fractionation of basaltic magma is precluded by these data.

Taylor's (1968) studies revealed how complex magmatic processes at individual centers are superimposed on broad regional patterns. Work by Lipman and Friedman (1975) stressed another complicating factor. They interpreted systematic oxygen isotope variations in the phenocryst phases of compositionally zoned ash-flow sheets and related flows in southern Nevada as being due to the influx of meteoric water into silicic magma chambers. Interaction of the water and the hot magma resulted in the magma becoming progressively lighter in  $^{18}\text{O}$  with decreasing age. In contrast, Stuckless and O'Neil (1973) found no evidence of significant interaction between melts and meteoric water during the evolution of five ash-flow sheets in the Superstition-Superior area, Arizona. Measurement of  $^{18}\text{O}$  in quartz phenocrysts of the Lava Creek Tuff showed that the Yellowstone magma

chamber had a modest  $^{18}\text{O}/^{16}\text{O}$  gradient at the time of this caldera-producing eruption (Hildreth, 1981) and that oxygen was systematically, isotopically lighter at the top of the chamber. These examples apparently point to the existence of isotopic variability in some, but not all, large chambers. The mechanisms generating the variability are still not understood.

However, in studies of zoned ash-flow sheets, great care must be taken in interpreting isotopic variations in glass samples that may have been secondarily hydrated. Six whole-rock samples covering the compositional range in the Bishop Tuff, California (Halliday and others, 1984), gave  $\delta^{18}\text{O}$  in the range 5.9–10.3 per mil, whereas the sanidine phenocrysts from the same rocks gave 6.7–7.9 per mil. The  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios were essentially constant at  $0.51258 \pm 0.00001$ . Halliday and others (1984) suggest that the extreme isotopic disequilibria resulted from low-temperature, post-eruptive interaction with meteoric water and that the magmas were isotopically uniform prior to eruption.

Muehlenbachs (1973) has reported the occurrence on Iceland of rhyolitic obsidians with  $\delta^{18}\text{O}$  values as low as 2.8 per mil. He suggests that at least some of these rhyolites were formed by the partial melting of hydrothermally altered basalts within the crust. It would be very valuable if low  $\delta^{18}\text{O}$  values could be used to characterize basaltic source rocks in this way. Chemically, the Icelandic rocks are most similar to the St. Andrew Strait rhyolites and, somewhat less closely, to those from Salton Sea, California. No oxygen isotope data have been published for the St. Andrew Strait rocks, but one analysis is available for a Salton Sea rock (Taylor, 1968, table 1). The value of  $6.1 \pm 0.2$  per mil, though by no means anomalously low, is among the lowest values for American obsidians.

#### TITANIUM

The range of  $\text{TiO}_2$  abundances is large, 0.02–0.9 weight percent. Its strongest positive correlations are with  $\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{P}_2\text{O}_5$ , and, like those oxides and trace elements Co and Sc, it shows negative correlations with  $\text{SiO}_2$  and  $\text{K}_2\text{O}$ .

The only clear effect of crustal type on  $\text{TiO}_2$  relative to  $\text{SiO}_2$  is that calcic obsidians from mature island arcs have higher  $\text{TiO}_2$  contents than the other rhyolite groups. The lower average  $\text{TiO}_2$  in continental-interior obsidians (table 7) is largely a function of the higher  $\text{SiO}_2$  in these rocks.

On a  $\text{SiO}_2$ - $\text{TiO}_2$  plot (fig. 30H), the trends of rock-glass pairs, the Woodson stock, magma mixing

series, and CIPP systems are subparallel, suggesting that they are all equally efficient in fractionating  $\text{TiO}_2$ . Rocks having  $\text{TiO}_2 < 0.1$  weight percent are predominantly from CIPP systems, but several CLPD rocks from all the main rhyolite groups also show low values. No field unique to CIPP may thus be distinguished on this plot.

Within-group variations are relatively pronounced. The Newberry obsidians have lower  $\text{TiO}_2$  than those from Medicine Lake at equivalent  $\text{SiO}_2$ . Yellowstone base-level rocks have rather high  $\text{TiO}_2$ . Obsidians from the U.S. Gypsum mine, Nevada, Government Mountain, Arizona, and Xalapasquillo, Mexico, are all anomalously low in  $\text{TiO}_2$ .

$r \approx 0.60$	$\text{TiO}_2$
$\text{SiO}_2$ -----	-0.79
$\text{FeO}$ -----	0.78
$\text{FeO}_i$ -----	0.80
$\text{MgO}$ -----	0.87
$\text{CaO}$ -----	0.85
$\text{K}_2\text{O}$ -----	-0.67
$\text{P}_2\text{O}_5$ -----	0.84
$\text{Co}$ -----	0.66
$\text{Sc}$ -----	0.71
$\text{Eu}$ -----	0.61

#### PHOSPHORUS

Although the range of  $\text{P}_2\text{O}_5$  values is very large, 0.00X to 0.55 weight percent, approximately two-thirds of the samples have  $< 0.05$  percent  $\text{P}_2\text{O}_5$  and about one-third have  $< 0.02$  percent  $\text{P}_2\text{O}_5$ . CIPP rocks in particular show extreme P depletion, few samples having more than 0.02 percent  $\text{P}_2\text{O}_5$ . Hildreth (1979, p. 71) has already noted the tendency of CIPP to produce low-temperature magmas with  $\text{P}_2\text{O}_5 \sim 230$  ppm.

At such low levels, analytical uncertainty might contribute to disguising significant intergroup and intragroup variations. For example, there is a large difference in average  $\text{P}_2\text{O}_5$  values in the new and published analyses of obsidians from mature island arcs (table 7), which is almost certainly due to overestimations of  $\text{P}_2\text{O}_5$  contents in many older analyses. Even in the internally consistent data set of the obsidian data bank, it is difficult to distinguish chemically CLPD rocks from different tectonic settings (fig. 30I). It is possible that, at higher  $\text{SiO}_2$  levels, rocks of the arcs and continental margins show a much wider range of  $\text{P}_2\text{O}_5$  values than those from the continental interiors. In lower silica rocks, obsidians from oceanic extensional zones tend to have relatively low  $\text{P}_2\text{O}_5$  contents. The high  $\text{P}_2\text{O}_5$  abundance in the macusanite glass (up to 0.55 percent, Nos. 160, 315,

316) is one of the most puzzling features of this unusual material.

$\text{P}_2\text{O}_5$  shows strong correlations ( $r \approx 0.6$ ) only with  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{TiO}_2$ , and Sr (positive) and  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  (negative).

$r \approx 0.60$	$\text{P}_2\text{O}_5$
$\text{SiO}_2$ -----	-0.67
$\text{Al}_2\text{O}_3$ -----	0.62
$\text{MgO}$ -----	0.82
$\text{CaO}$ -----	0.77
$\text{K}_2\text{O}$ -----	-0.61
$\text{TiO}_2$ -----	0.84
$\text{Sr}$ -----	0.71

#### MANGANESE

In contrast to the other major oxides in the obsidians,  $\text{MnO}$  shows no correlation coefficient  $> 0.45$ . This may partly be an analytical problem; the majority of specimens lie in the range 0.01 to 0.1 weight percent (fig. 29K), where analytical uncertainties will be relatively large (see the stepwise nature of the data in fig. 30J), and these might disguise significant relations. It may also be due in part to the behavior of Mn in CIPP systems. Though crystal-liquid processes tend to produce a negative relation between  $\text{SiO}_2$  and  $\text{MnO}$  (see the relevant trends in fig. 30J), CIPP results in Mn enrichment in lower temperature magmas, at least in the Bandelier, Bishop, and Coso systems (Hildreth, 1979; Bacon and others, 1981). This reversal of behavior will have the result of lowering correlation coefficients with other elements.

The  $\text{MnO-SiO}_2$  plot (fig. 30J) shows no simple relation between  $\text{MnO}$  concentration and tectonic setting; neither do the mean concentrations of  $\text{MnO}$  in the various rhyolite groups (fig. 29K).

#### CHLORINE

Chlorine abundances in the obsidians range from 0.0 to 0.3 weight percent (fig. 29L). The correlation coefficient with  $\text{SiO}_2$  is low,  $-0.28$ , owing to important differences between rocks of different tectonic settings.

Lack of reliable data for Cl in rhyolites of the primitive island arcs is a major shortcoming. In continental-margin obsidians, Cl shows a scattered, but real, negative correlation with  $\text{SiO}_2$ . This is an apparent anomaly in that crystal-liquid processes, as judged from rock-glass tielines, tend to slightly enrich Cl in residual liquids. It is possible that the

overall decrease against  $\text{SiO}_2$  is in some way related to the mobility of Cl in the magma chambers. It may be lost from more silicic magmas as a volatile phase or added to less silicic types by injection of mafic magma into the chamber. Alternatively, the effect may be related in some way to the sources of the rhyolites. Many of the lower silica, higher Cl margin rocks belong to the Cascades subtype (p. 39), whereas many rocks of the southwestern Oregon subtype contain higher silica and lower Cl. The lower Cl values may be a result of relative Cl impoverishment of the sources which may have a substantial mafic component.

Some of the Cl scatter at constant  $\text{SiO}_2$  reflects areas of relatively high Cl abundances (for example, the Chilean obsidians). CIPP results in upward concentration of Cl and the average value in CIPP rocks is higher than in CLPD types. Hildreth (1981) refers to the scattered nature of Cl data in CIPP systems but suggests that enrichments of two are normal. This is certainly a minimum value, because in the Bandelier magma, enrichments of 4–6 are likely (R.L. Smith, unpub. data).

Continental-interior obsidians show no significant correlation with  $\text{SiO}_2$ . CLPD continental-interior rocks show the same compositional range as CLPD continental-margin types. Certain CIPP specimens tend toward higher concentrations, up to 0.2 weight percent Cl; but others, such as rocks from the San Francisco Peaks, Arizona (Nos. 108, 109), have low abundances, <0.05 weight percent. It is not yet known whether base-level Cl was low in this system or Cl was lost from the magma.

The highest Cl concentrations in the data bank are in the obsidians from the Eolian arc, Italy (Nos. 180, 181, 182, 326, 327) and in the oceanic-extensional rhyolites. These latter rocks can be subdivided into those from the Admiralty Islands and the Salton Sea (Cl > 0.30 percent) and those from Iceland (<0.20 percent). The Icelandic rocks show the negative correlation between  $\text{SiO}_2$  and Cl noted for the continental-margin glasses. The low Cl content of the Askja mixed rock (0.02 weight percent, No. 176) suggests a potential mechanism for producing Cl depletion: loss, as a volatile phase, due to superheating on mixing with mafic magma.

Cl values of obsidians from mature island arcs overlap with the continental-margin types, but, at given  $\text{SiO}_2$  (fig. 30K), extend to higher values, a feature also indicated by the average abundances (table 7).

It is particularly notable that Cl has no correlation coefficient greater than 0.6 with any other element. Our prejudice is that this does not bear on the lack of systematic behavior of Cl in magmatic sys-

tems but rather on the relative ease with which Cl can be added to, and removed from, the magmas. The highest coefficients, 0.3–0.4, are with FeO, Hf, Y, Zr, and the REE excluding Eu. The coherence of this group of elements may be related to their ability to complex with Cl.

## FLUORINE

Fluorine shows a similar range as chlorine, 0.0 to 0.5 weight percent (fig. 29M). The distribution of F is strongly related to geographic setting and geologic process, causing a correlation coefficient with  $\text{SiO}_2$  (0.11) even lower than that of Cl. A marked aspect of F distribution is its strong enrichment in extension-related, as opposed to subduction-related, obsidian types. This enrichment of CLPD compositions is increased by CIPP, and only CIPP rocks have F values above 0.19 percent. CLPD rocks from arcs and margins show a relatively restricted range, between 0.02 and 0.08 weight percent, which has no systematic variation with  $\text{SiO}_2$  (fig. 30L). Continental-interior rocks show a wider range, 0.03–0.18 weight percent, with notable intergroup differences, for example, the high-F Yellowstone rocks and the low-F Jemez Mountain rocks.

In sharp contrast to Cl, F shows many strong (>0.6) positive correlations with other elements. All of these have similar behavior in that they are enriched in interior obsidians, as opposed to subduction-related rocks, and in that they are all up-elements during CIPP. The common factor may be their tendency to complex with F.

$r \geq 0.60$	F
Be -----	0.82
Nb -----	0.72
Pb -----	0.63
Rb -----	0.72
Sn -----	0.76
Ta -----	0.75
Th -----	0.65
U -----	0.63
Y -----	0.69
Tb -----	0.61
Tm -----	0.70
Yb -----	0.71
Lu -----	0.72

## Cl/F RATIOS

The averages of each rhyolite group (table 7) show that the continental-interior average has Cl < F, but the reverse is true in the other rhyolite groups. How-



ever, use of averages disguises certain important features.

1. Cl is more abundant in all the obsidians from mature island arcs.

2. Though the average exceeds 1, there are obsidians in the continental margins where the ratio  $Cl/F < 1$  (fig. 39), for example, in many of the eastern Oregon domes and in the Clear Lake field. Most CIPP continental-margin rocks have  $Cl/F < 1$ .

3. Obsidians with  $Cl/F > 1$  are uncommon in the continental interiors (fig. 39). Notable exceptions are domes and flows from the Jemez Mountains volcanic complex, New Mexico.

4. The oceanic-extensional rocks have, on average, Cl in excess of F. They form two subgroups, however, rocks from Salton Sea, Papua New Guinea, Alcedo, Galapagos, and Oraefajökull, Iceland, where  $Cl > F$ , and other Icelandic obsidians where  $F > Cl$ .

The data for the subalkalic obsidians are broadly consistent with the conclusions of Bailey (1980), based on peralkaline obsidians, that oceanic rhyolites (with the notable exception of Iceland) have  $Cl > F$ , but continental varieties have  $Cl < F$ . This fundamental difference is in some way related to the nature of the source rocks and (or) the processes involved in each setting. Given the different complexing affinities of different

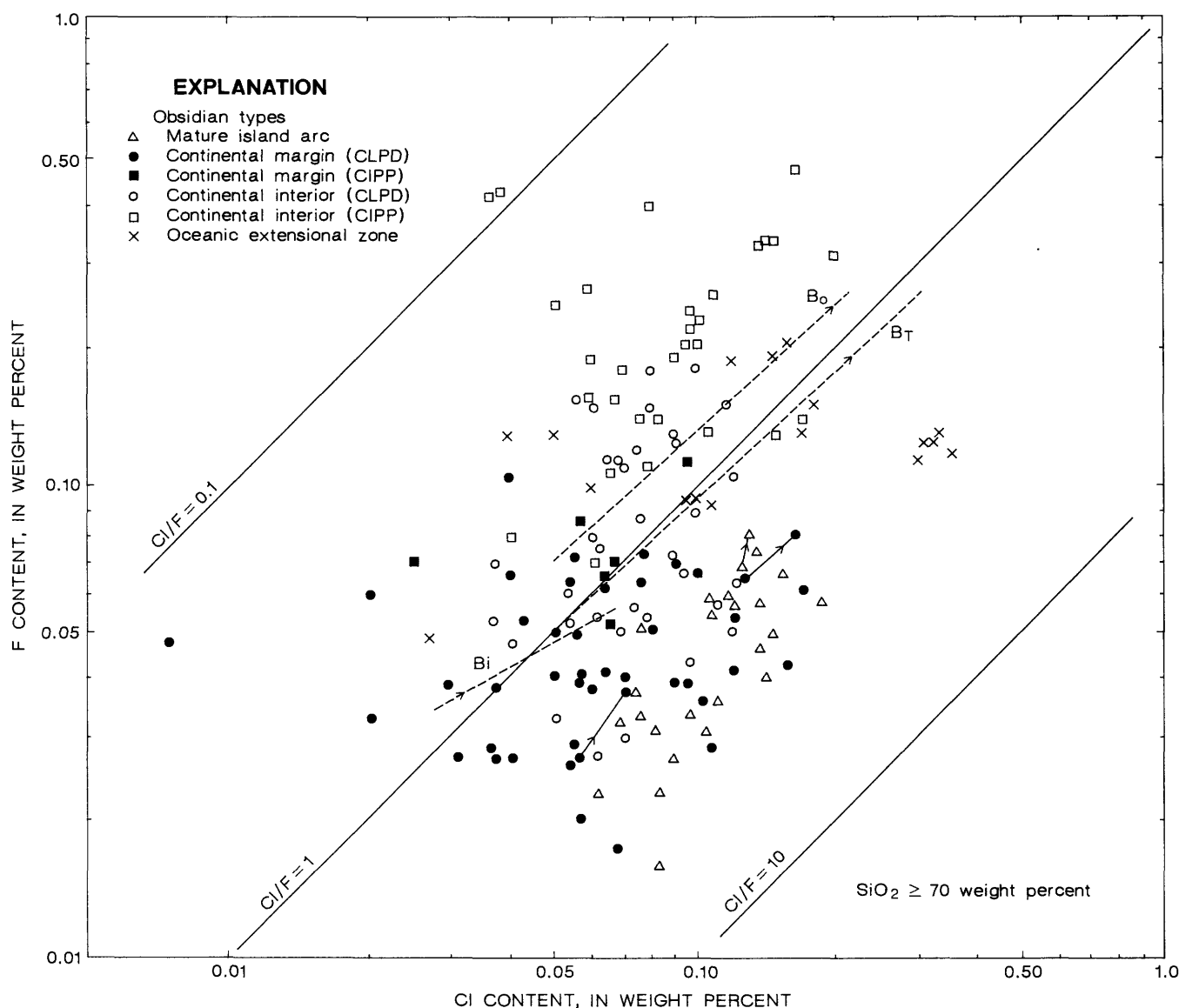


FIGURE 39.—Cl content versus F content for obsidians. Data sources are same as for figure 5. Solid tielines are rock-glass pairs; Bandelier Tuff (Otow Member,  $B_0$ , and Tshirege Member,  $B_T$ ); Bishop Tuff, Bi. Arrows indicate direction of liquid fractionation.

elements for F and Cl, the regional variations in F-Cl relations may have important effects on the trace-element chemistry of the relevant silicic magmas.

It is also notable that within the limited data set for CIPP systems and CLPD rock-glass pairs (fig. 39) there seems no strong tendency for shifts in Cl/F ratios with

fractionation, and the trends are subparallel on the Cl-F plot. Slight deviations (for example, a slight increase in Cl/F with increasing fractionation), as can be seen for both the Bishop and Bandelier systems, may be related as well to analytical or sample problems as to a real change in magmatic ratios.

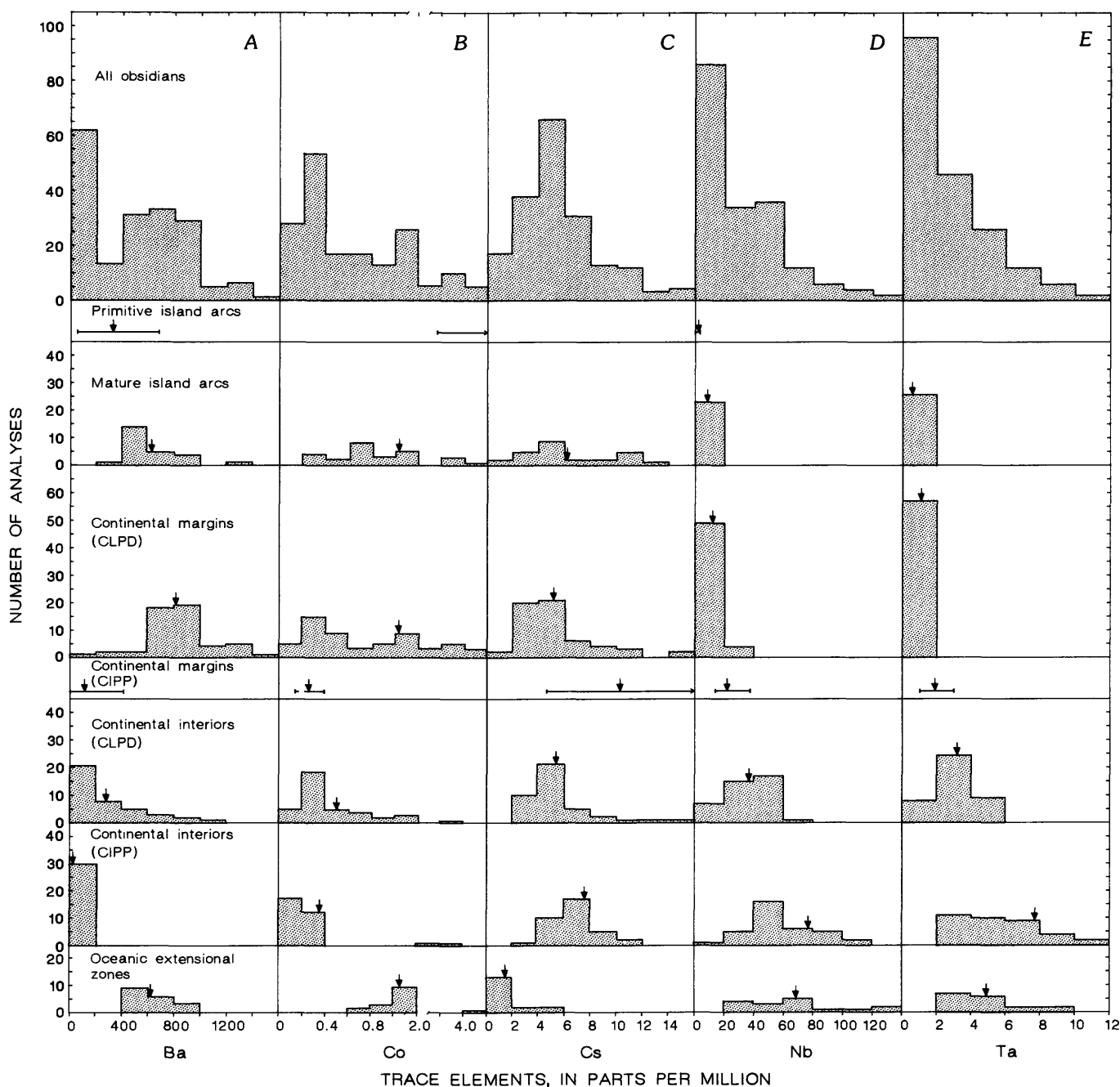


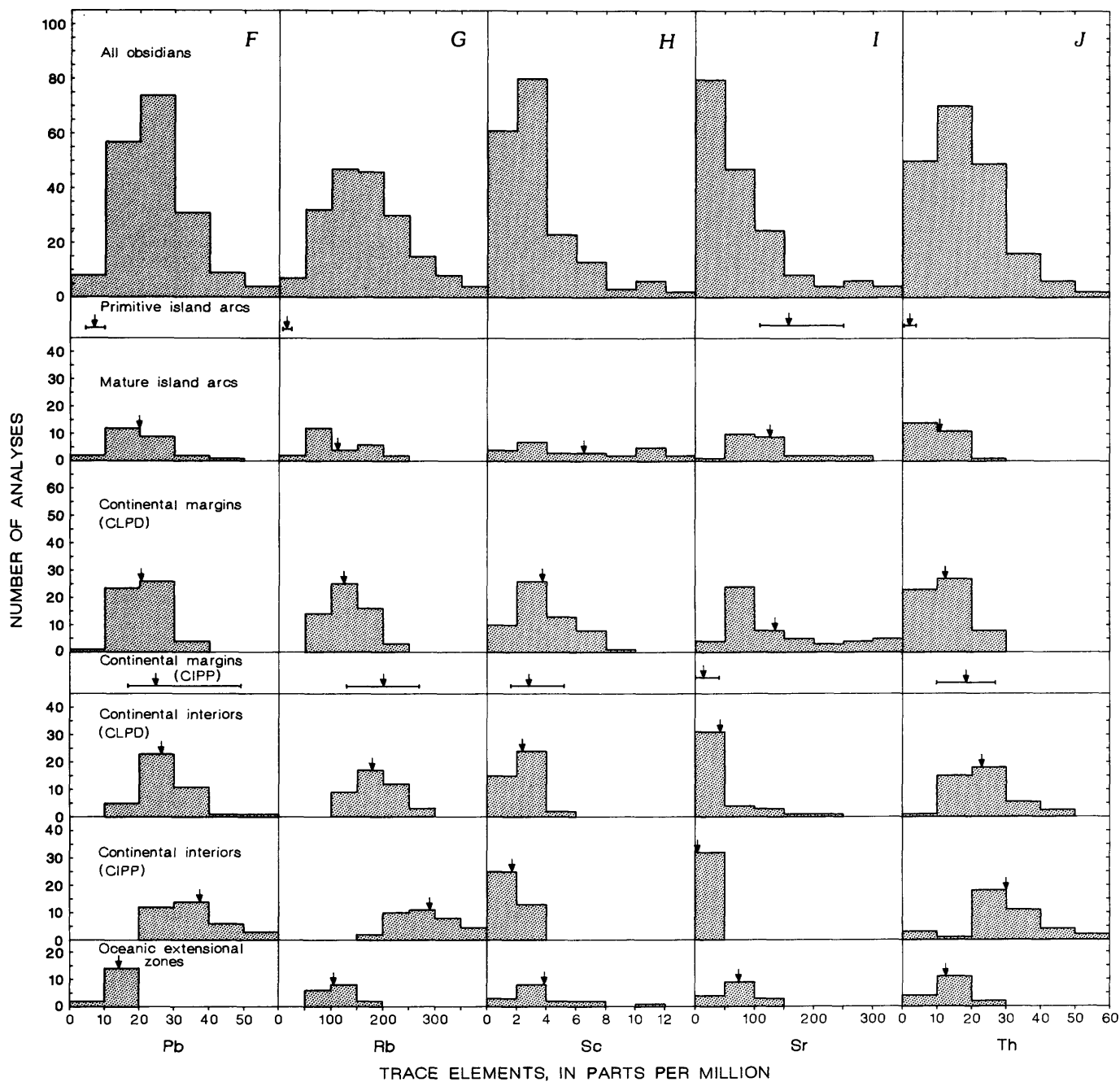
FIGURE 40.—Distribution of trace elements in obsidians. Obsidians of primitive island arcs and continental margins (CIPP types) are shown as ranges only. Primitive arc data missing on C, E, H, and N. Arrows indicate average values. Data from appendixes I and V. A, Ba. B, Co (note change in scale on Co axis). C, Cs (samples 86–88, 160, and 188 omitted to preserve scale). D, Nb (samples 83, 108, and 109 omitted to preserve scale). E, Ta (samples 83, 108, 109, and 160 omitted to preserve scale, and sample 12 omitted

## BARIUM

In appendixes I, II, and IV, we report X-ray fluorescence determinations for Ba <5 ppm. Although these values were precisely determined, we have insufficient cross-checks using other analytical tech-

niques to assess their accuracy. Until such checks are available, Ba values <50 ppm should be treated with caution.

Ba concentrations cover a 3-order-of-magnitude range, from 1 to 1,440 ppm. Averages and ranges are given in tables 7-9 and shown in figure 40A.



because of suspected contamination). *F*, Pb (samples 83, 108, and 109 omitted to preserve scale). *G*, Rb (samples 86-88 and 160 omitted to preserve scale). *H*, Sc (sample 111 omitted—its high value may indicate analytical error or contamination of sample). *I*, Sr (sample 19 omitted to preserve scale). *J*, Th. *K*, U. *L*, Zn (sample 83 omitted to preserve scale). *M*, Zr (samples 156, 157, 172, 174, 175, and 193 omitted to preserve scale). *N*, Hf.

Obsidians from the primitive island arcs have the lowest Ba contents on a  $\text{SiO}_2$ -normalized basis. Calcic rocks from the mature island arcs have values transitional between the primitive island arc rocks and the calc-alkalic types from mature arcs. These calc-alkalic rocks from mature island arcs have a range comparable to the rocks of the continental margins, with a lower average. This general increase of Ba contents from primitive arc to continental margin has been noted by Jakes and White (1972, p. 35). At  $\text{SiO}_2$  values <75 percent, base-level, continental-

interior obsidians have clearly lower Ba abundances than mature-arc or continental-margin types. The difference persists at higher  $\text{SiO}_2$  levels, but rocks of all three groups can show extreme Ba depletion in this composition range. It is noteworthy that mature-island-arc rocks do not show the very low Ba contents found in continental rocks.

Obsidians from oceanic extensional zones show a range of Ba values, even on a  $\text{SiO}_2$ -normalized basis. Rocks from Papua New Guinea and certain of the Icelandic complexes are relatively rich in Ba, but those

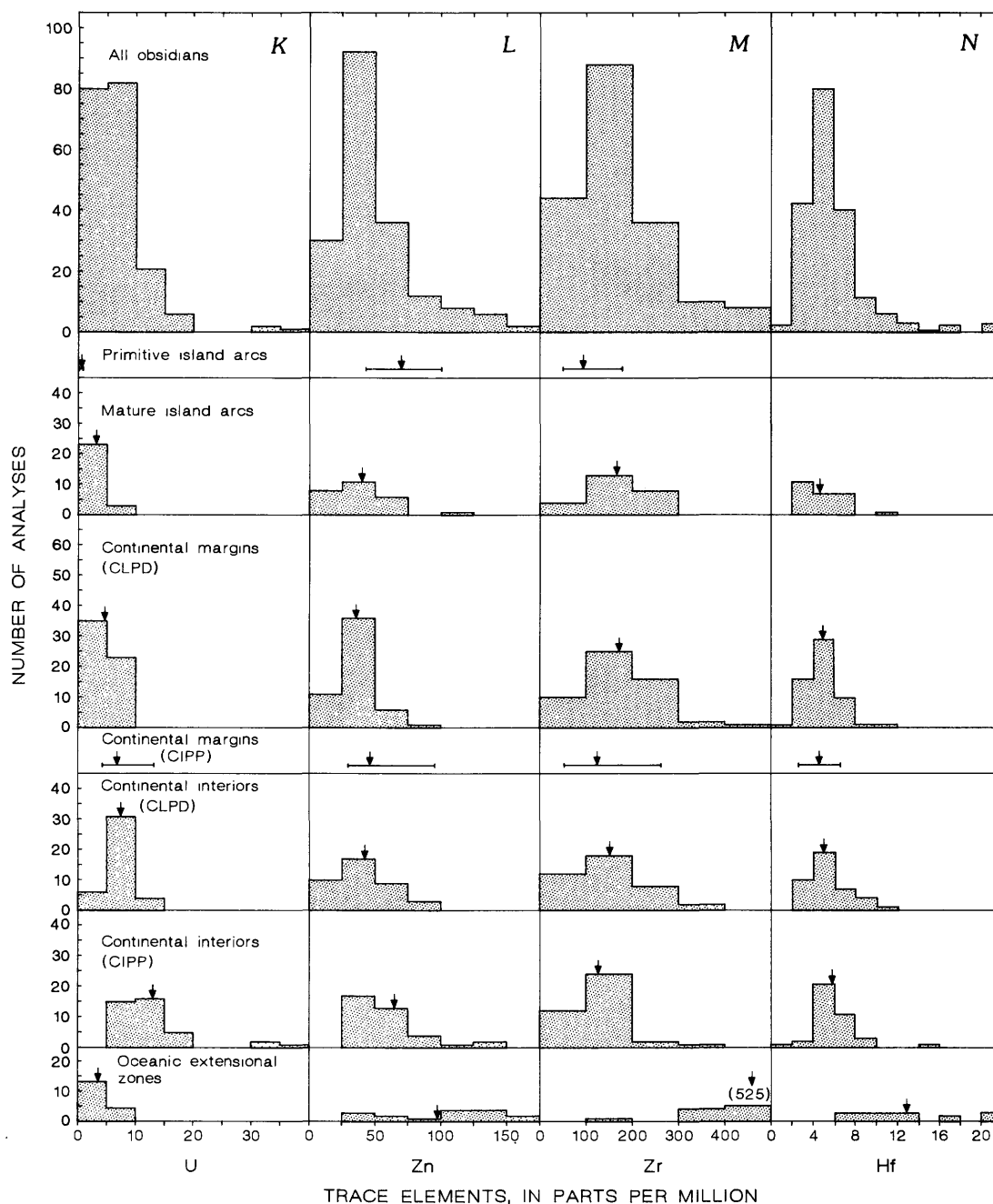


FIGURE 40.—Continued.

from the Salton Sea, Alcedo, and the remaining Icelandic centers have very low Ba contents.

Within-group variations tend to be low, about a factor of 2, in rocks with  $\text{SiO}_2 < 75$  percent but are up to two orders of magnitude in more silicic rocks. Certain specimens may be noted as rich in Ba, even for subduction-related obsidians, for example, certain rocks from eastern Oregon (Nos. 26–28) and synresurgence rhyolites in the Long Valley caldera (data from Noble and others, 1972). The Ba enrichment is not accompanied by any apparently related anomaly and may represent Ba-rich source rocks.

The data for rock-glass pairs indicate either constant or increased Ba concentrations in residual liquids. This is broadly consistent with the absence of a highly significant correlation between Ba and  $\text{SiO}_2$  (app. VI), even in rocks with  $\text{SiO}_2 < 75$  percent.

The tielines for more silicic pairs (not illustrated) show Ba increase in the glass. A real petrogenetic problem is posed by the low Ba abundances in some CLPD obsidians ( $< 20$  ppm). As discussed by Hildreth (1981, p. 10169), those low abundances imply either sources abnormally depleted in Ba, or very protracted feldspar fractionation from parental melts.

CIPP also produces extreme depletion of both Ba and Sr in lower temperature rocks (fig. 41). There is a variation of a factor of 60 from top to bottom in the Bishop Tuff (Hildreth, 1981); in the erupted part of the Coso system, the variation was 16. Values of Ba  $< 20$  ppm belong characteristically, but not exclusively, to CIPP rocks.

Ba has no strong ( $r > 0.60$ ) correlation coefficient for another element. It is normally regarded as a

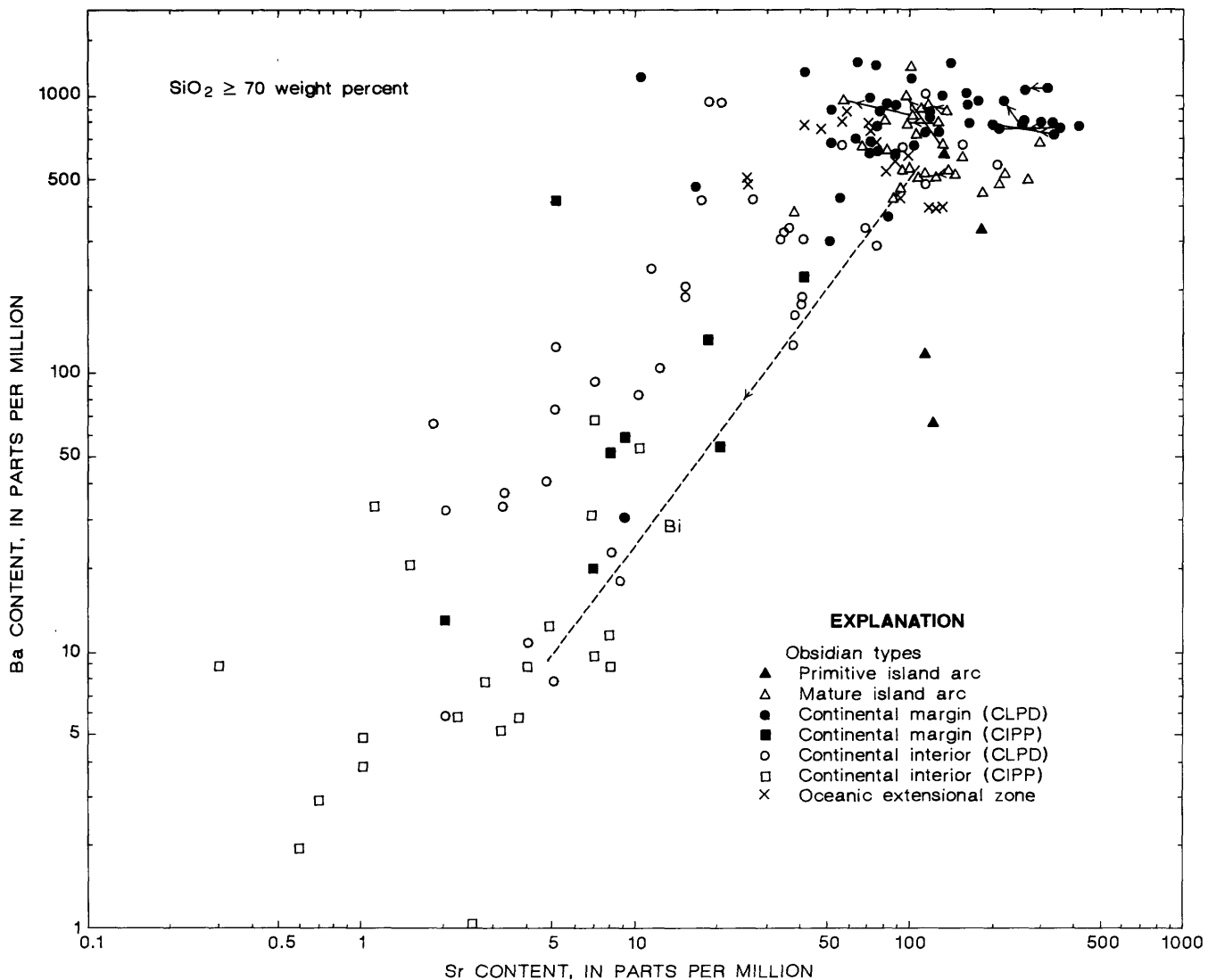


FIGURE 41.—Ba content versus Sr content for obsidians and various comparative rocks. Data sources are same as for figure 5. Solid tielines represent rock-glass pairs; dashed line represents Bishop Tuff (Bi). Arrows indicate direction of liquid fractionation.

K-related element, yet the two show dissimilar behavior in the obsidians. The sharp decrease in Ba in continental-interior rocks as opposed to subduction-related types stands in contrast to a K increase. CIPP depletes roof-zone magmas in Ba much more rapidly than K, and high K/Ba ratios characterize CIPP rocks.

#### COBALT

Cobalt occurs at very low levels (<5 ppm) in the obsidians (fig. 40B), and analytical problems are notable. Although the analytical precision ( $1\sigma$ ) at levels above 2 ppm is estimated at 5 percent, at 0.2 ppm, it is 30 percent. Discussion of intersuite and intrasuite differences at low levels has to be made with caution. Interlaboratory comparison of data is even less rewarding. For example, the Co data obtained by Jack and Carmichael (1969) and Jack (1971) are higher than the INAA values for samples from the same localities by about an order of magnitude.

Contamination during sample preparation is an additional problem. Four Icelandic obsidians (Nos. 173, 221, 222, 226) have Co concentrations in the range 12–22 ppm. These values are not accompanied by unusually high Cr or Sc contents, which might indicate basalt contamination. Furthermore, comparison of one sample (173) with an otherwise almost identical rock (174) from the same complex shows Co values of 13.6 and 1.7 ppm, respectively. It may thus be suspected that these high Co samples were contaminated during sample preparation in tungsten carbide mills. Similarly, we suspect that the rock-glass pair from The Watchman, Crater Lake (Nos. 11, 12), has been contaminated, mainly on the basis of high Ta and Cr contents, as well as elevated Co abundances. These various samples are not used in computations or figures.

The new obsidian determinations are all less than 5 ppm, and the great majority <1 ppm, Co (fig. 40B). Published data for rhyolites of primitive arcs are higher, up to 10 ppm. There is a broad, negative correlation ( $r = -0.63$ ) between Co and  $\text{SiO}_2$ . The 40 times variation in Co concentrations makes it unsuitable for plotting against  $\text{SiO}_2$ , so Co variation is here discussed on the basis of a Co-CaO graph (fig. 42). Crystal-liquid trends and CIPP trends are approximately parallel, indicating that both processes are equally efficient in decreasing Co in lower-temperature magmas. Although CIPP rocks have Co in the range 0.1–0.4 ppm, many CLPD rocks have equally low abundances.

The average Co concentrations of silicic obsidians from mature island arcs, continental magmas, and oceanic extensional zones are very similar (table 7). The higher and lower averages for primitive-arc and continental-interior specimens, respectively, reflect their lower and higher  $\text{SiO}_2$  contents. There is no good evidence that the rocks from one setting are systematically different from any other, although such evidence may be masked by analytical imprecision.

Apart from  $\text{SiO}_2$ , Co shows strong ( $r > 0.60$ ) correlations only with MgO (0.69), CaO (0.66), and  $\text{TiO}_2$  (0.66), as would be expected from an element whose distribution is controlled more by bulk rock composition than by crustal or dominant genetic processes.

$r > 0.60$	Co
$\text{SiO}_2$ -----	-0.63
MgO -----	0.69
CaO -----	0.66
$\text{TiO}_2$ -----	0.66

#### CHROMIUM

The data for Cr stress the unsatisfactory analytical uncertainties associated with the determination of this element at low concentrations (table 7).

1. The values of Johnson and others (1978) on Cr in obsidians from Papua New Guinea are about an order of magnitude higher than our new values. Because the samples were prepared in different laboratories, the higher values may alternatively indicate contamination.

2. Zielinski and others (1977) provide values for Rocky Mountain obsidians which are two or more times higher than our values.

3. Our value for Napa Glass Mountain is lower than that of Bowman and others (1973).

Locality	Specimen No. <sup>1</sup>	This paper	Zielinski and others (1977)	Johnson and others (1978)	Bowman and others (1973)
St. Andrew Strait, Papua New Guinea	25NG0011 (211)	2.7	—	26	—
	25NG0025 (213)	<7.0	—	23	—
	25NG0059 (104)	<6.0	—	24	—
Nathrop, Colorado	66L-230A (104)	<6.0	11	—	—
Napa Glass Mt., California	Average (44)	<5.0	—	—	6.7

<sup>1</sup>First number is published specimen number; the number in parentheses specimen number from this paper.

Additionally, there is the problem that samples may be contaminated with Cr during grinding in materials such as tungsten carbide and colmonoy. We ascribe, for example, anomalously high Cr contents in specimens 11 and 12 to sample contamination.

Interlaboratory comparison of Cr results for obsidians appears to be unproductive at present. Though the data of this study provide at least an

internally consistent body of results, replication of determinations at levels <2 ppm was in many cases unsatisfactory, varying by a factor of two or more in the worst cases. Reportable values were obtained for only 51 rocks. This precludes a detailed charting of Cr distribution in the obsidians, which is particularly unfortunate in that Cr, like Co, is potentially a useful element in assessing the amount of admixed mafic material in rhyolites.

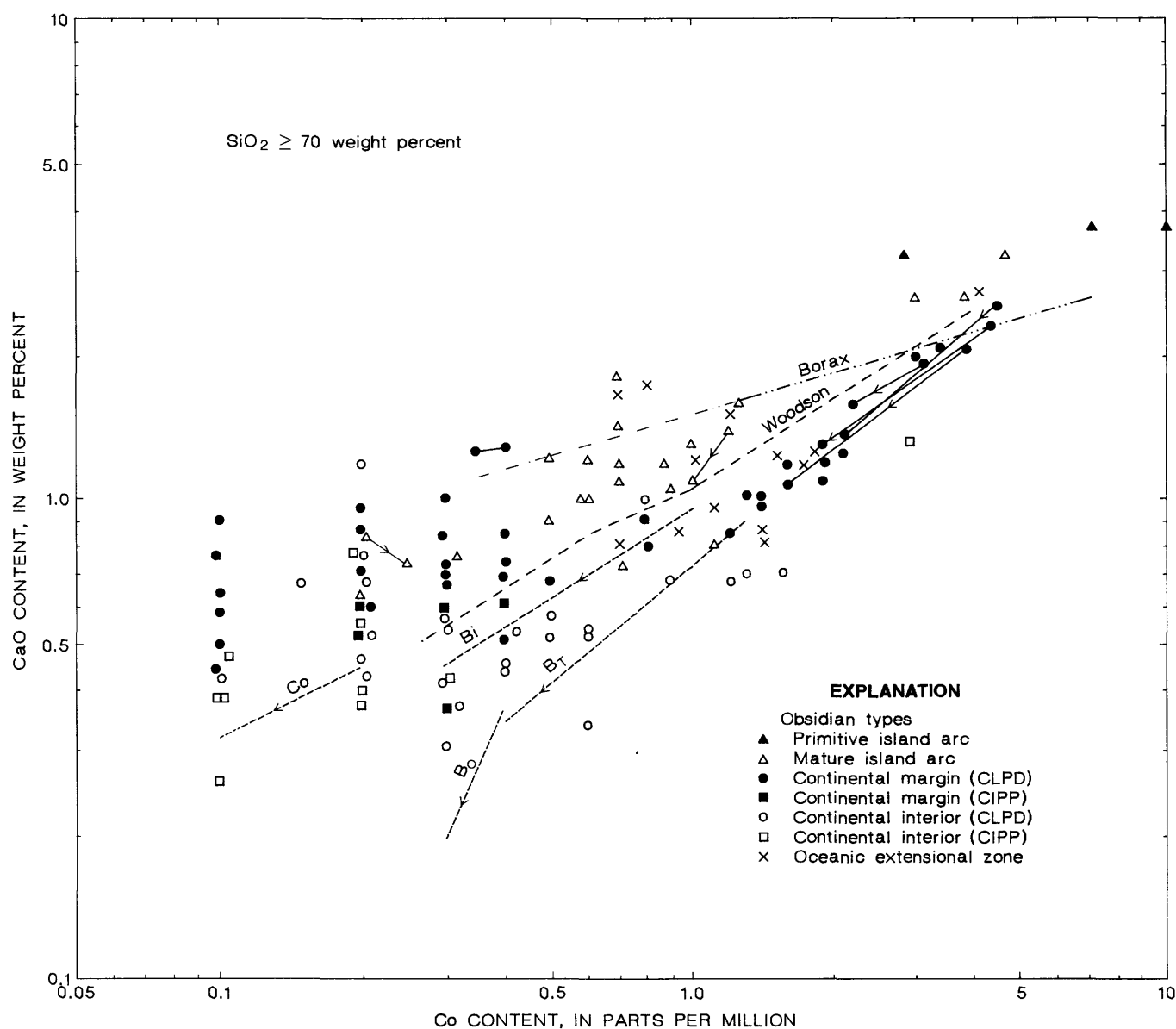


FIGURE 42.—Co content versus CaO content for obsidians and various comparative rocks. Data sources are same as for figure 5. Solid tielines indicate rock-glass pairs, arrows indicate direction of glass separate. Dashed lines indicate CIPP systems; Bishop Tuff (Bi);

Bandelier Tuff, Otowi ( $B_o$ ) and Tshirege ( $B_r$ ) Members; Coso Range (Co); arrows indicate direction of liquid fractionation and decreasing temperature. Also shown are the Borax Lake (Borax) mixed magma system, and the Woodson Grandiorite (Woodson) system.

Field observations clearly demonstrate the ubiquity of this process, yet we are unable to test quantitatively the chemical effects of small amounts of such mixing.

The data bank seems to show the following features:

1. The majority of silicic obsidians contain <4 ppm Cr.
2. There are no confirmed values of Cr>11 ppm, except in rocks known to be contaminated with mafic material, for example, Borax Lake (Bowman and others, 1973).
3. It is possible that all high-silica obsidians having Cr>5 ppm are mixed or contaminated rocks, for example, White Mountain, Utah (No. 96, Cr=9 ppm). The obsidian from US Gypsum perlite quarry, Nevada (No. 78), has several unusual geochemical features, including a high Cr value of 10.7 ppm.

#### CESIUM

Cesium abundances range from 0.5 to 21 ppm, with quite exceptional values of 500–550 ppm in macusanite<sup>5</sup> glass. The element's distribution in the obsidians is complex, showing important variations related to tectonic setting, genetic processes, and local causes.

The single available determination for rhyolites of primitive island arcs (No. 220) indicates that Cs levels are probably low (<1 ppm). Obsidians from other settings have Cs ranges and averages similar to each other, except for those from oceanic extensional zones where the maximum and average Cs concentrations are significantly lower (fig. 40C). This apparently is a characteristic feature of oceanic-extensional-zone rhyolites, and though mature-island-arc rocks may have similarly low Cs levels, the Rb/Cs ratio is lower in mature arc than in oceanic types.

Within-group variations account for much of the scatter of Cs data. The Cs contents of obsidians from Clear Lake and Medicine Lake, California, are among the highest in the data bank. Obsidians of Java have high Cs contents for mature-island-arc rocks. CLPD continental-interior rocks at 76 percent SiO<sub>2</sub> show a range of Cs values from <2 to 16 ppm. It is not known whether these are features which char-

acterize all the volcanic products of these provinces or the silicic rocks only. The Cs enrichment of the subduction-related sequences relative to the other K-related elements would suggest that it is a function of source-rock composition rather than being process controlled.

One of the four rock-glass pairs from the Taupo, New Zealand (Ewart and others, 1968), volcanics shows a positive correlation between SiO<sub>2</sub> and Cs, indicating enrichment of Cs in the residual liquids (fig. 43A). A similar relation exists for the Crater Lake pairs. In the remaining three Taupo pairs, the higher Cs occurs in the lower SiO<sub>2</sub> rock, rather than in the glass. For one pair (Nos. 9R, 9A), the SiO<sub>2</sub> difference is so small (0.2 percent) that analytical error in SiO<sub>2</sub> determination or minor quartz fractionation may be suspected, a point apparently confirmed by the anomalous behavior of this pair on almost all diagrams. For the other two pairs, the negative relation between SiO<sub>2</sub> and Cs is accompanied by a similar relation between K<sub>2</sub>O and Cs (fig. 44). This remains an anomaly. These rocks do not contain phenocrystic biotite, which might preferentially incorporate Cs (Ewart and others, 1968).

Alternative explanations are: (1) there is analytical error in at least one Cs determination, or (2) some Cs has been lost by leaching of the glass. The latter explanation seems unsatisfactory for pair 12, where the glass contains only 0.3 percent H<sub>2</sub>O<sup>+</sup>.

CIPP concentrates Cs in lower-temperature liquids. Enrichment factors of 3 to 4 have been recorded for the Bishop Tuff (Hildreth, 1979, 1981). The Bandelier Tuff (R.L. Smith, unpub. data) has an apparent enrichment factor of 6 and a probable enrichment factor of more than 10. The enrichment factors for Cs in the Bishop and Bandelier sheets are greater than those for Rb, Th, and U, and the ratio of Cs to each of these elements increases with increasingly CIPP character (for example, see fig. 45).

Correlation coefficients between Cs and related elements of large ionic radius are given below:

	Cs
Rb -----	0.64
Th -----	0.56
U -----	0.60
K <sub>2</sub> O -----	0.34
Ba -----	-0.25

The low correlation coefficients with K<sub>2</sub>O and Ba result from differing behaviors during CIPP. Those with Rb, Th, and U are higher and positive, though the highest is only 0.64. This is a function of the Cs

<sup>5</sup>Macusanite occurs as pebbles in gravel in the Macusani area, Peru. The unusual phenocryst assemblage includes high Al phases such as andalusite and sillimanite. It is also unusual chemically, in having very high concentrations of As, B, and Li, and high Cs, F, Rb, Sn, and Te (Barnes and others, 1970).



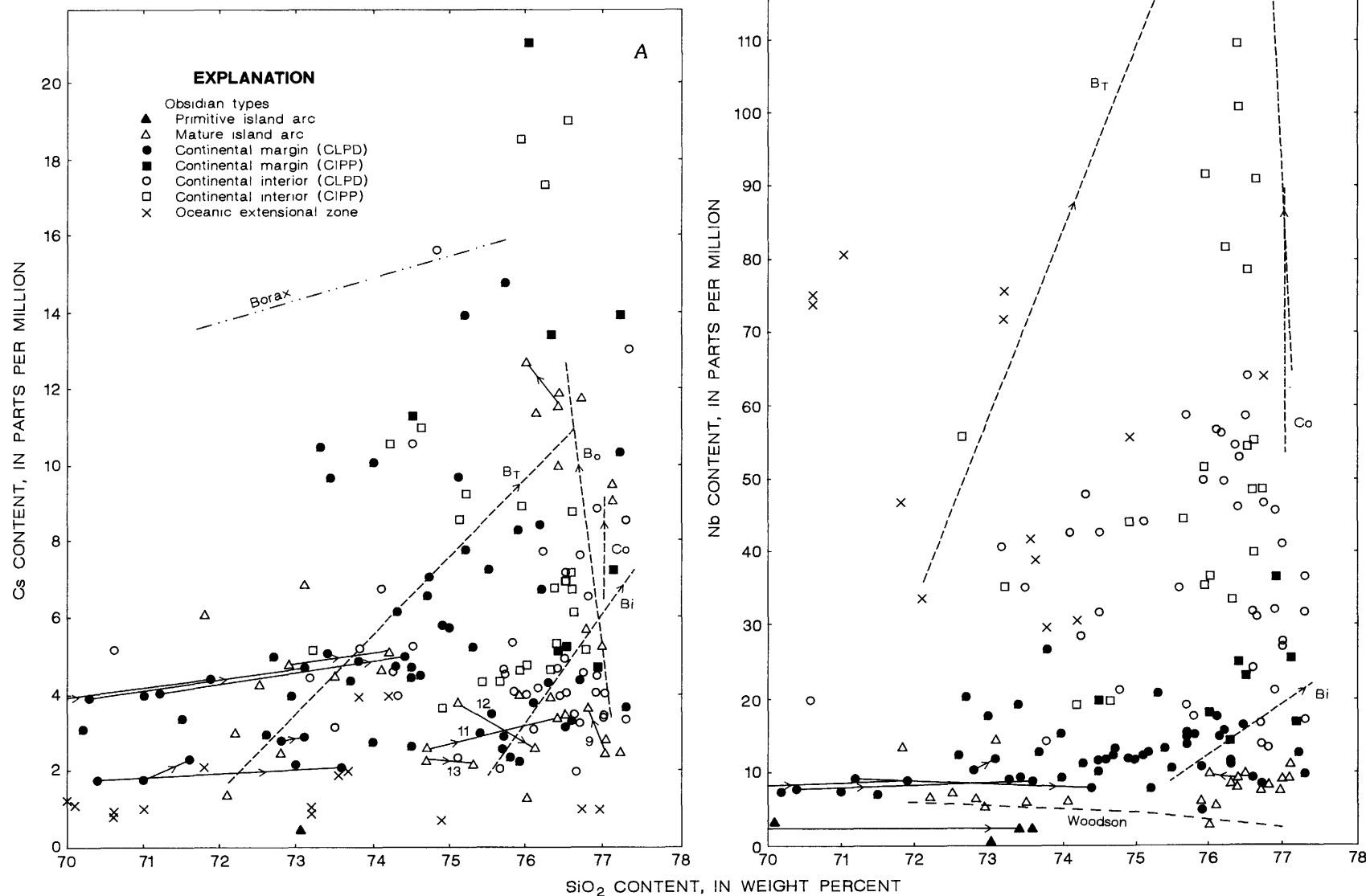


FIGURE 43.—Trace-element silica-variation diagrams for obsidians and various comparative rocks. Data sources are same as for figure 5. A, Cs (sample 160 omitted to preserve scale); numbered tielines: Taupo, New Zealand (Ewart and others, 1968, samples 9, 11, 12, 13). B, Nb (samples 83, 108, and 109 omitted to preserve scale). C, Pb (rock-glass tielines are numbered as follows: 2, Halmahera [app. I, Nos. 209, 210]; 3, 4, 8, 9, Crater Lake [app. I, Nos. 15, 16, 17, 18, 11, 12, 13, 14]; 5, South Sister [app. I, Nos. 9, 10]; 6, Okushiri [app. I, Nos. 186, 187]; 7, Capital Mountain [app. I, Nos. 4, 5]). D, Rb (sample 160

omitted to preserve scale). E, Th. F, U (samples 86–88 omitted to preserve scale). G, Zn (sample 83 omitted to preserve scale). H, Zr. I, Hf. Solid tielines represent rock-glass pairs; arrows point toward glass separate. Dashed lines represent rock systems; Bishop Tuff, Bi (Hildreth, 1981); Bandelier Tuff, Otowi, B<sub>o</sub>, and Tshirege, B<sub>T</sub>, Members (R.L. Smith, unpub. data); Coso Range, Co (Bacon and others, 1981); Borax Lake mixed magma, Borax (Bowman and others, 1973); Woodson Granodiorite stock, Woodson (D. Gottfried, written communication, 1975). Arrows indicate direction of liquid fractionation.

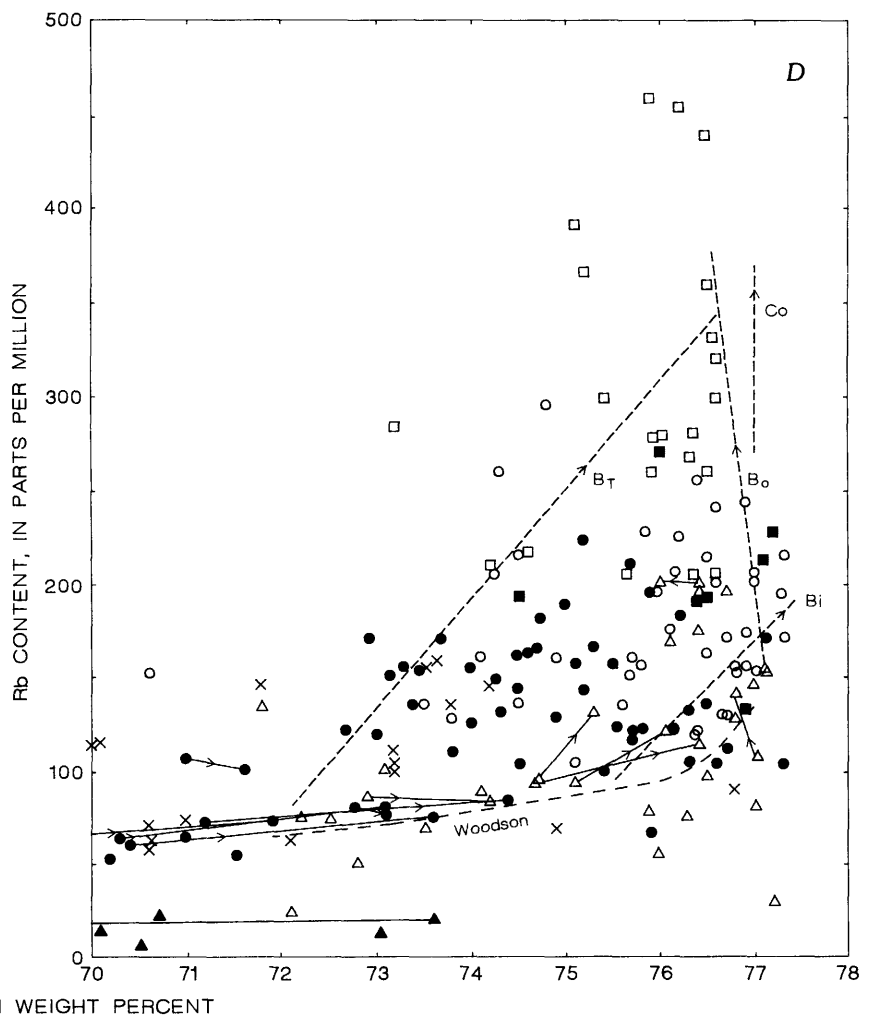
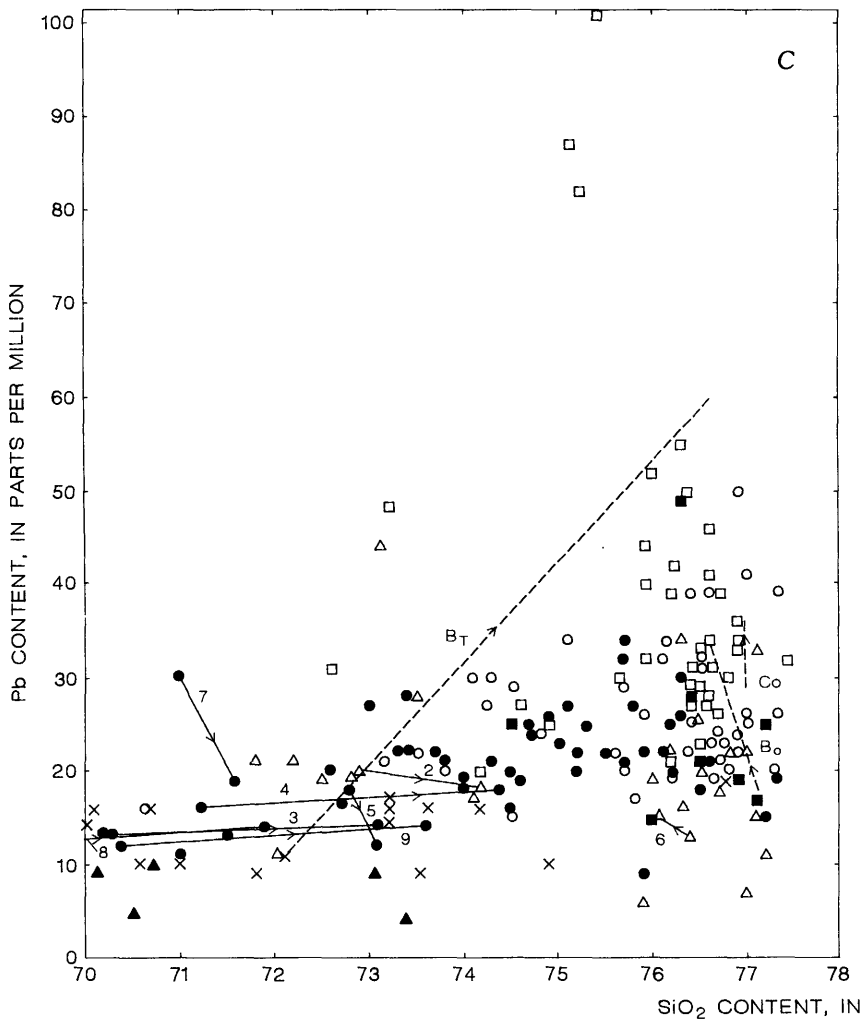


FIGURE 43.—Continued.

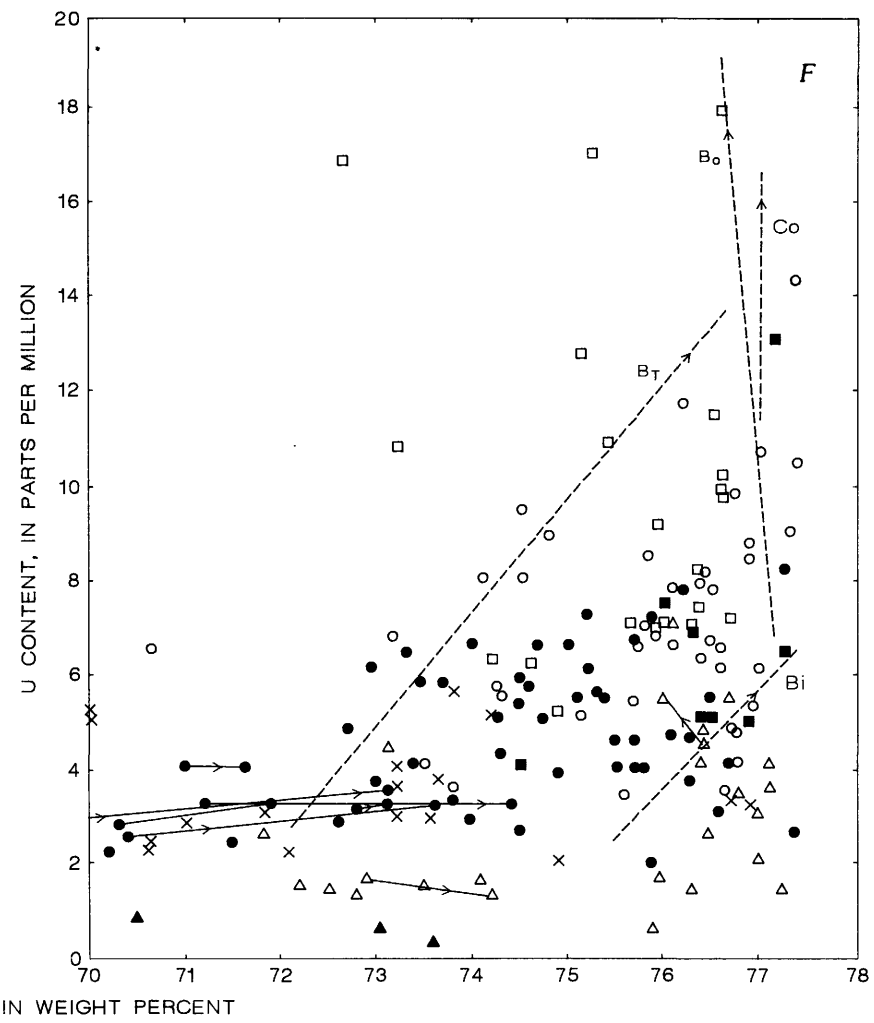
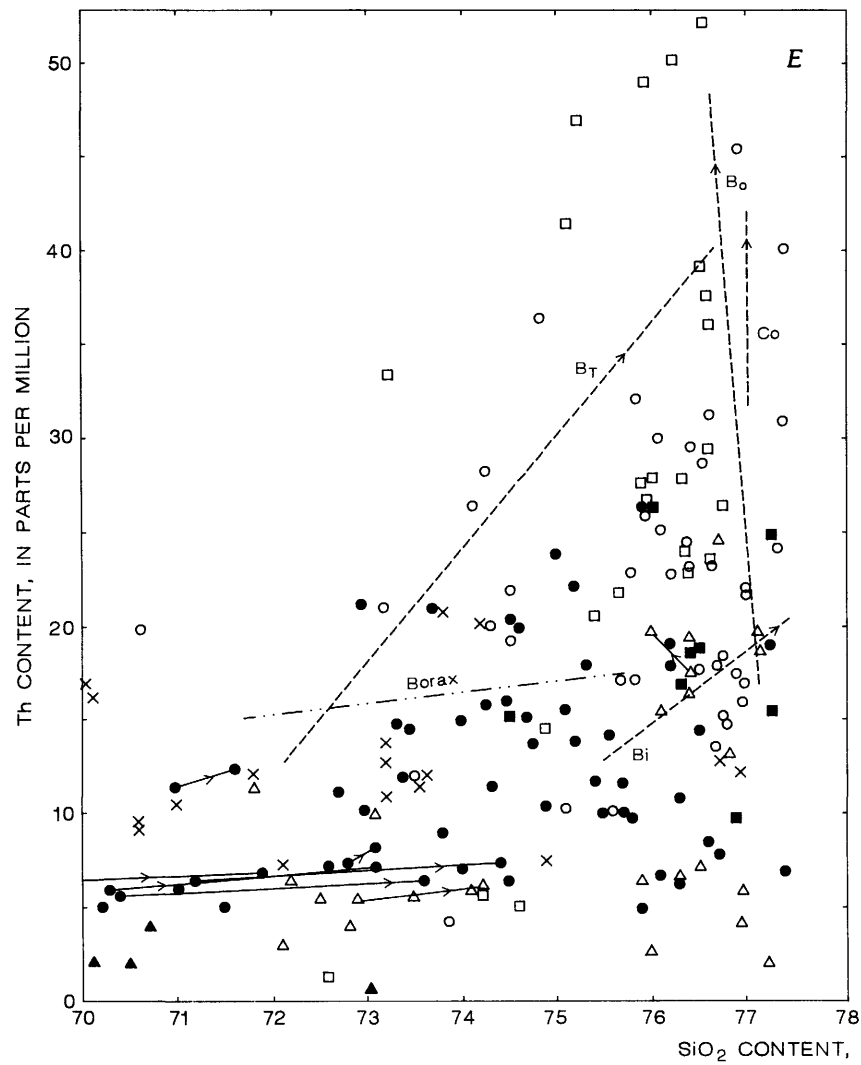


FIGURE 43.—Continued.

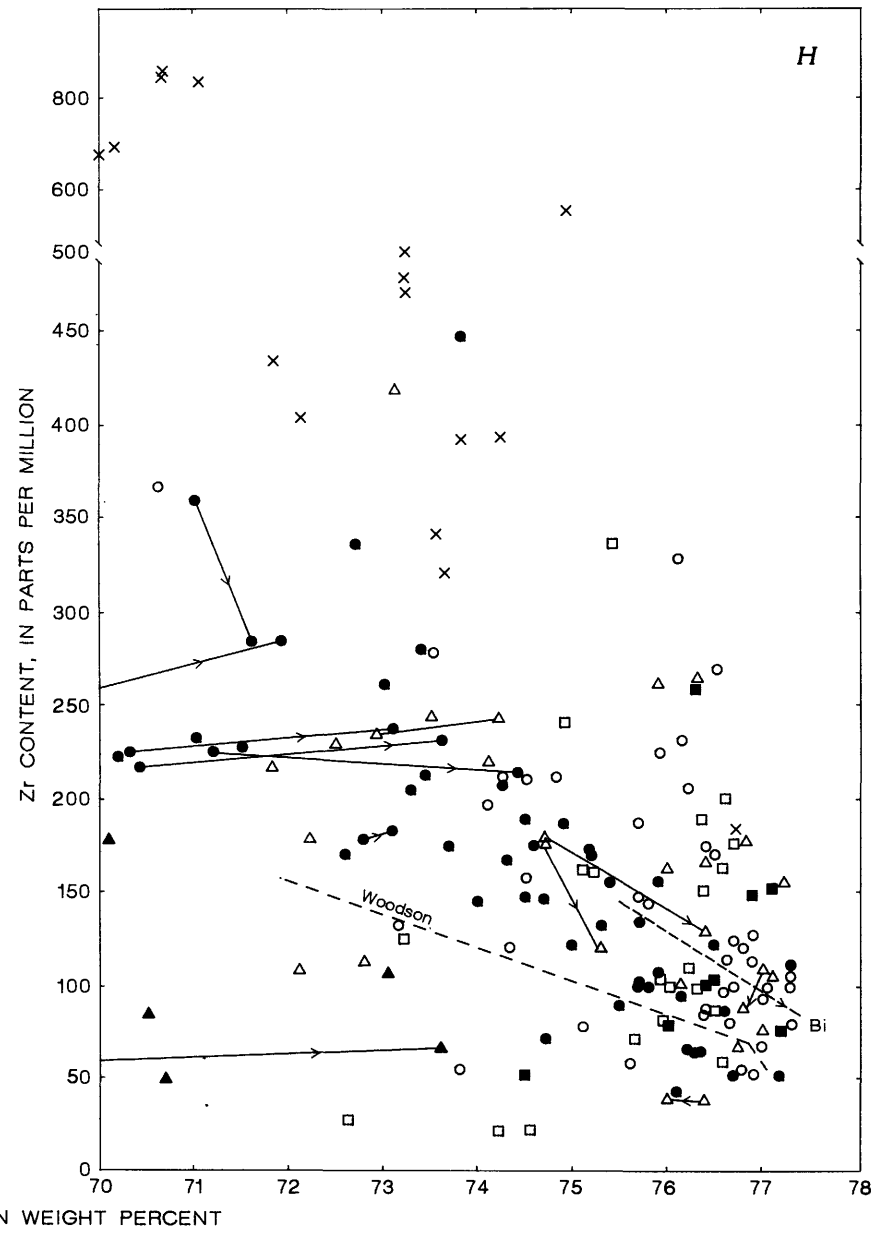
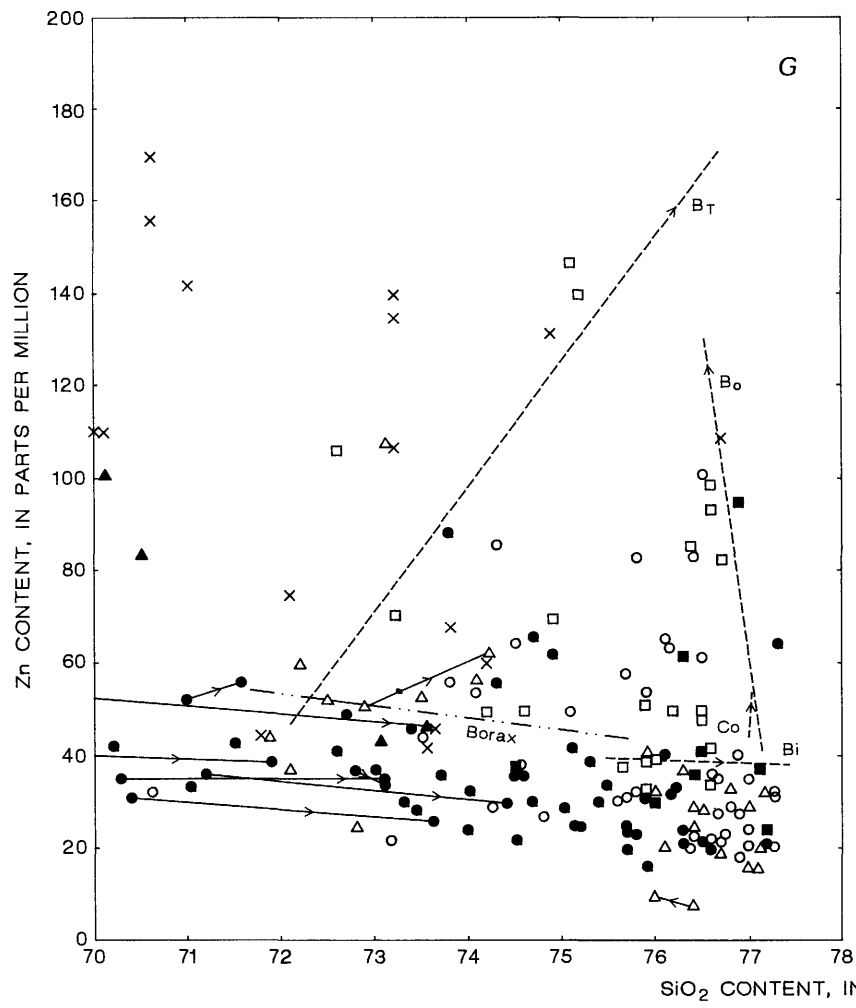


FIGURE 43.—Continued.

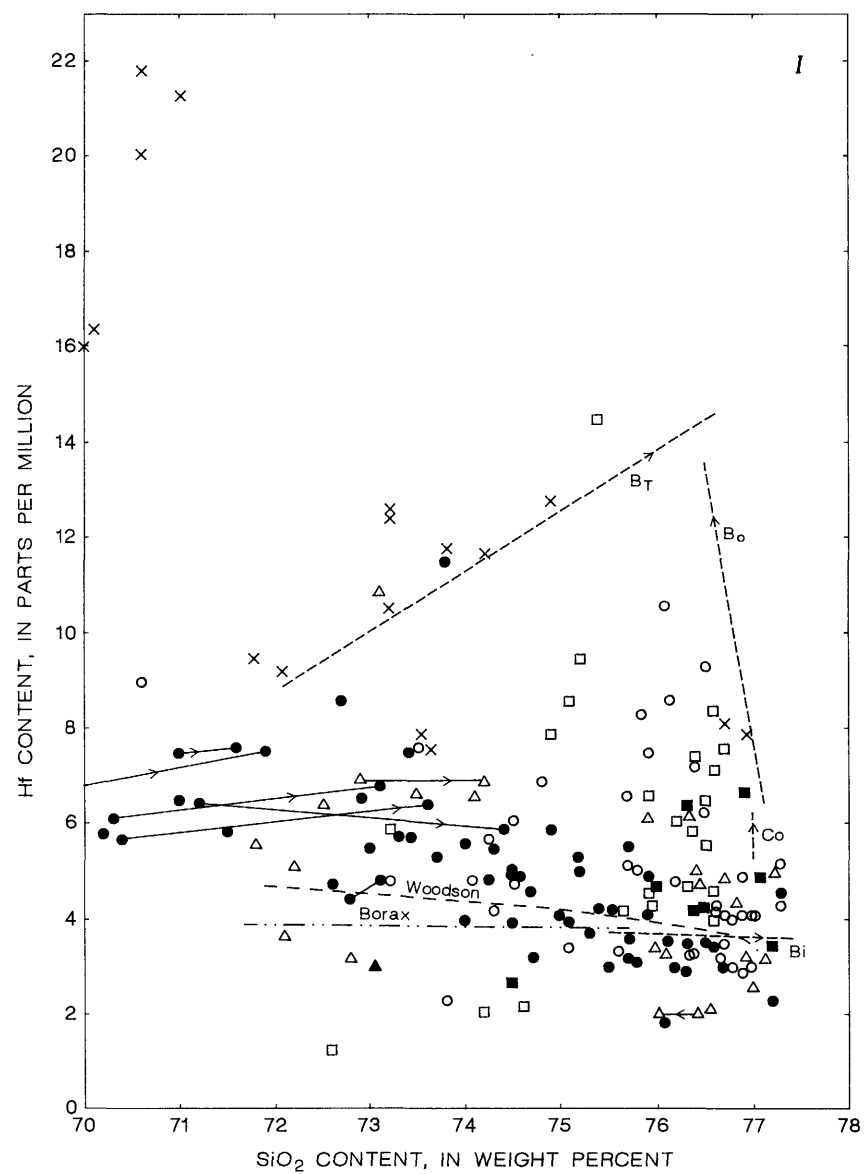


FIGURE 43.—Continued.

enrichment of certain subduction-related obsidians, as noted above.

The Rb-Cs plot (fig. 45) illustrates many of the more important points of Cs geochemistry. There is a systematic relation between Rb/Cs ratio and tectonic setting, the average ratio increasing in the sequence arc→margin→continental interior (compare with table 7). The process leading to this relative enrichment of Rb is as yet unidentified, but it contrasts with the effects of CIPP, which tends to decrease Rb/Cs ratios.

The Rb-Cs plot also neatly shows an important aspect of the rhyolites of oceanic extensional zones. Their Rb/Cs ratios indicate that the Cs depletion characteristic of such rocks is not accompanied by strong Rb depletion. Separation of this rhyolite group geographically stresses a point made in the section "Geochemical Features of Main Obsidian Groups," group V. The Iceland and Galapagos (Alcedo) rocks, generated entirely within oceanic crust, do not overlap the fields of

arc and continental-margin obsidians. The Salton Sea rhyolites, on the other hand, have Rb and Cs contents closely comparable to margin types, their transitional composition reflecting their transitional tectonic setting. The Admiralty Islands glasses occupy an intermediate position on the plot, perhaps an indication that they were erupted in a complex tectonic zone where oceanic-type crust in a back-arc basin is related to an overall subduction regime.

The partly contrasting behaviors of K and Cs permit a qualitative description of Cs distribution. On a  $K_2O$ -Cs plot (fig. 44), a relatively "depleted" field ( $K/Cs$  greater than 16,600) contains the majority of oceanic extensional rocks plus a few CLPD arc and continental rocks. In a "normal" field ( $K/Cs=5,000$ –16,600), the majority of the obsidians show no significant correlation between  $K_2O$  and Cs, mainly due to the source effects in Cs abundances. An enriched field ( $K/Cs<5,000$ ) is comprised of CIPP specimens and high-Cs CLPD rocks.

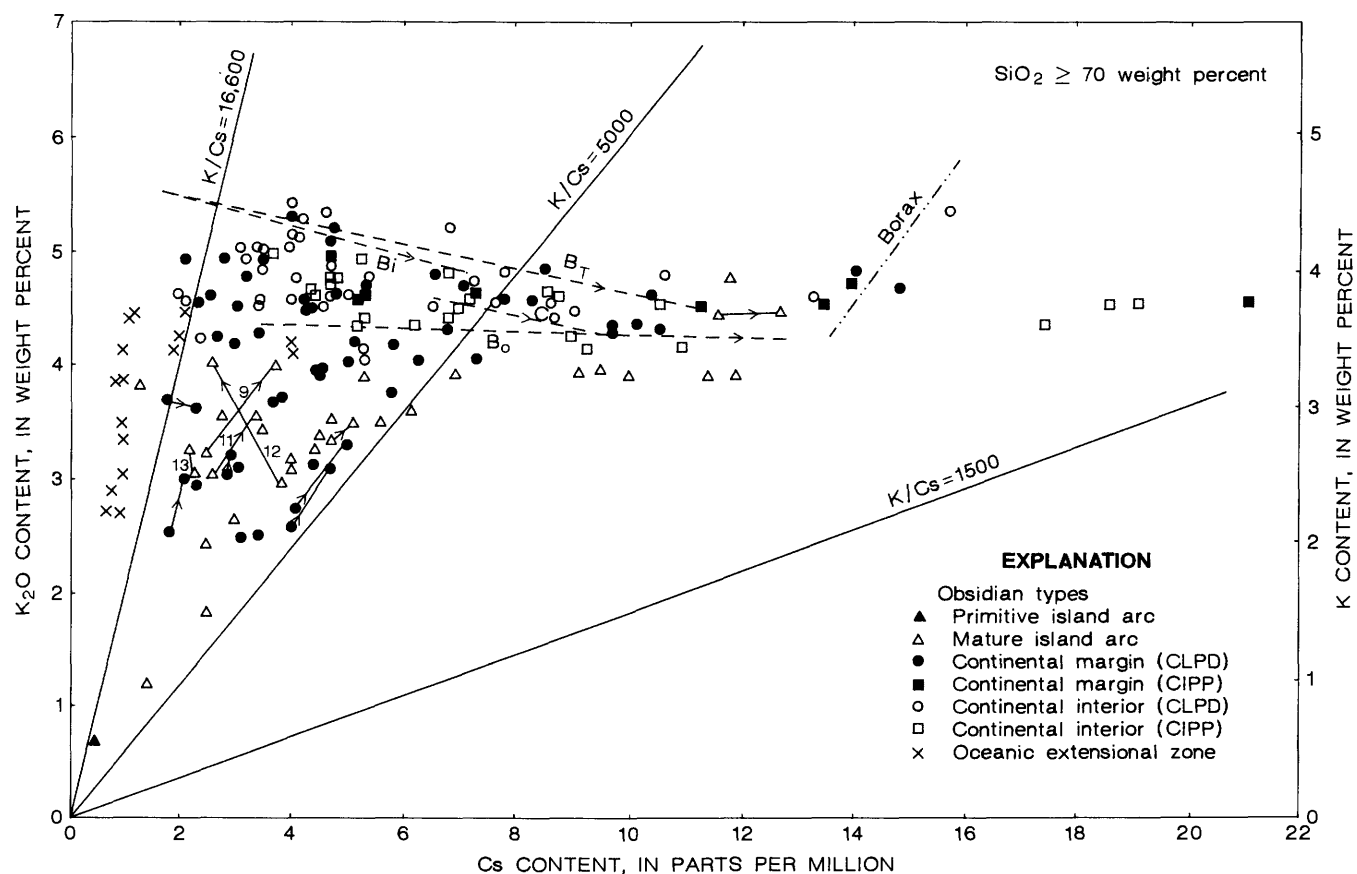


FIGURE 44.— $K_2O$  and K contents versus Cs content for obsidians and various comparative rocks. Data from appendix I. Sample 160 is omitted to preserve scale. Solid tielines connect rock-glass pairs; arrows point toward glass separate. Numbered tielines: Taupo, New Zealand; data from Ewart and others

(1968). Dashed lines include Bishop Tuff, Bi (Hildreth, 1981); Bandelier Tuff, Otowi, B<sub>0</sub>, and Tshirege, B<sub>1</sub> Members (R.L. Smith, unpub. data); Coso Range, Co (Bacon and others, 1981); and the Borax Lake, Borax, mixed magma (Bowman and others, 1973). Arrows indicate direction of liquid fractionation.

## NIOBIUM AND TANTALUM

Niobium and tantalum show wide variations in abundance in the obsidians, 0.6 to 258 ppm and <0.2 to 30 ppm, respectively. The wide range and low abundances of Ta in many specimens make it unsuitable for plotting on a linear scale against  $\text{SiO}_2$ , and the data are presented instead on a log CaO-log Ta plot (fig. 46).

The abundances of both elements are strongly controlled by crustal type, which makes them useful as indicators of tectonomagmatic settings. The lowest Nb concentrations are found in the rhyolites of primitive island arcs (table 7, app. V). Values less than 3 ppm are normal, and the 10 ppm Nb reported for a Tongan obsidian by Smith and others (1977) probably represents analytical error. There are no reported Ta determinations for these rocks; it almost certainly occurs in the 0.0X to 0.X ppm range and presents severe analytical problems.

Although the average Nb and Ta abundances in mature-island-arc and continental-margin rocks are notably different (table 7; fig. 40D, E), there is extensive overlap in ranges. The overlap between continental-margin and continental-interior obsidians is much smaller and, in fact, there is no overlap if CLPD rocks only are considered.

The relative success of Nb and Ta as discriminants results from their behavior during crystal-liquid-

controlled processes, which is closely related to the chemical affinities of the rock series (Gottfried, in Parker and Fleischer, 1968, p. 24). Both elements tend to behave in an increasingly incompatible or residual manner in more alkalic magmas, reflecting their enhanced solubility in such magmas. Thus, during differentiation of calcic suites, Nb and Ta concentrations tend to stay constant or decrease slightly with increasing  $\text{SiO}_2$  concentrations, for example, the Woodson Stock trend and the Metis Shoal and Crater Lake rock-glass tielines (figs. 43B, 47). In calc-alkalic suites, they stay constant or increase slightly (for example, the Okushiri and Capital Mountain tielines, fig. 47), whereas in alkali-calcic sequences, they rise as  $\text{SiO}_2$  rises (Bandelier Tuff tielines, fig. 47). Even small intergroup differences in Nb and Ta contents at 70 percent  $\text{SiO}_2$  are thus maintained or exaggerated with further crystal-liquid differentiation.

Nb and Ta are strongly concentrated upwards during CIPP. A Nb-enrichment factor of about 6 has been recorded for the Bandelier Tuff (Smith, 1979) and a factor of 2–3 for Ta in the Bishop Tuff by Hildreth (1979). This process is very potent at enriching continental silicic magmas in Nb and Ta; though CLPD interior rocks have a maximum of 55 ppm Nb, CIPP obsidians contain up to 270 ppm.

The strong controls over Nb-Ta distribution exerted by crustal type and genetic process result in relatively small, intragroup variations. At constant  $\text{SiO}_2$  values, such variations are typically only a factor of two.

A correlation matrix for elements with which one or both of Nb and Ta show  $r > 0.60$  is given below. All are elements which concentrated in rhyolites of the continental interiors and which are up-elements during CIPP. Their strong correlations may reflect similar behavior during a variety of differentiation processes, rather than geochemical coherence, but there may be an important common link in their ability to complex with F.

## Nb/Ta RATIOS

Analytical uncertainties are important in any discussion of variations of the Nb/Ta ratio. In a rock for which Nb and Ta are reported as  $8 \pm 1$  ppm and  $0.5 \pm 0.1$  ppm, respectively, the range of possible Nb/Ta ratios is 11.7 to 22.5, a considerable proportion of the whole range in the data bank (fig. 48). Subduction-related rhyolites may have abundances even lower than those in this example, and the problems of producing meaningful values of the Nb/Ta ratio are severe. It is not possible at this stage, for example, to provide firm figures for Nb/Ta ratios in rhyolites of primitive island arcs.

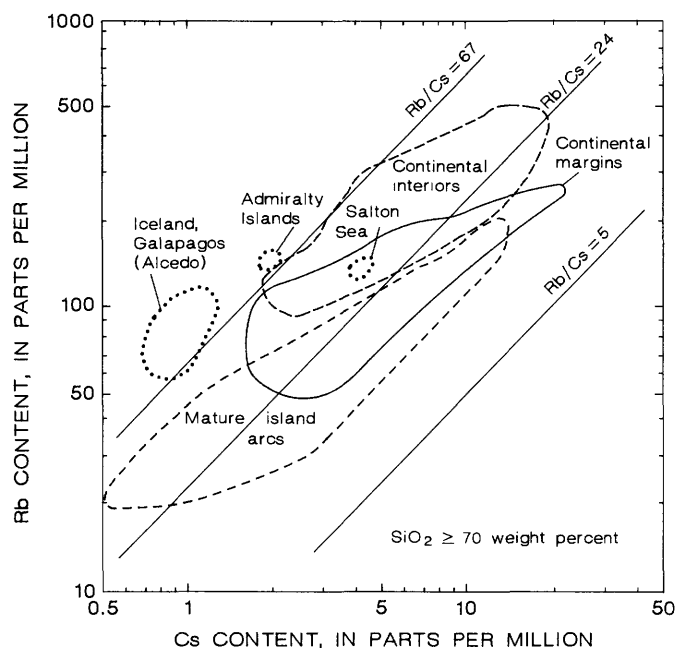


FIGURE 45.—Cs content versus Rb content showing generalized relations between Rb/Cs ratio and tectonic setting. Obsidians from oceanic extensional zones are separated into three groups (Iceland-Galapagos, Admiralty Islands, Salton Sea) according to locality.

The average ratios for the rhyolite groups may be significant (table 7). They seemingly indicate a progressively lower average in rhyolites from increasingly sialic settings. Breakdown of the data into CLPD and CIPP varieties complicates the issue a little. Basal-level obsidians in continental margins and continental interiors have similar ratios of 11.5 and 11.8, respectively. Those from mature island arcs and oceanic extensional zones have probably significantly higher averages of 13.7 and 14.0. Cratonization apparently results in Ta enrichment relative to Nb.

The average CIPP obsidian from the continental interior has a distinctly lower Nb/Ta ratio than CLPD obsidians. This suggests that the ratio tends to decrease during CIPP. Sufficiently precise data to test this are available only for the Bandelier Tuff (Smith and Gottfried, unpublished data). Here the ratio decreases with increasing differentiation from 12.9 to 11.5 in the Otowi Member and 14.9 to 11.2 in the Tshirege Member.

Despite the analytical uncertainties, it is possible to see variations in Nb/Ta ratio on a complex or center basis. For example, four samples from Medicine

Lake, Calif., have low Nb/Ta ratios in the range 7.4 to 9.4. By contrast, four glasses from Halmahera have high ratios between 16.2 and 21.5. These may represent the extremes of Nb-Ta fractionation during crystal-liquid processes. Alternatively, they may be partial cumulates, in that they contain amongst the highest modal abundances of Fe-Ti oxides (app. VII).

$r \approx 0.60$	Nb	Ta
F -----	0.72 -----	0.75
Be -----	0.88 -----	0.91
Li -----	— -----	0.65
Nb -----	1.00 -----	0.96
Ta -----	0.96 -----	1.00
Pb -----	0.64 -----	0.68
Sn -----	0.72 -----	0.73
Y -----	0.68 -----	0.64
Zn -----	0.74 -----	0.61
Tb -----	0.61 -----	—
Tm -----	0.67 -----	0.72
Yb -----	0.63 -----	0.61
Lu -----	0.60 -----	—

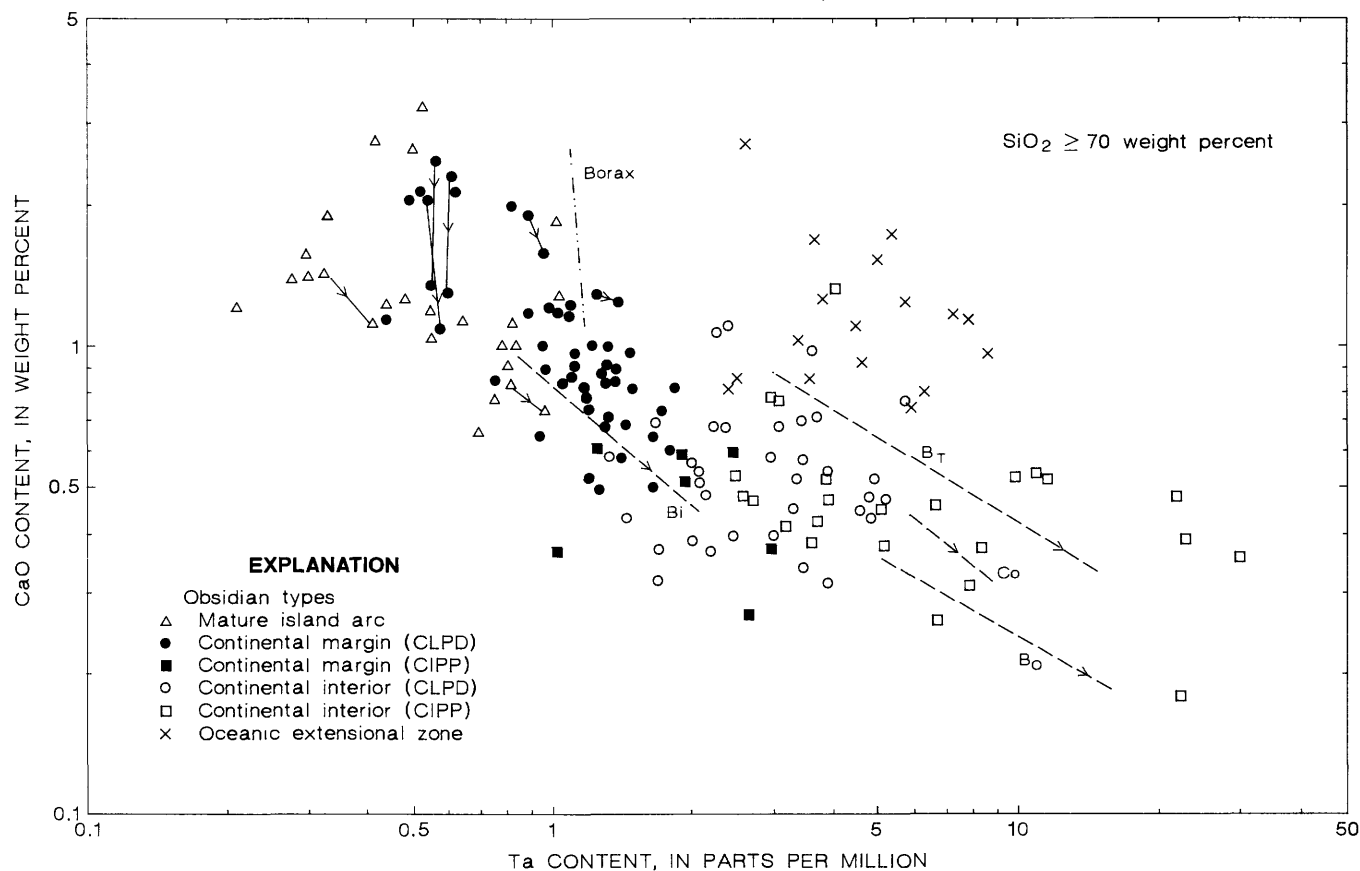


FIGURE 46.—Ta content versus CaO content for obsidians and various comparative rocks. Data from appendix I. Solid tie-lines represent rock-glass pairs with arrow pointing toward glass separate. Dashed lines: Bishop Tuff, Bi (Hildreth, 1981);

Bandelier Tuff, Otowi, B<sub>o</sub>, and Tshirege, B<sub>T</sub>, Members (R.L. Smith, unpub. data); Coso Range, Co (Bacon and others, 1981); and the Borax Lake, Borax, mixed magma (Bowman and others, 1973). Arrows indicate direction of liquid fractionation.



## LEAD

The range of Pb abundances is 4 to 101 ppm (fig. 43C). The lowest abundances (<10 ppm) occur in rhyolites of primitive island arcs. Obsidians from mature island arcs and continental margins have higher Pb contents but cannot be distinguished from each other on the basis of either their averages or ranges. The average base-level continental-interior rock has a Pb content of 26.4 ppm, probably not significantly different from the subduction-related group on a  $\text{SiO}_2$ -normalized basis. Oceanic-extensional rhyolites tend to have low Pb abundances; the range is 9–19 ppm and the average 14 ppm (fig. 40F). This is consistent with the generally low levels of large-radius cations in these rocks.

The tielines for rock-glass pairs from Crater Lake and Okushiri show modest Pb enrichment in the glass

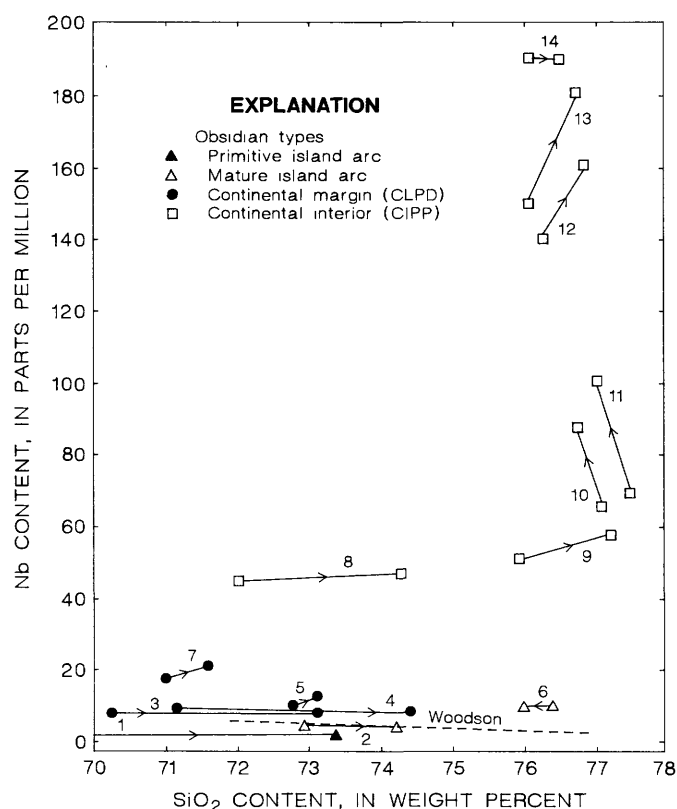


FIGURE 47.— $\text{SiO}_2$  content versus Nb content showing behavior in various systems controlled by crystal-liquid processes. Rock-glass tielines are numbered as follows: 1, Metis Shoal, Tonga (app. V; David Gottfried, unpub. data); 2, Halmahera (app. I, Nos. 209, 210); 3, 4, Crater Lake (app. I, Nos. 15, 16; 17, 18); 5, South Sister (app. I, Nos. 9, 10); 6, Okushiri (app. I, Nos. 186, 187); 7, Capital Mountain (app. I, Nos. 4, 5); 8, 9, 12, 13, from the Tshirege Member, Bandelier Tuff; 10, 11, 14, from the Otowi Member, Bandelier Tuff (R.L. Smith, unpub. data). Arrows indicate direction of liquid fractionation (glass). Woodson, Woodson Granodiorite trend (David Gottfried, unpub. data).

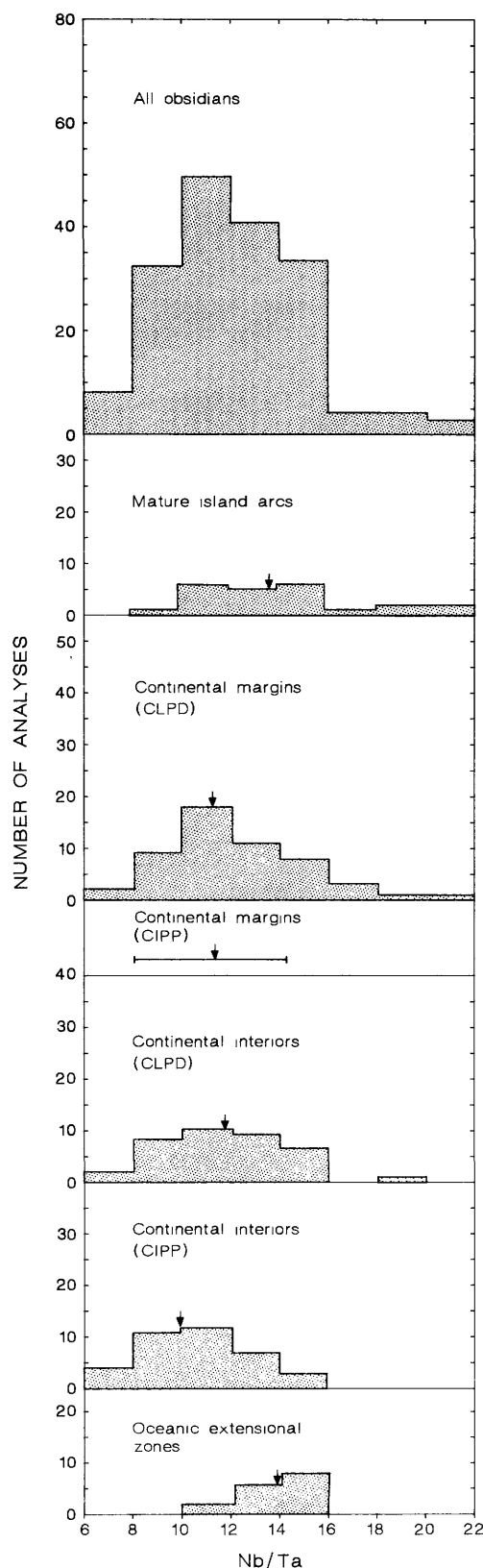


FIGURE 48.—Distribution of Nb/Ta ratio in obsidians. Obsidians of continental margins (CIPP types) are shown as ranges only. Arrows indicate average values. Data from appendix I. Sample 160 is omitted to preserve scale.

(fig. 43C), indicating a bulk distribution coefficient not much less than one for these samples. The decrease in Pb content in the glass for pairs from Capital Mountain, South Sister, and Halmahera requires an explanation. The Capital Mountain rock contains biotite phenocrysts, and it is possible that Pb has been strongly partitioned into that phase. The South Sister and Halmahera rocks have the phenocryst assemblages Pl+Opx+Ox and Pl+Opx+Cpx+Ox, respectively. None of these minerals has a distribution coefficient for Pb greater than 1 (Leeman, 1979), and their crystallization should have resulted in Pb increase in the residual liquids. A possible explanation is that a submicroscopic Pb-sulfide phase is associated with the phenocryst minerals. Alternatively, there may be analytical error in the Pb determinations.

Evidence from the Coso (Bacon and others, 1981) and Bandelier (R.L. Smith, unpub. data) systems indicates that Pb is an upward-concentrating element during CIPP. In the obsidians, the highest values ( $\geq 35$  ppm) have been recorded mainly from CIPP rocks, and the average CIPP continental-interior obsidian has a Pb content (38.4 ppm) considerably in excess of the base-level rocks (26.4 ppm).

The behavior of Pb in the rhyolites thus seems to match that of such elements as Nb and Rb, namely, modest increases in abundance within the crystal-liquid field and sharp increases for limited major-element variations when CIPP is the dominant differentiation mechanism. Another comparison with Pb is that within-group variations appear modest. At a given  $\text{SiO}_2$  level, within-group, base level Pb contents typically vary only by a factor of 2 or 3. Occasional samples are somewhat anomalous; for example, the obsidian from Umnak (No. 2) has a high Pb content (44 ppm) for a base-level rock with 73.1 percent  $\text{SiO}_2$ .

$r \geq 0.60$	Pb
F .....	0.63
Be .....	0.74
Li .....	0.63
Nb .....	0.64
Ta .....	0.68
Rb .....	0.64

#### LEAD ISOTOPES

Inasmuch as secondary hydration may, by rock-ground water exchange, alter the lead isotopic composition of silicic rocks (for example, see Taylor and Forester, 1971), nonhydrated obsidians are a particularly valuable guide to the isotopic composition of the relevant magmas.

Available lead isotopic ratios are given in table 13. The range ( $^{206}\text{Pb}/^{204}\text{Pb}=16.58\text{--}19.16$ ) indicates the glasses are variably radiogenic as regards lead content. This variation is discussed using as a basis the comprehensive review by Zartman (1974) as a basis.

Zartman (1974) divided the American cordilleran region into three geographical provinces on their characteristic lead isotopic patterns (fig. 49). The igneous rocks of field I, with rather low  $^{206}\text{Pb}/^{204}\text{Pb}$ , are comparatively unradiogenic; obsidians representative of this province are from the Jemez Mountains,

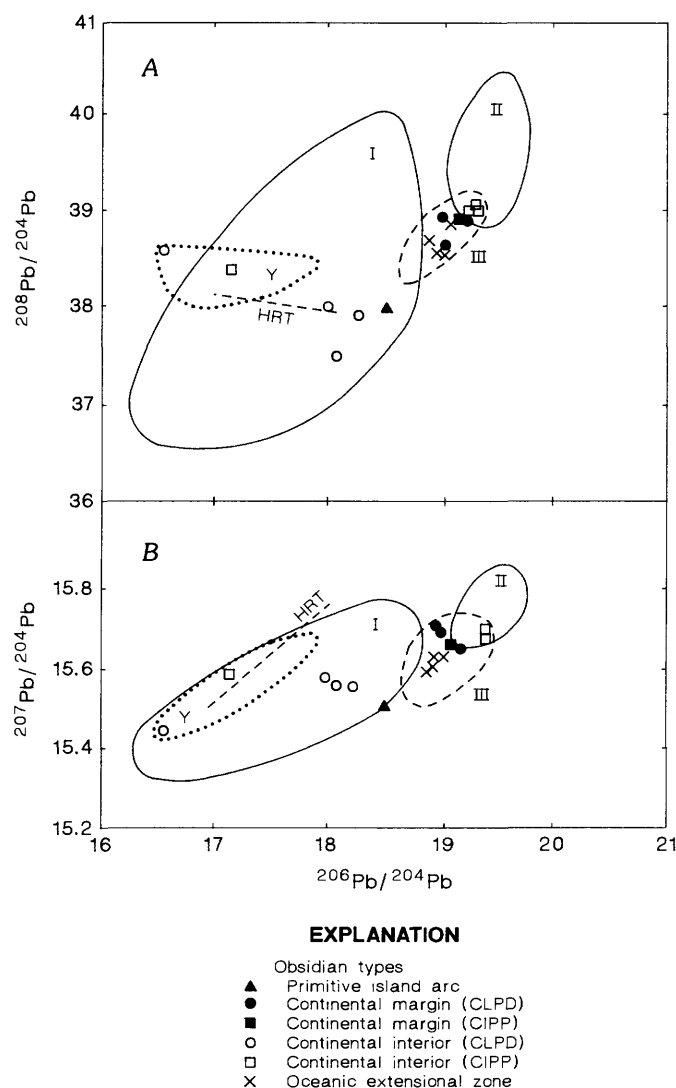


FIGURE 49.—Ratio of  $^{206}\text{Pb}/^{204}\text{Pb}$  versus ratios of  $^{208}\text{Pb}/^{204}\text{Pb}$  (A) and  $^{207}\text{Pb}/^{204}\text{Pb}$  (B) for obsidians. Fields I to III are lead isotopic provinces in Western United States recognized by Zartman (1974). Field Y encloses rhyolites of Yellowstone volcanic complex (Doe and others, 1982). Line HRT connects analyses of the Huckleberry Ridge Tuff, Yellowstone (Doe and others, 1982). Data from appendix I.

TABLE 13.—Lead isotopic ratios in silicic obsidians

Locality	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	Reference
<b>Western United States</b>				
Little Glass Mountain, Medicine Lake -----	18.98	15.69	38.93	Doe (1967)
	18.95	15.58	38.63	Church and Tilton (1973)
Lower Lake, Clear Lake -----	19.156	15.64	38.87	Doe (1967)
Do. (reanalysis) -----	19.172	15.653	38.918	Doe and Delevaux (1973)
Mono Craters -----	19.12	15.66	38.92	Doe (1968)
Coso volcanic field				
13-43-9 -----	19.297	15.678	38.993	Bacon and others (1984)
73-5 -----	19.298	15.682	39.001	Do.
73-20 -----	19.296	15.684	39.004	Do.
9-5-2 -----	19.294	15.684	39.002	Do.
9-6-11 -----	19.279	15.676	38.980	Do.
Obsidian Butte, Salton Sea -----	18.908	15.62	38.56	Doe and others (1966)
Red Island, Salton Sea -----	18.895	15.61	38.56	Do.
Cougar Creek flow, Yellowstone -----	16.58	15.44	38.58	Doe and others (1982)
	16.599	15.425	38.415	Do.
Obsidian Cliff flow, Yellowstone -----	17.137	15.538	38.289	Do.
Gibbon River flow, Yellowstone -----	17.18	15.59	38.40	Do.
Nellie Creek plug, San Juan Mountains ---	18.25	15.55	37.74	Lipman and others (1978)
Beaver Creek flow, San Juan Mountains --	18.10	15.55	37.46	Do.
Arroyo Hondo, Jemez Mountains -----	18.201	15.53	38.00	Doe (1967)
Los Posos, Jemez Mountains -----	18.012	15.57	37.99	Do.
<b>Iceland</b>				
Lodmundur, Kerlingarfjöll -----	18.82	15.59	38.68	Welke and others (1968)
Thorgeirsfell, Snaefellsnes -----	19.01	15.62	38.87	Do.
<b>Southwest Pacific</b>				
Metis Shoal glass -----	18.473	15.505	37.968	Oversby and Ewart (1972)

New Mexico, and Yellowstone Park, Wyoming, the continental interior of this report.

Rocks of Zartman's field III occupy a belt adjacent to the Pacific Ocean, the continental margin of this report. Field III igneous-rock lead isotopes are more radiogenic than those of Field I. The glasses plotted in field III in figure 49 come from Medicine Lake, Clear Lake, Mono Craters, and Salton Sea, all in California. The most radiogenic leads recognized by Zartman (field II) occur geographically between fields I and III. They are represented, among the obsidians, by the Coso rhyolites (Bacon and others, 1984).

Zartman (1974) suggests that the different lead patterns reflect different sources of the silicic magmas in each field. In field I, they have been derived from ancient (Precambrian) lower-crustal or possibly upper-mantle sources (compare with Lipman and others, 1978; Doe and others, 1982). The silicic rocks of field III have apparently been generated from thick eugeosynclinal piles, where subducted pelagic sediments and (or) basalts of the oceanic crust have recently contributed significant amounts of lead.

The non-American glasses plotted in figure 49 are from Metis Shoal (Oversby and Ewart, 1972) and

Iceland (Welke and others, 1968). Rocks from Iceland plot in field III; that is, they are moderately radiogenic. Because a contribution from subducted pelagic sediments would seem unlikely, the involvement of oceanic crust basalt (Zartman, 1974) during their evolution would seem to be a more viable alternative. The Metis Shoal glass is distinctly less radiogenic than other Tongan volcanics and actually plots in field I of American rocks. Oversby and Ewart (1972) have proposed that the parental magma to the Metis Shoal dacite was formed by partial fusion of mantle which had previously been injected by basalt, with low  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio, from deeper, lithospheric sources. The Pb-isotope data reflect this unusual mixed-source material.

The relation of this broad pattern of variation to that of Sr isotopes is noteworthy. Rocks of the continental interior are more radiogenic as regards Sr than those of the oceanic extensional zones and subduction-related types (fig. 50). An overall negative correlation between  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios is indicated by the obsidians. However, data from the Yellowstone volcanic field (Doe and others, 1982) show that the relation is not simple. For example, data for the Huckleberry Ridge Tuff, where

Sr isotopic determinations were made on the potassic feldspars, suggest a positive relation between the ratios. The ratios show no positive covariance in the Yellowstone rhyolites either; two flows (field B, fig. 50) have higher values of both ratios than the majority of flows (field A). The wider spread of both initial  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios in continental-interior obsidians may reflect the greater variability of the source rocks and the establishment of isotopic gradients in CIPP magma chambers.

#### RUBIDIUM

There is a large range of Rb concentrations in the obsidians, 6 to 460 ppm. Rhyolites from primitive island arcs have distinctly low abundances (<25 ppm; fig. 40G). Between the CLPD rocks of the other groups, there is a considerable amount of overlap, though the averages increase in the order mature arc→continental margin→continental interior (fig. 40G). Intragroup variations are low, typically a factor of two at a given  $\text{SiO}_2$  content (fig. 43D).

All but two of the rock-glass pairs show Rb enrichment in the glass, indicating, as does the trend for the Woodson stock, that Rb concentrates in residual melts. One of the two pairs which have slight Rb depletion in the glass (Nos. 4, 5) is from a biotite-phyric rock, and  $\text{K}_2\text{O}$  and Pb are also slightly reduced in the glass, presumably as a result of partitioning of these elements into the mica. In the other pair (Nos. 9, 10) there is only a small difference (2 ppm) in Rb content of rock and glass, and analytical imprecision may be suspected.

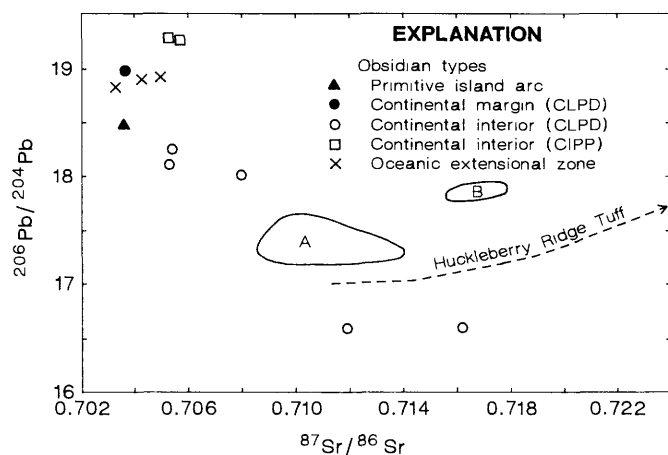


FIGURE 50.—Ratio of initial  $^{87}\text{Sr}/^{86}\text{Sr}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  for obsidians. Biscuit Basin and Canyon flows of Yellowstone volcanic complex plot in field B; other Yellowstone rhyolites in field A. Data are from appendixes I and II. Yellowstone data, including Huckleberry Ridge Tuff, from Doe and others (1982).

Rb is an up-element in CIPP systems. Enrichment factors of 5 to 6 have been recorded for the Bandelier Tuff (upper member) by Smith and Bailey (1966) and 2 to 3 for the Bishop Tuff by Hildreth (1979). In the Coso system, the factor is 1.4. CIPP produces the highest Rb concentrations recorded from continental-interior obsidians; all values greater than 300 ppm are of CIPP type.

$r \approx 0.60$	Rb
CaO -----	-0.61
F -----	0.72
Be -----	0.75
Cs -----	0.64
Li -----	0.62
Pb -----	0.64
Sn -----	0.65
Sr -----	-0.60
Th -----	0.89
U -----	0.84
W -----	0.67

Rb shows strong (>0.60) positive correlation with the rare metals Be, Li, Sn, and W, and with the large cations Cs, Th, U, Pb, and F. Strong negative relations with CaO and Sr probably reflect feldspar control during crystal-liquid processes and antithetic behavior during CIPP. The correlations with the other elements may reflect, in part at least, a tendency to complex with F.

#### K/Rb RATIOS

Crystal-liquid processes tend to maintain a positive correlation between K and Rb, although the K/Rb ratio of more potassic rocks may be as low as 150. CIPP produces sharp changes in the ratio, invariably becoming lower in lower-temperature liquids, and all specimens with K/Rb less than about 150 are CIPP rocks. The apparent contradiction to this statement, as shown by figure 51, is an artifact of the histogram interval. As a graphic illustration of the problems of overlap of CLPD and CIPP compositions, the late-erupting magma of the Bishop Tuff and Tshirege sheet have two of the highest ratios (485 and 565, respectively) shown by the data bank (fig. 25).

#### ANTIMONY

Analytical problems were severe at the low levels (mainly <2 ppm) of Sb found in the obsidians. Duplication of analyses was difficult, in the worst cases duplicate analyses differed 100–200 percent. Any detailed discussion of Sb variations, such as rock-glass tieline orientations and intragroup variations, is unwarranted.

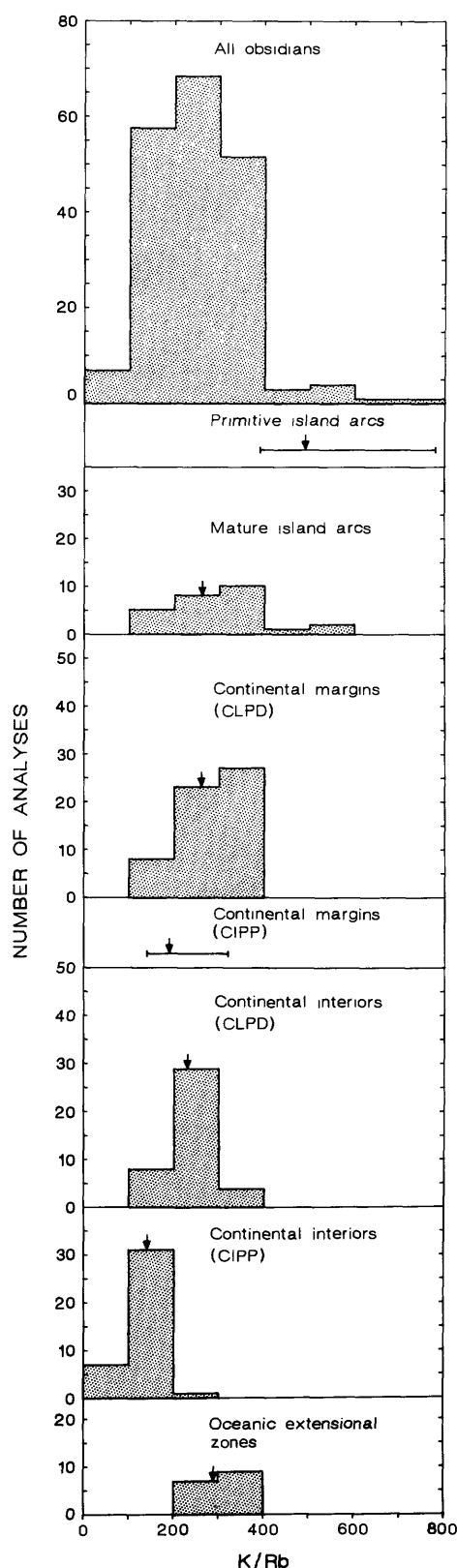


FIGURE 51.—Distribution of K/Rb ratio in obsidians. Obsidians of primitive island arcs and continental margins (CIPP types) are shown as ranges only. Arrows indicate average values. Data from appendixes I and V.

There are few published data with which to compare the new analyses. Tanner and Ehmann (1967) found 0.52 ppm Sb by neutron activation analysis in an obsidian from Big Glass Mountain, Calif., which is close to the 0.7 ppm obtained on a sample of the flow prepared for this study (No. 42). However, for the USGS standard RGM-1, also from Big Glass Mountain, Katz and Grossman (1976) report 1.52 ppm Sb and Schwarz and Rowe (1976) give 1.30 ppm, whereas the updated USGS value determined by INAA (No. 43) is 1.20 ppm. Differences may be due both to analytical error and to sample heterogeneity in this mixed lava flow.

Bowman and others (1973) report a range of  $0.93 \pm 0.10$  to  $1.2 \pm 0.2$  ppm Sb in the obsidian at Borax Lake, close to the value of  $0.8 \pm 0.1$  ppm obtained on a separate sample for this study (No. 48). These various comparisons suggest that although our Sb data may be imprecise, they are of the right order of magnitude. The following comments are therefore offered with caution.

Obsidian group	Sb range, in ppm	Sb average, in ppm
Primitive island arcs -----	(no data)	—
Mature island arcs -----	0.2–2.3	0.7
Continental margins		
CLPD -----	0.3–1.9	.8
CIPP -----	0.6–1.3	1.0
Continental interiors		
CLPD -----	0.1–1.3	.5
CIPP -----	0.3–2.9	.9
Oceanic extensional zones ----	0.3–0.6	.5

The average data indicate that the highest CLPD compositions are in rocks from mature island arcs and continental margins, and the lowest in obsidians from oceanic extensional zones. Also judging from the averages, CIPP would appear to concentrate Sb in lower-temperature liquids. In the Bishop Tuff, Sb shows one of the highest enrichment factors of all up-elements, about 3 (Hildreth, 1979); a slight enrichment from 1.0 to 1.3 ppm was recorded in the Coso system by Bacon and others (1981). The highest value in the data bank, 39 ppm, was recorded in the macusanite glass, a rock inferred to have evolved strongly by CIPP.

Sb shows no correlation coefficient greater than 0.4. The largest values (0.36) are for Cs and Li. These are at least partly due to intragroup variations, perhaps themselves related to variable source-rock compositions. Thus, the Utah obsidians (including both CLPD and CIPP rocks), already noted as being relatively depleted in Cs and Li, have Sb contents lower than their group average (fig. 52). On the other hand, the Java obsidians, already noted for their high Cs contents, have Sb contents near or slightly higher than

their group average. The Clear Lake or Medicine Lake high Cs obsidians are variable for Sb content but tend to confirm the general Sb-Cs affinity.

### SCANDIUM

The ranges and averages of Sc abundances in the rhyolites are as follows:

Obsidian group	Sc range, in ppm	Sc average, in ppm
Primitive island arcs -----	10.2 (one sample)	--
Mature island arcs -----	1.72-12.40	6.4
Continental margins		
CLPD -----	1.1-8.4	3.7
CIPP -----	1.57-5.15	2.8
Continental interiors		
CLPD -----	1.03-4.23	2.3
CIPP -----	0.12-3.85	1.6
Oceanic extensional zones ---	0.43-11.05	3.9

Sc concentrations in arc rocks are higher than those in CLPD continental-margin rocks, which in turn are higher than those in CLPD continental-interior types, both in terms of averages and at similar  $\text{SiO}_2$  values. There are rather wide within-group variations, typically about a factor of 4 at constant  $\text{SiO}_2$  or MgO (fig. 53).

CIPP rocks have, on average, lower Sc contents than CLPD types in both continental-margin and continental-interior groups. The behavior of Sc in CIPP systems is, however, complex. In the Bishop Tuff system, Sc was an up-element, with an enrichment factor of 1.6 to 1.7 (Hildreth, 1979, 1981), but in both Bandelier sheets, it was a down-element. The possible relevance to the obsidian data bank is shown in an Sc-Ta plot (fig. 54). Ta is enriched upwards in all known CIPP systems. The spread of CIPP obsidian points suggests that Sc, as in the ash-flow sheets, shows variable behavior from system to system. The reasons for this are not yet understood.

Scandium concentrations are also useful as indicators of contamination of silicic magmas by more mafic material. For example, the  $\text{SiO}_2$ -poor end of the Borax Lake mixed-magma trend contains 10.48 ppm Sc (Bowman and others, 1973), higher than any other continental-margin obsidian but comparable to island-arc types. Similarly, the Askja mixed obsidian (No. 176) contains about twice as much Sc as any other rhyolite from oceanic extensional zones. Wide variations in within-group CLPD abundances of Sc mean that it is impossible to generalize about the degree of contamination on the basis of Sc abundances alone. Careful evaluation of Sc data (and of Co, Cr, and Ni analyses) for individual

suites should reveal anomalies consistent with mixing or assimilation.

The strongest ( $r > 0.60$ ) correlations shown by Sc are for the major elements Fe, Mg, Ca, K, and Ti, reflecting concentration of Sc in the least silicic, highest Ca liquids. The MgO-Sc plot (fig. 53) provides a useful summary of Sc distribution in the silicic obsidians. CLPD rocks cover a broad, positive field, whose width represents mainly within-group variations in Sc abundances. In certain magmatic systems, CIPP results in upward-enrichment of Sc and a sharp increase in Sc/Mg ratios. There is a concomitant tendency for the field of CIPP rocks to be displaced toward higher Sc/Mg ratios than CLPD types. Other CIPP rocks plot at very low MgO-Sc values; these lie close to trend Co of figure 54 and are rocks where crystal-liquid controls have also affected Sc distribution.

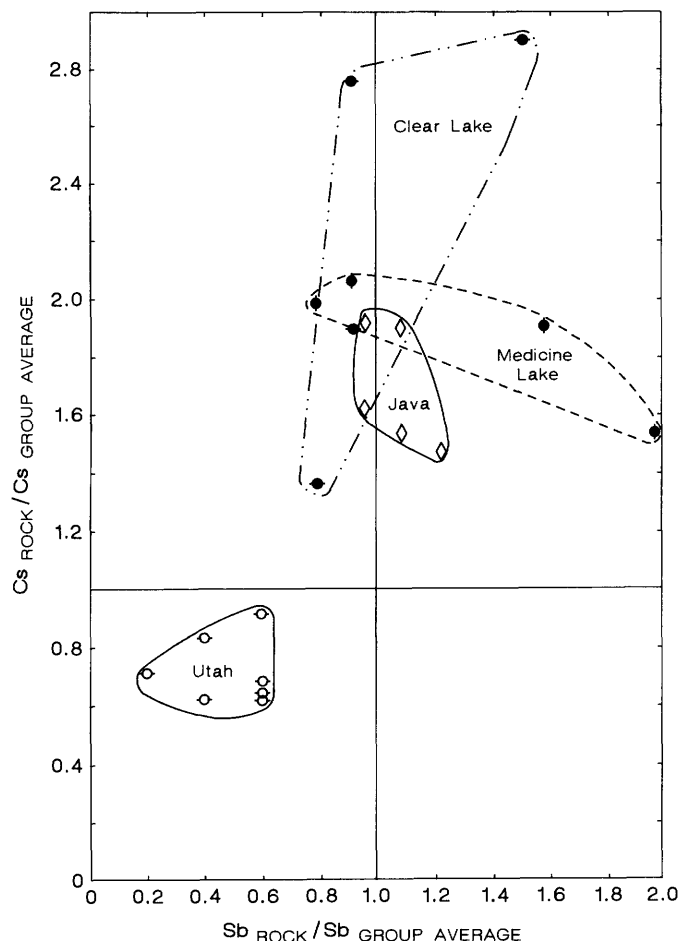


FIGURE 52.—Sb versus Cs relations in obsidians from selected areas. Element abundances were normalized by dividing by average value for each group. Fiducial lines, for each axis, separate positions of sample, or fields, relative to their respective group averages. Sample symbols simply differentiate geographic localities in overlapping fields.

$r \geq 0.60$	Sc
FeO -----	0.63
FeO <sub>t</sub> -----	0.61
MgO -----	0.65
CaO -----	0.72
K <sub>2</sub> O -----	-0.67
TiO <sub>2</sub> -----	0.71

## STRONTIUM

The range of Sr abundances, 0.3 to 402 ppm, is one of the largest in the data bank and makes a linear plot of Sr against SiO<sub>2</sub> unsuitable. Ranges

and averages for each of the rhyolite groups are given in tables 7-9. Obsidians from oceanic extensional zones have relatively low Sr abundances for CLPD rocks, on both average and SiO<sub>2</sub>-normalized bases. The rocks from primitive island arcs overlap the lower end of the field of specimens from mature island arcs (fig. 40I), the higher average value in the primitive-arc rocks reflecting their lower SiO<sub>2</sub> contents. The averages and ranges for obsidians of mature island arcs and continental margins are very similar. Jakes and White (1972) have suggested that calc-alkalic volcanic rocks of island arcs generally have lower contents of Sr at the same SiO<sub>2</sub> and K<sub>2</sub>O values than rocks from continental

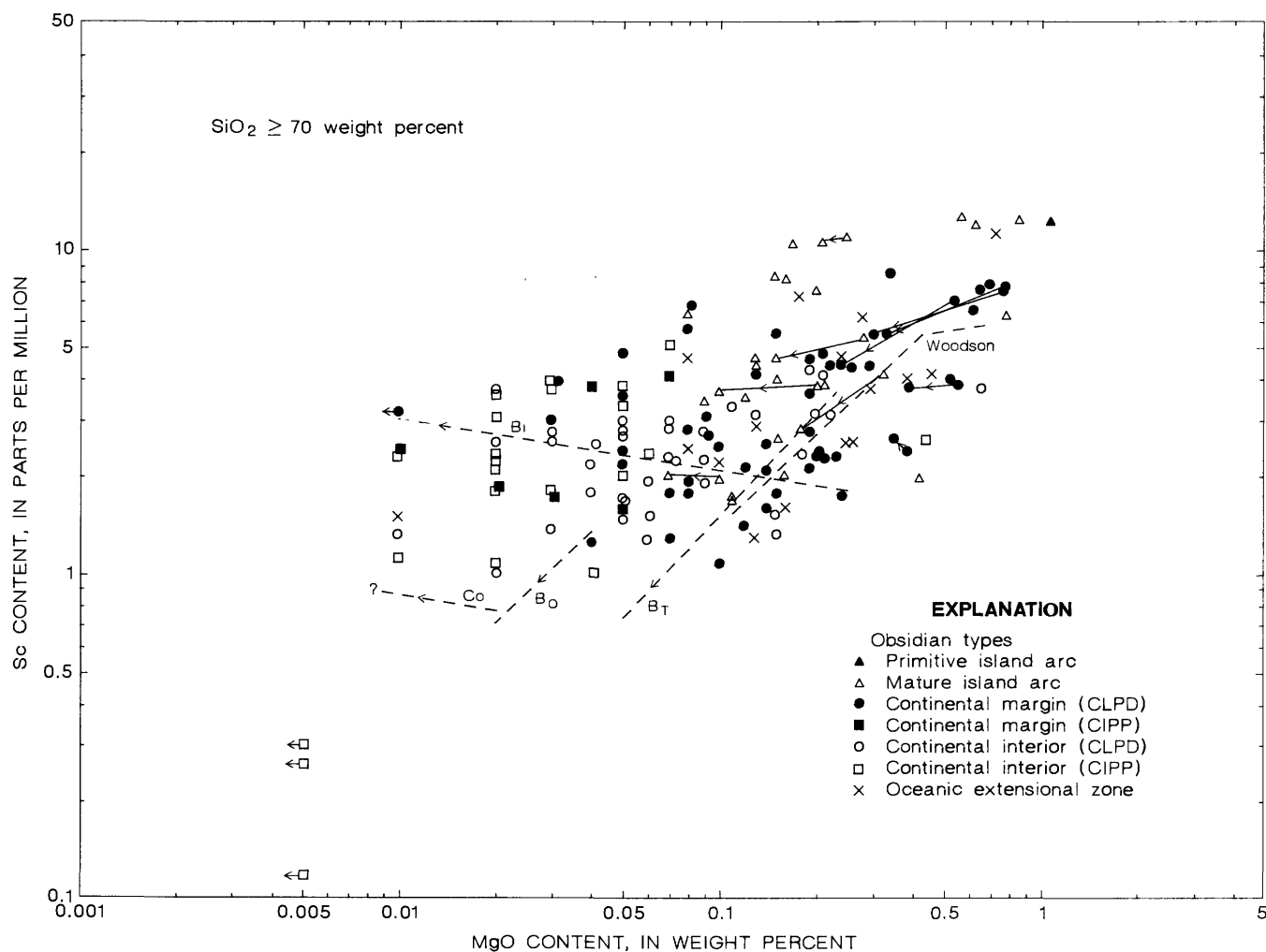


FIGURE 53.—MgO content versus Sc content for obsidians and various comparative rocks. Data sources are same as for figure 5. Sample 111 is omitted. Solid tielines represent rock-glass pairs, arrows point toward glass separate. Dashed lines represent various systems: Bishop Tuff, Bi

(Hildreth, 1981); Bandelier Tuff, Otowi, B<sub>O</sub>, and Tshirege, B<sub>T</sub>, Members (R.L. Smith, unpub. data); Coso Range, Co (Bacon and others, 1981); and Woodson Granodiorite, Woodson (D. Gottfried, unpub. data). Arrows indicate direction of liquid fractionation.

margins. We cannot distinguish systematic differences between the two groups at equivalent  $\text{SiO}_2$  contents. The  $\text{K}_2\text{O}$ -Sr relation of Jakes and White (1972) possibly holds for higher CaO rocks but is more a function of lower  $\text{K}_2\text{O}$  values in the arc rocks than lower Sr.

CLPD obsidians of the continental interiors have, on any basis, notably lower average Sr abundances than subduction-related obsidians. Levels of 1–2 ppm in certain of these rocks indicate that crystal-liquid processes may produce extreme Sr depletion in rhyolites (compare with Noble and others, 1972). Several mechanisms may be involved: extensive plagioclase fractionation from parental melts; retention of plagioclase as a residual phase in the source rocks during crustal anatexis; and (or) generation of the melts in Sr-depleted source rocks, this condition being transmitted to the melts regardless of whether plagioclase is a residual phase after fusion.

The data for rock-glass pairs and the Woodson stock point to modest Sr depletion in residual liquids where  $\text{SiO}_2$  is less than 75–76 percent, but to very rapid depletion in more silicic liquids. Fractionation accentuates within-group variations, especially at the high-silica end, where factors of 3–4 are common. CIPP also results in extreme Sr depletion in lower-temperature liquids. Hildreth (1981) records a factor of 23 depletion in the Bishop Tuff. In the Coso rocks, the factor is about 5 (Bacon and others, 1981). Very low Sr abundances (<1–10

ppm, average 3.8 ppm) are characteristic of CIPP continental-interior rocks but, as noted above, are not exclusive to them.

Sr has high ( $r > 0.60$ ) correlation coefficients mainly with certain major elements, reflecting its tendency to concentrate in the high MgO-CaO rhyolites of the island arcs and continental margins. The highest value of  $r$  is with CaO, a relation predictable from classical considerations. A CaO-Sr plot (fig. 55A) clearly shows the two main factors controlling Sr-Ca covariation in the obsidians.

1. There is a tendency, indicated by the average values, toward lower Ca/Sr ratios in the sequence obsidians of primitive island arcs (173)→calcic varieties from mature island arcs (93)→calc-alkalic varieties from mature island arcs (71)→CLPD continental-margin rocks (56). The trend is reversed in the CLPD continental-interior obsidians, the average (103) indicating either that the source rocks of the rhyolites were depleted in Sr relative to Ca, that Sr was preferentially retained by the source rocks during melting, or that the ratio was increased by substantial crystal fractionation.

2. In rocks with CaO greater than 1 percent and Sr greater than 100 ppm, crystal-liquid processes produce little change in the Ca/Sr ratio of about 120 (fig. 55). However, in less calcic rocks, they can result in sharp increases in the Ca/Sr ratio (see the Woodson trend, for example). CIPP has the same effect, in extreme cases giving Ca/Sr ratios greater than  $10^4$ .

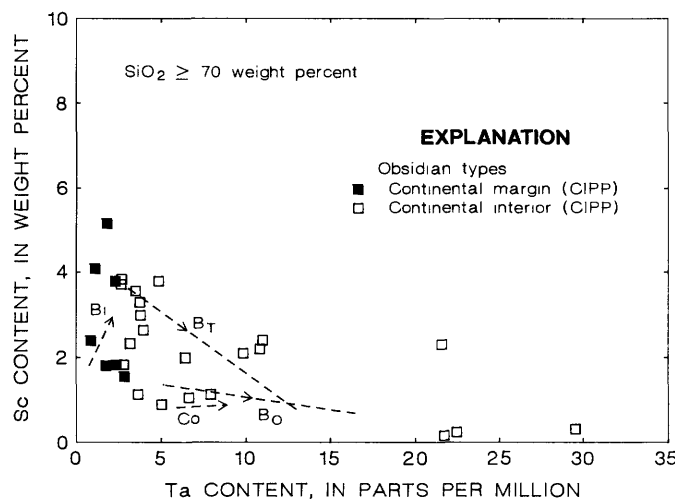


FIGURE 54.—Ta content versus Sc content showing possible effects of CIPP on silicic magmas. Data sources are same as for figure 5. Dashed lines represent CIPP systems: Bishop Tuff, B<sub>1</sub> (Hildreth, 1981); Bandelier Tuff, Otowi, B<sub>0</sub>, and Tshirege, B<sub>7</sub>, Members (R.L. Smith, unpub. data); Coso Range, Co (Bacon and others, 1981). Arrows indicate direction of liquid fractionation.

$r \geq 0.60$	Sr
$\text{SiO}_2$ -----	-0.65
$\text{Al}_2\text{O}_3$ -----	0.73
$\text{MgO}$ -----	0.80
$\text{CaO}$ -----	0.83
$\text{K}_2\text{O}$ -----	-0.69
$\text{TiO}_2$ -----	0.71
$\text{P}_2\text{O}_5$ -----	0.70
Rb -----	-0.60

Rb/Sr ratios vary from <0.1 to >1,000 in the obsidians, the ratio increasing with increasing crystal fractionation and with increasing degrees of CIPP (fig. 55B). The majority of obsidians fall within a broad band elongated parallel to the various differentiation trends. Rocks from the primitive island arcs fall to the Rb-poor side of this band; a trend drawn from these rocks transverse to the main band follows a trend of increasing crustal maturity.

The Ta-Sr plot (fig. 55C) makes a useful tectonomagmatic discrimination diagram. The field boundaries are arbitrary and correctly assign 89.1 percent



of obsidians to their respective groups as we have classified them. The general usefulness of this plot is unfortunately limited by the mobility of Sr during low-temperature alteration processes.

### STRONTIUM ISOTOPES

Initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are compiled in table 14. The ranges in each obsidian group are:

Obsidian group	$^{87}\text{Sr}/^{86}\text{Sr}$ range
Primitive island arcs	(0.7038)
Mature island arcs	0.7033–0.7045
Continental margins	0.7036–0.7064
Continental interiors	0.7046–0.7162
Oceanic extensional zones	0.7032–0.7050

These values bear out the observation (Hedge and Peterman, 1974) that volcanic rocks emplaced through old sialic crust generally have higher and more variable initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios than those from island arcs and relatively young continental-margin settings. The proportion of continental crust to mantle components in its rhyolites is increasing as cratonization proceeds.

The ranges of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of five isotopically zoned, voluminous ash-flow sheets are also given in table 14. In each case, the ratios show an increase with inferred height in the magma chamber. The systematic nature of the increases suggests that the process is not random and that development of the isotopic gradients is an integral part of the zonation of the magma chamber (Hildreth, 1981).

Various mechanisms may have played roles in establishing isotopic variability in the melts, including isotopic exchange with wall and roof rocks (Noble and Hedge, 1969; Doe and others, 1982; Michael, 1983), interaction with high-temperature meteoric waters or hydrothermal fluids (Lipman and Friedman, 1975; Lipman and others, 1978; Doe and others, 1982), and inheritance of variable source-rock isotopic signatures (Hildreth, 1981), but the relative contribution of each mechanism remains unknown, even for individual magmatic systems. In some cases, post-eruptive hydration of glassy samples may have contributed to isotopic variability. In the Bishop Tuff, California, Halliday and others (1984) reported initial ratios in glassy, whole-rock samples in the range 0.7061–0.7069. The variability in the whole-rock samples was ascribed to low-temperature, post-eruptive interaction with meteoric water (see "Oxygen Isotopes").

"These considerations indicate that it is dangerous to assume that the Sr \*\*\*isotopic variability of a\*\*\*

TABLE 14.—Strontium isotopic ratios in silicic obsidians

Locality	$^{87}\text{Sr}/^{86}\text{Sr}$ Initial	Reference
Big Obsidian Flow, Newberry, Oreg. -----	0.70362	(1)
Little Glass Mtn., Medicine Lake, Calif. ----	.7037±.00011	(2)
Casa Diablo Hot Spr., Long Valley, Calif. ---	.7064±.0005	(3)
Coso volcanic field, Calif.		
13-43-10 -----	.7058±.0005	(4)
9-5-2 -----	.7053±.0003	(4)
9-6-11 -----	.70585±.00010	(4)
Obsidian Butte, Salton Sea, Calif. -----	.7056	(5)
Red Island, Salton Sea, Calif. -----	.7049	(5)
U.S. gypsum mine, Nev. -----	.07054±.0003	(6)
Steamboat Springs, Nev. -----	.7055±.0002	(6)
Black Rock Range, Nev. -----	.7046±.0003	(6)
Cougar Creek, Yellowstone, Wyo. -----	.7119±.0003	(7)
Cougar Creek, Yellowstone, Wyo. -----	.7162±.0003	(7)
Beaver Creek, San Juan Mtns., Colo. -----	.7053±.0002	(8)
Nellie Cr., Lake City caldera, Colo. -----	.7054±.0002	(8)
Los Posos, Jemez Mts., N. Mex. -----	.7087	(5)
<i>Zoned ash-flow tuffs</i>		
Huckleberry Ridge Tuff, Yellowstone ----	.7112–.7268	(7)
Lava Creek Tuff, Yellowstone -----	.7091–.7102	(7)
Bishop Tuff, Long Valley, Calif. -----	.7060–.7092	(9)
Timber Mountain Tuff, Nev. -----	.7065–.7113	(10)
Paintbrush Tuff, Nev. -----	.7103–.7128	(10)
Hrafninnuhryggur, Iceland -----	.70327±.00009	(11)
Kerlingarfjöll, Iceland -----	.70333±.00007	(11)
Oraefajökull, Iceland -----	.70379±.00005	(12)
Krafla, subglacial ridge, Iceland -----	.70323±.00005	(12)
Askja, 1875 eruption, Iceland -----	.70322±.00005	(12)
	.70324±.00004	(13)
Krafla, Iceland -----	.70324±.00003	(13)
Landmannalaugar, Iceland -----	.70344±.00005	(13)
Rocche Rosse, Lipari, Italy -----	.7057±.001	(14)
	.70615±.00007	(15)
Forgia Vecchia, Lipari, Italy -----	.70592±.00006	(15)*
Vulcano, Italy -----	.70583±.00006	(15)†
Fukushima, Japan -----	.7033	(16)
Pam Mandiam, Papua New Guinea -----	.7043	(17)
Garove Harbour, Talasea, New Britain ----	.7038	(17)
	.70345±.00004	(18)
	.7035±.00011	(19)
Near Mt. Lotomgan, Talasea -----	.7034±.00011	(19)
Moresby Strait, Papua New Guinea -----	.70405±.00006	(20)
Taupo, New Zealand -----	.7045±.00045	(21)
Glass, Metis Shoal pumice -----	.7036	(22)

\* Average of 5 determinations

† Average of 2 determinations

#### References:

- (1) M.W. Higgins (unpublished data)
- (2) Peterman and others (1970a)
- (3) Noble and others (1972)
- (4) Bacon and others (1984)
- (5) Doe (1968)
- (6) Noble and others (1973)
- (7) Doe and others (1982)
- (8) Lipman and others (1978)
- (9) Halliday and others (1984)
- (10) Noble and Hedge (1969)
- (11) O'Nions and Grönvold (1973)
- (12) Condomines and others (1983)
- (13) Wood and others (1979)
- (14) Barberi and others (1974)
- (15) Gale (1981)
- (16) Shuto and Yashima (1974)
- (17) Page and Johnson (1974)
- (18) DePaolo and Johnson (1979)
- (19) Peterman and others (1970b)
- (20) Smith and Johnson (1981)
- (21) Ewart and Stipp (1968)
- (22) Ewart and others (1973)

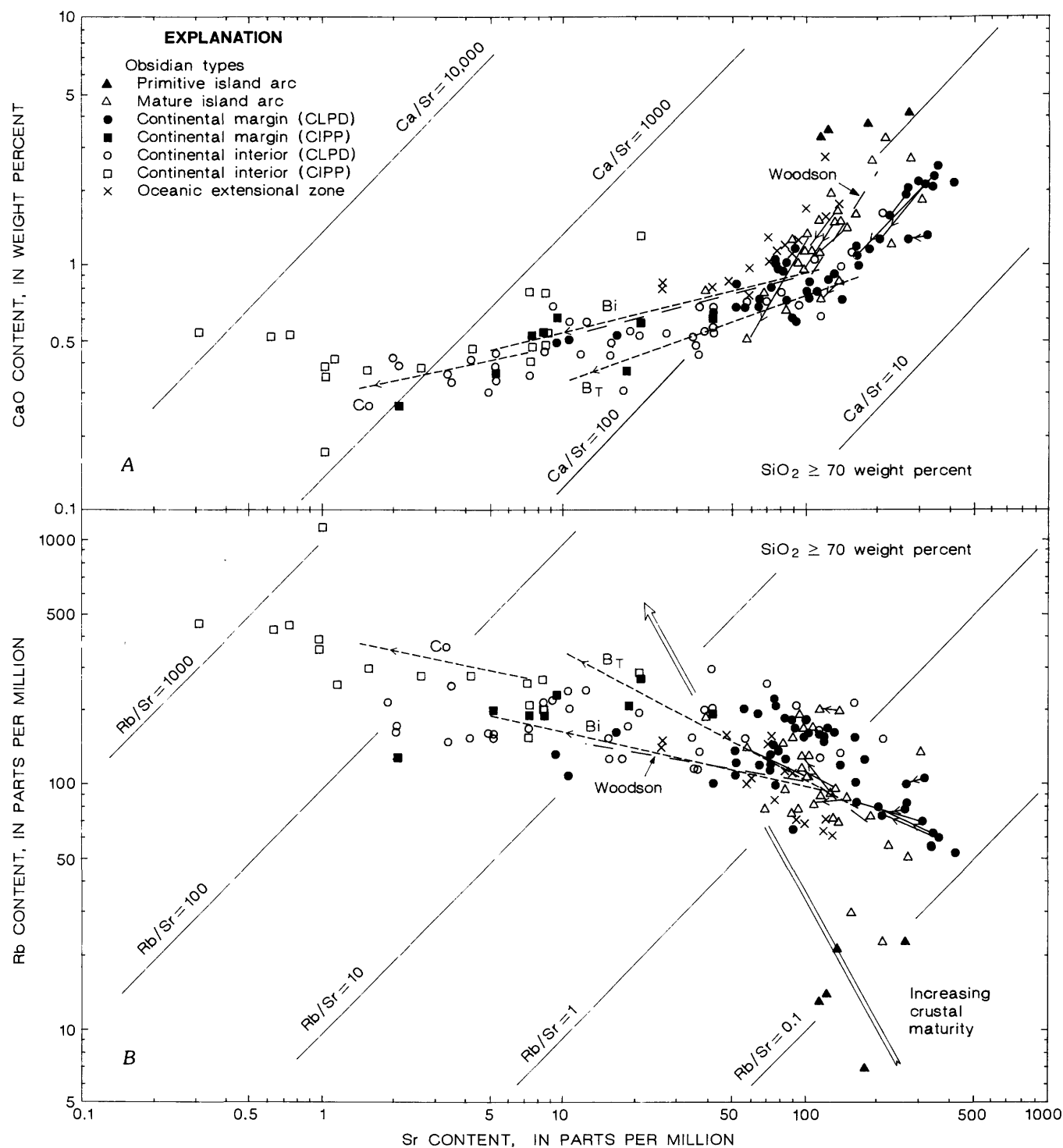


FIGURE 55.—Sr content versus CaO content (A), Rb content (B), and Ta content (C) for obsidians and various comparative rocks. Data sources are same as for figure 5. Solid tielines (A, B) represent rock-glass pairs; arrows point toward glass separate. Dashed lines (A, B) represent rock systems: Bishop

Tuff, Bi (Hildreth, 1981); Bandelier Tuff, Tshirege Member, B<sub>T</sub> (R.L. Smith, unpub. data); Coso Range, Co (Bacon and others, 1981); and Woodson Granodiorite, Woodson (D. Gottfried, unpub. data). Field boundaries in C are arbitrary and dashed where questionable.

volcano, or even a single eruptive unit is adequately represented by one or a few samples and that silicic magma may become isotopically distinct from some or all of the rocks that melted to produce it" (Hildreth, 1981, p. 10164). Use of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios as indicators of the nature of the source rocks is premature until the factors causing isotopic variations within rhyolitic magma bodies are properly understood.

#### THORIUM AND URANIUM

The range of U abundances is sufficiently large that the main features of U distribution in the obsidians are not disguised by analytical imprecision. Detailed assessment of such variables as Th/U is rather more difficult.

Some comparisons of the new data with published analyses are listed at the top of page 108.

With the exception of the Los Posos glass, the analyses are the same, within stated analytical pre-

cisions. The reason for the discrepancy in the analyses for the Los Posos rocks is not known.

The ranges and averages for the two elements are given in figure 40J, K. The lowest abundances are found in rhyolites of primitive island arcs. At constant  $\text{SiO}_2$ , there is a general increase in Th and U, reflected in the averages (tables 7 and 8) in the sequence calcic obsidians of mature island arcs  $\rightarrow$  calc-alkalic mature island arcs  $\rightarrow$  continental margin  $\rightarrow$  continental interior (fig. 43E, F). The rhyolites of the oceanic extensional zones have Th and U concentrations similar to those of the continental margins and mature island arcs. The obsidian data largely confirm the observations of Jakes and White (1972) and Ewart and others (1977) that Th and U contents of silicic rocks from areas underlain by thick continental crust are higher than those from areas of immature or primitive crust.

Data for Th and U in differentiated plutonic series such as the Tuolumne Intrusive Suite (Peck, 1980, data from Bateman and Chappell, 1979) and

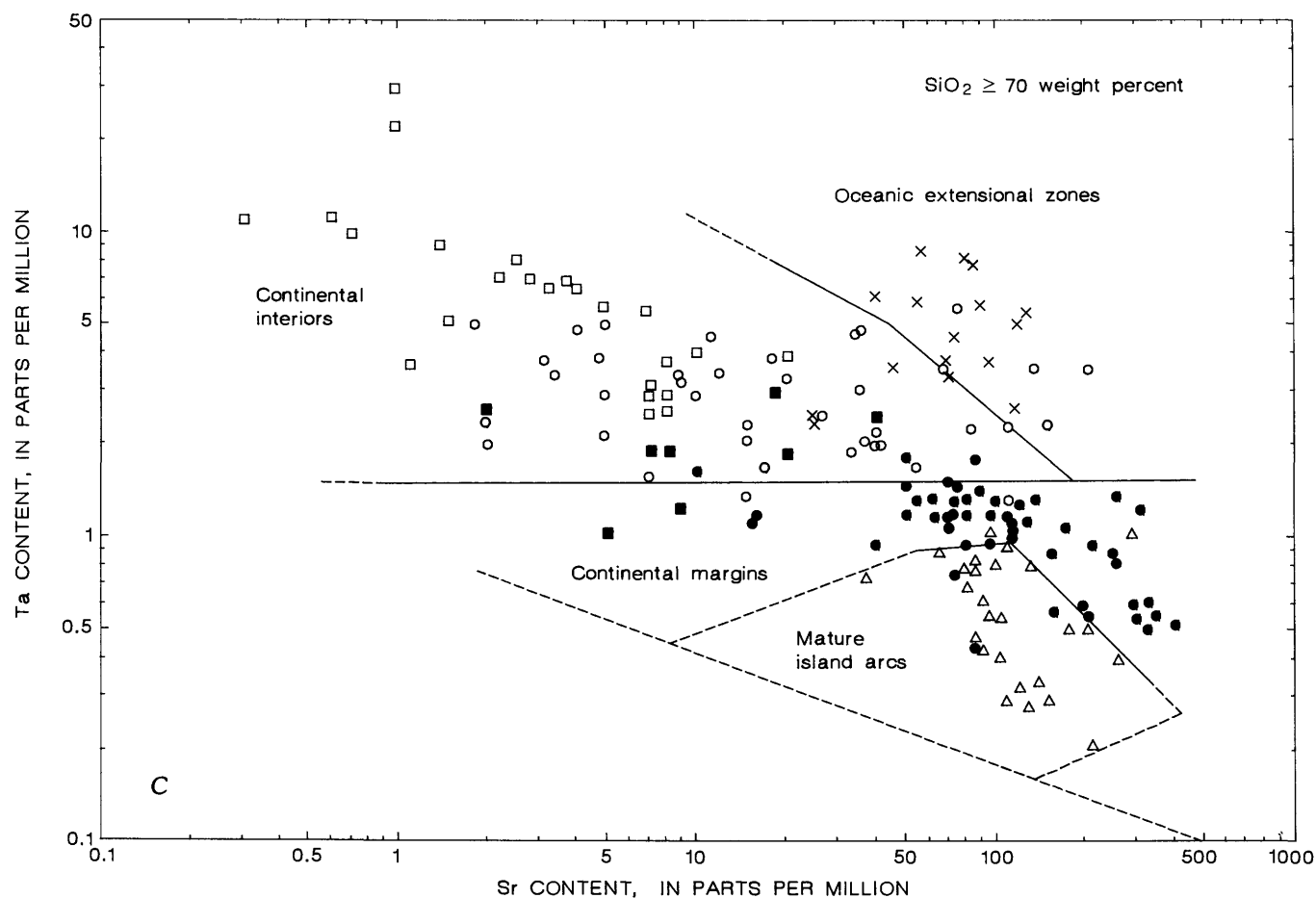


FIGURE 55.—Continued.

Locality	Th		U		References (published values; new values)
	Published	New	Published	New	
Llao Rock, Crater Lake -----	—	5.1	2.94	2.9	Noble and others (1980); No. 15
Redcloud, Crater Lake -----	—	6.4	2.88	3.3	Noble and others (1980); No. 16
Big Glass Mtn., Medicine Lake -----	15.3	—	5.68	—	Rosholt and others (1971)
Big Glass Mtn., (RGM-1) -----	—	14.6	—	5.9	No. 43
Big Glass Mtn., (RLS-141) -----	—	14.8	—	6.5	No. 42
Borax Lake mixed flow, Clear Lake --	15.1-17.6	15.6	5.77-6.75	6.6	Bowman and others (1973); No. 48
Obsidian Butte, Salton Sea -----	19.5	20.8	6.06	5.7	Rosholt and others (1971); No. 73
Shoshone Mtn., Nevada -----	27.2	28.2	6.34	5.8	Rosholt and others (1971); No. 82
Obsidian Cliff, Yellowstone -----	29.4	26.4	7.19	7.3	Doe and others (1982); No. 94
Ruby Mtn., Colorado -----	37.7	37.7	15.3	18.0	Rosholt and others (1971); No. 104
Grants Ridge, New Mexico -----	—	23.2	8.2	8.1	Zielinski (1978); No. 219
Los Posos, Jemez Mts. -----	24.8	17.7	5.24	6.8	Rosholt and others (1971); No. 120
Rocche Rosse, Italy -----	56	—	17	—	Belluomini and Taddeucci (1970)
Do. -----	—	—	15.6	—	Gale (1981)
Do. -----	—	55.7	—	18.5	No. 180

the Woodson stock (Tilling and Gottfried, 1969) are sufficiently scattered when plotted against  $\text{SiO}_2$  that some secondary remobilization of these elements must be suspected. Nevertheless, the overall behavior of Th and U during differentiation of magmas is to increase in residual liquids (Rogers and Adams, 1969), and this is the type of behavior also indicated by the rock-glass tielines of this study. The Bishop (Hildreth, 1979, 1981), Bandelier (Smith and Bailey, 1966), and Coso (Bacon and others, 1981) systems all show strong upward enrichment of both elements. The Th and U enrichment factors in the Bishop Tuff are 1.7 and 2.4, respectively, and in the Tshirege Member of the Bandelier Tuff are 3.2 and 4.9, respectively (R.L. Smith, unpub. data). Although the highest values reached are in CIPP continental-interior rocks, CLPD samples may have values sufficiently high that there is very substantial overlap of CIPP and CLPD fields for both Th and U.

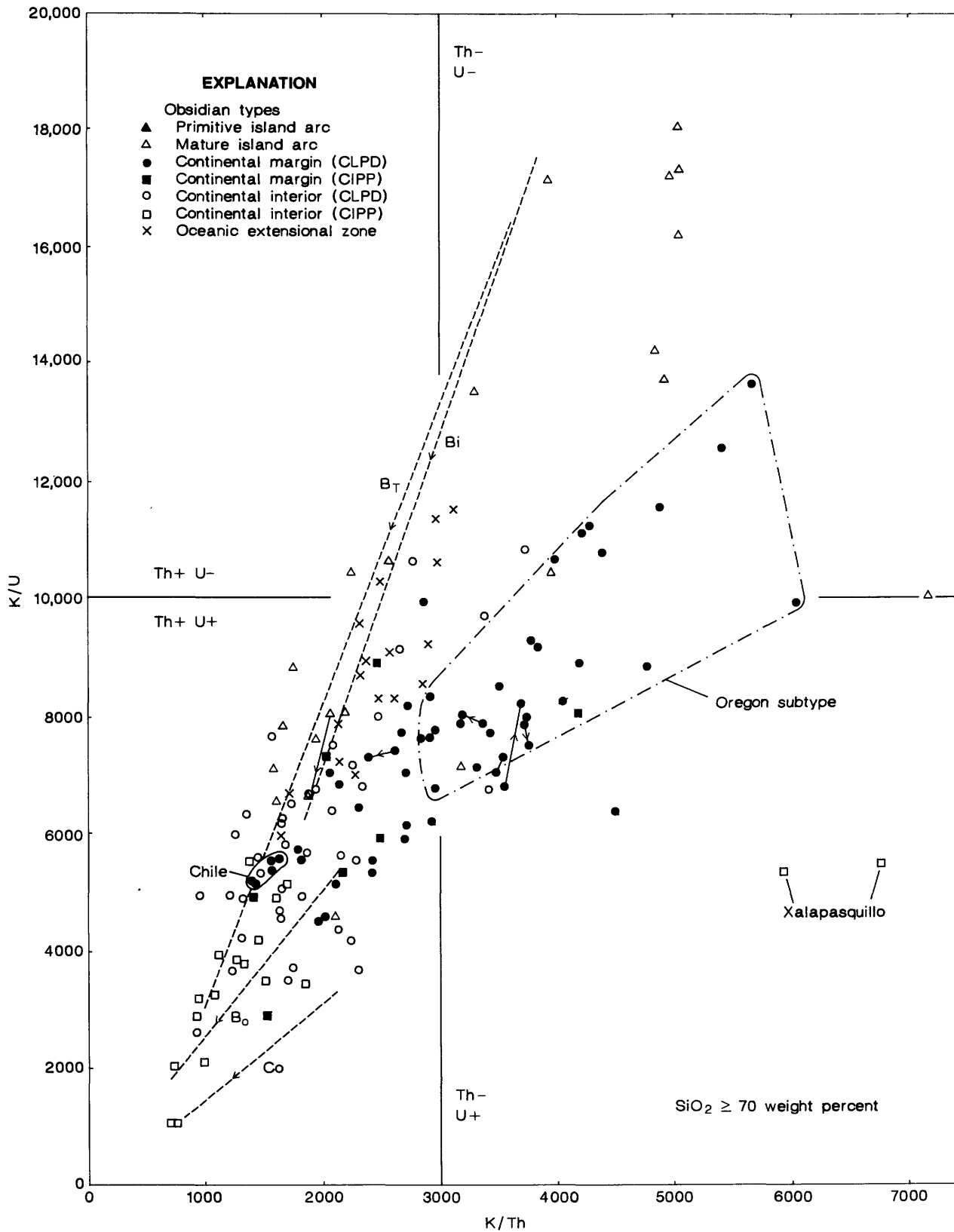
It has been known for some time (see discussion in Phair and Gottfried, 1964) that there are lateral regional variations in Th and U distribution in the crust, lending to the concept of Th and U provinces. Notable examples are the high U concentrations shown by obsidians from the Rocky Mountain area—greater than 40 ppm U in the specific case of the rhyolite of Nellie Creek, Colorado (Zielinski, 1978, table 1). This general Rocky Mountain high characterizes obsidians from New Mexico to Alaska but its cause remains enigmatic.

A convenient way of depicting rocks that are high or low in Th and U is by comparing them with the crustal averages for K/Th and K/U ratios of  $3 \times 10^3$  and  $1 \times 10^4$ , respectively, suggested by Rogers and Adams (1969). Use of ratios rather than absolute

abundances tends to normalize variations in abundances resulting from major-element variations. A K/Th-K/U plot (fig. 56) shows, for example, the relatively high Th and U contents of obsidians from Chile and the low Th of many continental-margin rhyolites of the Oregon subtype. On a more local scale, the relative Th depletion of the obsidians from Xalapasco, Mexico (Nos. 146, 147), and Macusani (No. 160; not shown on fig. 56) are notable.

The K/Th-K/U plot may also be used to make more general comments on Th and U distribution in rhyolites, though the large variation within the Bishop Tuff suggests that the comments are most relevant to CLPD rocks. The majority of obsidians have an excess of Th and U relative to common crustal materials. There are two partial explanations for this: first, the high-silica rocks of this study have higher  $\text{SiO}_2$  contents and thus higher Th and U contents than the average crustal rock used in computing the averages; and, second, many crustal rocks may have been leached of Th and U in the near-surface environment during various low-temperature processes. Obsidians from continental margins show a roughly linear relation between K/Th and K/U,

FIGURE 56.—Ratio of K/Th versus ratio of K/U for obsidians and various comparative rocks. Rocks of southeastern Oregon subtype are defined in text. Fields (for example, Th-U+) refer to rocks that have Th and U concentrations higher or lower relative to K than average continental crust. Samples 145, 160, 203, 210, and 215 are omitted to preserve scale. Solid tielines represent rock-glass pairs; arrows point toward glass separate. Dashed lines represent CIPP systems: Bishop Tuff, Bi (Hildreth, 1981); Bandelier Tuff, Otowi, B<sub>0</sub>, and Tshirege, B<sub>T</sub> Members (R.L. Smith, unpub. data); Coso Range, Co (Bacon and others, 1981). Arrows indicate direction of liquid fractionation.



suggesting that though the absolute abundances of these elements vary widely within such obsidians, genetic processes did not significantly partition them. It is noteworthy that the range of values is from Th-U-excess to Th-U-depleted compositions, reflecting either the varying Th-U chemistry of the source rocks or different behavior of the Th-U host phases during the melting process.

The majority of island-arc obsidians lie to the U-poor side of the margin rocks. Perhaps their source materials were relatively low in U. If continental-margin volcanics represent a further stage in the cratonization process, then that process has resulted in U enrichment relative to K.

Remobilization of U in epicratonic settings is apparently indicated by the wide spread in K/U values for the rhyolites from such settings.

#### Th/U RATIOS

Thorium and uranium are normally regarded as geochemically coherent in igneous-rock series. In the obsidians ( $r=0.84$ ), the effects of within- and between-group differences and analytical imprecision produce a significant range in Th/U ratios, a total range from 1 to 6.

The Th/U ratio has been recorded as increasing, decreasing, or staying constant during the differentiation of igneous-rock series (Rogers and Adams, 1969). The U data acquired in this study for rock-glass pairs are not sufficiently precise to assess changes in Th/U ratio. Significant changes in the ratio are reported from CIPP systems; the trend in the Bishop, Bandelier, and Coso systems is toward lower Th/U ratio in lower-temperature liquids. The respective values for each system are 5.00 to 3.13 (Hildreth, 1979), 4.50 to 2.93 (R.L. Smith, unpub. data), and 2.80 to 2.52 (Bacon and others, 1981). Hildreth (1981, p. 10177) has argued that for up-elements more highly charged than  $3^+$ , thermo-gravitational transport of volatile complexes is the most likely mechanism of enrichment. The relative enrichment of U over Th reflects its enhanced ability to form complexes with halogens, especially in systems where F is a more important ligand than Cl.

The great majority of silicic obsidians from continental margins have Th/U ratios between 2 and 3. CLPD rocks of the continental interiors have a slightly higher average ratio but also show a wider, and less unimodal, spread of ratios (fig. 57). Though the higher ratio may mean an overall increase in Th/U ratio during the growth and development of continental crust (compare with Rogers and Adams, 1969), the wider spread indicates that continental-interior obsidians are probably derived from sources where substantial fractionation of Th and U has taken place. Possible mecha-

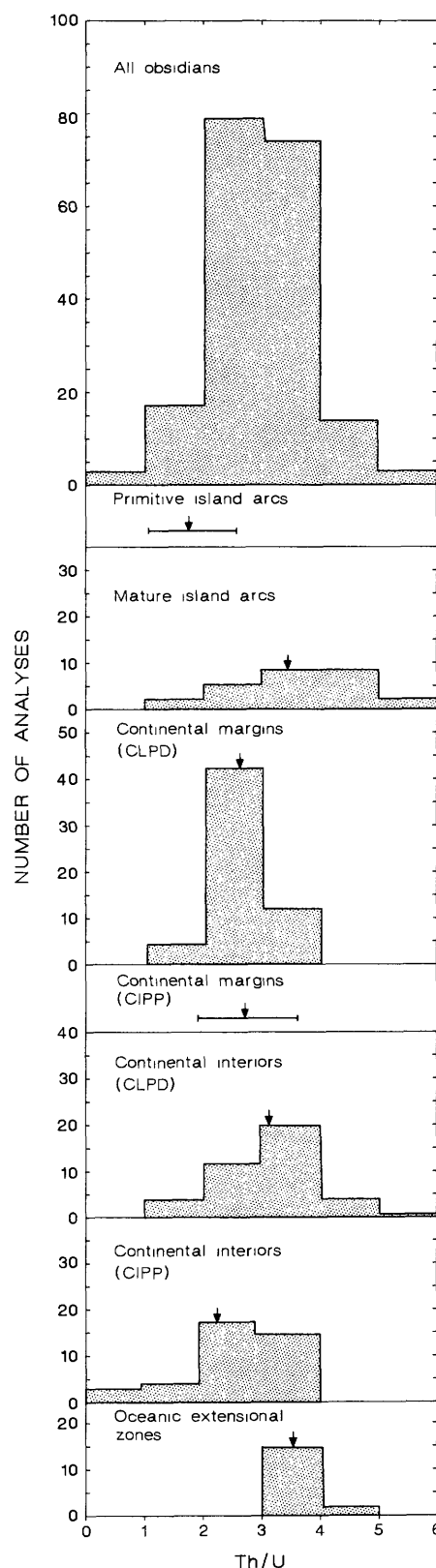


FIGURE 57.—Distribution of Th/U ratios in obsidians. Obsidians of primitive island arcs and continental margins (CIPP types) are shown as ranges only. Arrows indicate average values. Data from appendixes I and V. Sample 203 is omitted to preserve scale.

nisms include migration of both elements, and particularly U, to higher crustal levels during high-grade metamorphism and redistribution of Th and U by previous crustal fusion events.

Obsidians from mature island arcs also have a higher average Th/U ratio than those of continental margins (compare with Jakes and White, 1972, table 3). Although data are scarce, obsidians from primitive island arcs are notable for low Th/U ratios, commonly less than 2. There is thus no simple progression in Th/U ratio to match the presumed tectonic progression, primitive arcs→mature island arcs→continental margins→continental interiors. The behaviors of Th and U are different in some complex way during crustal development.

Thorium and uranium show the highest ( $r > 0.60$ ) correlations with other elements of large ionic radius (Cs and Rb), with the rare metals Be, Sn, and W, and with F. The common feature is probably the tendency to form complexes with F.

$r > 0.60$	Th	U
F -----	0.65 -----	0.63
Be -----	0.67 -----	0.70
Cs -----	— -----	0.60
Rb -----	0.89 -----	0.84
Sn -----	— -----	0.65
Th -----	1.00 -----	0.84
U -----	0.84 -----	1.00
W -----	0.65 -----	—

## ZINC

Zinc abundances show a large range, 8 to 282 ppm, although only one specimen contains more than 170 ppm. Four specimens from primitive arcs have Zn concentrations in the range 43–101 ppm, average 69 ppm. Obsidians of mature island arcs and continental margins are comparable in the spread of the data and the average (table 7; fig. 40L). CLPD obsidians of the continental interiors have a slightly higher average Zn concentration, but there is very extensive overlap between them and the subduction-related types on a  $\text{SiO}_2$ -Zn plot (fig. 43G). The rocks from oceanic extensional zones have higher Zn contents, on average, and  $\text{SiO}_2$ -normalized bases. Within-group variations are high, commonly a factor of 4 at constant  $\text{SiO}_2$  values (fig. 43G).

Data from rock-glass pairs from Crater Lake and South Sister, which are calcic systems, indicate slight Zn depletion in residual liquids, a trend also found in the Tuolumne Intrusive Series (Bateman and Chappell, 1979). On the other hand, the calc-alkalic rocks from Capital Mountain, Okushiri, and Halmahera demonstrate Zn enrichment in the glass.

The possibility that Zn behavior, like that of Nb and Ta, is related to the magmatic affinity of the suite deserves further study.

The average Zn contents of CIPP rocks in the continental margin and interior groups are higher than those for the corresponding CLPD rocks (fig. 40L). Similar to Sc, however, Zn behavior in CIPP systems is complex. In the Bishop system (Hildreth, 1979, 1981) Zn stayed about constant in all rocks, but in the Coso system it enriched upward slightly (Bacon and others, 1981) and in the Bandelier systems extreme enrichments of Zn occur (R.L. Smith, unpublished data). Some aspects of the complexity are displayed on a Yb-Zn plot (fig. 58), Yb being an up-element in all CIPP systems. Eighty-two percent of continental-interior CLPD obsidians plot within the marked field. Three possible types of Zn behavior are shown. Along trend Y, Zn acts as a strongly upward-enriching element. CIPP rocks of this type include the San Francisco Peaks and Big Southern Butte. These are colinear with the Bandelier Tuff. Trend X connects the Big Pine and Olancha rocks and is roughly colinear with that of the Coso system, with which it may be connected. This type of trend, which also includes the Blackfoot domes, represents mild Zn up-enrichment during CIPP. The Bishop trend is developed in a continental margin system. This type of trend may be represented in the interior rocks by the Xalapasquillo

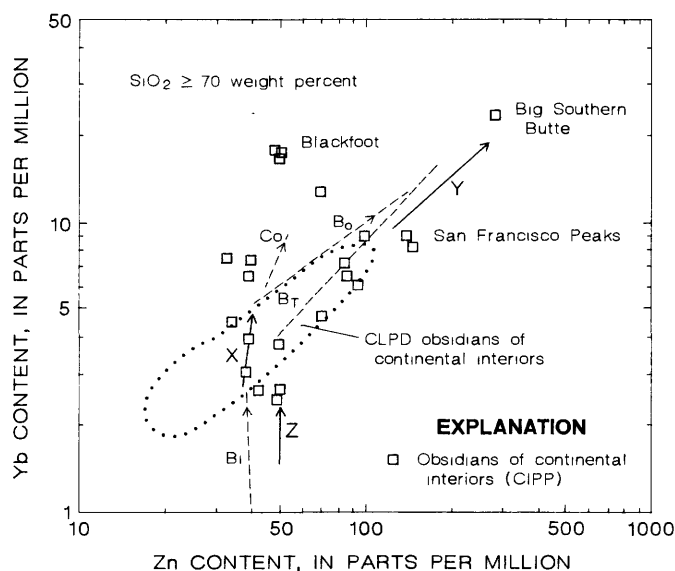


FIGURE 58.—Zn content versus Yb content showing possible effects of CLPD in CIPP silicic systems. Trends X, Y, and Z are discussed in text. Data from appendix I. Samples 145 and 160 are omitted to preserve scale. Dashed lines show CIPP system trends: Bishop Tuff, Bi (Hildreth, 1981); Bandelier Tuff, Otowi, B<sub>o</sub>, and Tshirege, B<sub>r</sub>, Members (R.L. Smith, unpub. data); Coso Range, Co (Bacon and others, 1981). Arrows indicate direction of liquid fractionation.

obsidians, Mexico, that is, trend Z (fig. 58), which involves no significant Zn enrichment.

The reasons for the contrasting Zn behavior in different systems is not clear. Smith (1979) noted that Zn (along with lesser enrichments of Zr, Hf, and La), after strong upward enrichment in the magma chamber preceding the eruptions of both Bandelier Tuff sheets, showed completely different concentration trends during the subsequent evolution of the Valles Rhyolite domes. He suggested that crystal fractionation of heavy minerals was probably involved as the thermal energy of the systems waned. Hildreth (1981) noted that strong partitioning of Zn into ferromagnesian phenocrysts relative to the coexisting liquid and crystal-liquid control superimposed on upward enrichment of Zn may explain Zn distribution.

The elements with which Zn shows strong ( $>0.60$ ) correlation fall into three groups: (1) Y and the HREE, (2) Zr, Hf, Nd, and Sn, and (3) Nb and Ta. Each correlation stresses different aspects of Zn behavior. Zinc shows good correlations (1) with Y and the HREE in CLPD obsidians and in those CIPP systems where it is an up-element, (2) with Zr and Hf in systems where it is a down-element and in CLPD rocks, and (3) with Nb and Ta in systems where it is an up-element and because all three have high abundances in obsidians of oceanic extensional zones.

$r \geq 0.60$	Zn
Nb -----	0.74
Ta -----	0.61
Zr -----	0.64
Hf -----	0.78
Y -----	0.75
Nd -----	0.65
Sm -----	0.76
Tb -----	0.78
Tm -----	0.68
Yb -----	0.68
Lu -----	0.67

#### ZIRCONIUM AND HAFNIUM

The ranges of Zr and Hf abundances in the silicic obsidians are 22 to 860 ppm and 1.3 to 21.8 ppm, respectively (fig. 40M, N). The spreads of Zr values in base-level rocks from mature island arcs, continental margins, and continental interiors are very similar, especially on a  $\text{SiO}_2$ -normalized basis. The higher average value in the interior glasses reflects higher  $\text{SiO}_2$  contents (fig. 43H). The comparability of Zr abundances in rocks from these tectonic settings precludes its use as a tectonomagmatic indicator. The situation for Hf is slightly different. Abundances

in obsidians from mature island arcs and continental margins are similar but are higher in continental-interior types, resulting in lower Zr/Hf ratios (table 7; fig. 59A). Both Zr and Hf are relatively enriched in obsidians from oceanic extensional zones, on a  $\text{SiO}_2$ -normalized basis and in terms of averages (table 7).

Within-group variations in Zr and Hf contents are substantial, commonly a factor of 4 at a given  $\text{SiO}_2$  value. Concentrations of both elements are very sensitive to small amounts of zircon fractionation and,

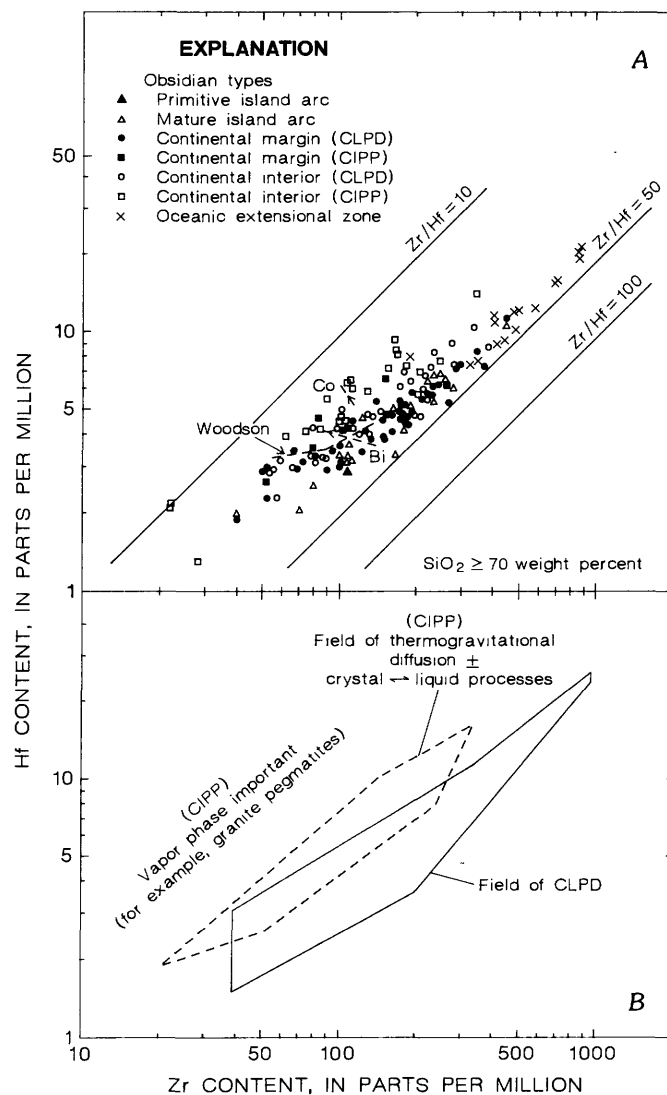


FIGURE 59.—Zr content versus Hf content for (A) obsidians and various comparative rocks. Data sources are same as for figure 5. Dashed lines indicate CIPP systems: Bishop Tuff, Bi (Hildreth, 1981); Coso Range, Co (Bacon and others, 1981). Arrows indicate direction of liquid fractionation. B, Fields of thermogravitational diffusion and CLPD showing that CIPP forms a link between crystal-liquid processes and hydrothermal activity.



given the common occurrence of zircon microphenocrysts in the obsidians (app. VI, VII), this may be a partial explanation of the spreads.

Data from rock-glass pairs in rocks with less than 74 percent  $\text{SiO}_2$  show only small changes in Zr and Hf concentrations, but there is greater Zr depletion in the glasses where the rocks have  $\text{SiO}_2$  greater than 74 percent  $\text{SiO}_2$ . The Woodson granodiorite stock shows an overall depletion of Zr in more fractionated rocks and a less strong depletion in Hf, such that the Zr/Hf ratio becomes progressively lower in more silicic samples.

The behavior of Zr and Hf during CIPP is complex. In the Bishop Tuff, Zr was depleted in roof-zone magmas, an effect unrelated to zircon fractionation (Hildreth, 1979).

Hafnium, on the other hand, showed no clear enrichment up or down. In the Coso system, Hf was an up-element, Zr a down-element (Bacon and others, 1981). Bulk rock data for the Bandelier Tuff indicate that Zr was a down-element. Analyses of glass separates show that Zr actually concentrated upward in the liquids (R.L. Smith, unpub. data). Apparently, zircon fractionation was being superimposed on upward concentration of Zr by CIPP.

If zircon is the major phase fractionating Zr and Hf in CIPP systems, its efficiency will be reduced in more alkalic systems due to increased solubility in the melt. The relative influences of crystal-liquid fractionation and CIPP on Zr and Hf distributions in CIPP systems may depend in part on the alkalinity of the melts.

The fractionation of Zr from Hf during CIPP in high-level silicic systems and in the transition from continental-margin- to continental-interior-type crusts is apparent in the lists of elements for which each shows strong ( $r > 0.60$ ) correlations. The upward-concentrating nature of Hf means that it has less significant correlations with  $\text{SiO}_2$  (negative) and FeO (positive) and more significant correlations with Y and the HREE. The higher correlation coefficient for  $\text{Na}_2\text{O}$ -Zr, 0.64, as opposed to 0.59 for  $\text{Na}_2\text{O}$ -Hf, initially appears anomalous, because both Na and Hf are up-elements. The slight difference is probably caused by the enrichment of Hf relative to Zr in continental-interior rocks while  $\text{Na}_2\text{O}$  decreases.

Both Zr and Hf show strong correlations with  $\text{FeO}_t$ , and a Zr- $\text{FeO}_t$  plot (fig. 60) is a useful way of summarizing Zr distribution in the rhyolites. Obsidians of primitive island arcs have Zr contents that overlap the lower to middle ranges of Zr abundances in the rhyolites of mature island arcs but that have distinctly higher Fe/Zr ratios. The calcic rhyolites of the mature island arcs have Fe/Zr ratios intermedi-

ate to those of the calc-alkalic types. These latter rocks and CLPD rocks from the continental margins and interiors overlap almost completely on the Zr- $\text{FeO}_t$  plot, but rhyolites of oceanic extensional zones have a lower average ratio, indicating relative Zr enrichment.

The broad, positive correlation between  $\text{FeO}_t$  and Zr in CLPD obsidians has been noted earlier, in connection with Fe, Na, and Cl distributions. The positive relation is maintained by the trend of the Woodson granodiorite stock but only by some of the rock-glass pairs; several tieline orientations are present. Such within-group differences obviously contribute to the scatter of base-level data in this plot.

As discussed above, Zr and Fe behavior in CIPP systems is complex. No marked fractionation of Zr and Fe was achieved in the erupted parts of the Bishop and Coso systems. The tendency of CIPP rocks to plot to the Zr-rich side of the CLPD field is perhaps an indication, that in at least some systems, Zr is concentrated upward. In contrast, the CIPP rocks that plot on the Zr-poor side of the Woodson trend (fig. 60) must either have been derived from unusual base-level melts or underwent Zr depletion relative to Fe, probably by zircon fractionation.

$r > 0.60$	Zr	Hf
$\text{SiO}_2$ -----	-0.66 -----	—
$\text{Fe}_2\text{O}_3$ -----	0.61 -----	—
FeO -----	0.81 -----	0.73
$\text{FeO}_t$ -----	0.83 -----	0.75
$\text{Na}_2\text{O}$ -----	0.64 -----	—
Zn -----	0.64 -----	0.78
Zr -----	1.00 -----	0.94
Hf -----	0.94 -----	1.00
Y -----	— -----	0.63
La -----	0.60 -----	0.61
Ce -----	0.64 -----	0.68
Nd -----	0.74 -----	0.80
Sm -----	0.72 -----	0.83
Eu -----	0.85 -----	0.73
Gd -----	— -----	0.60
Tb -----	— -----	0.73

#### Zr/Hf RATIOS

There are systematic variations in Zr/Hf ratios with regard to tectonic setting and genetic process (fig. 61). The highest average ratio (41) is found in the obsidians of oceanic extensional zones. CLPD rocks from mature island arcs and continental margins have averages of 34.6 and 34.3, respectively, which are significantly higher than the value of 27 for CLPD

continental-interior glasses. There is thus a negative relation between the Zr/Hf ratio of rhyolites and the maturity of the crust in which they were emplaced.

Crystal-liquid processes, as exemplified by the Woodson trend and the tielines for rock-glass pairs, and CIPP both tend to produce lower Zr/Hf ratios in more evolved (lower temperature) liquids. Very low

Zr/Hf ratios of less than 20 can be achieved by both mechanisms. In this context, it is important to note that these low values overlap those found in granitic pegmatite bodies (Klemic and others, 1973), which we see as having formed during the lower temperature, vapor-dominated stages of the CIPP continuum (figs. 27, 59B).

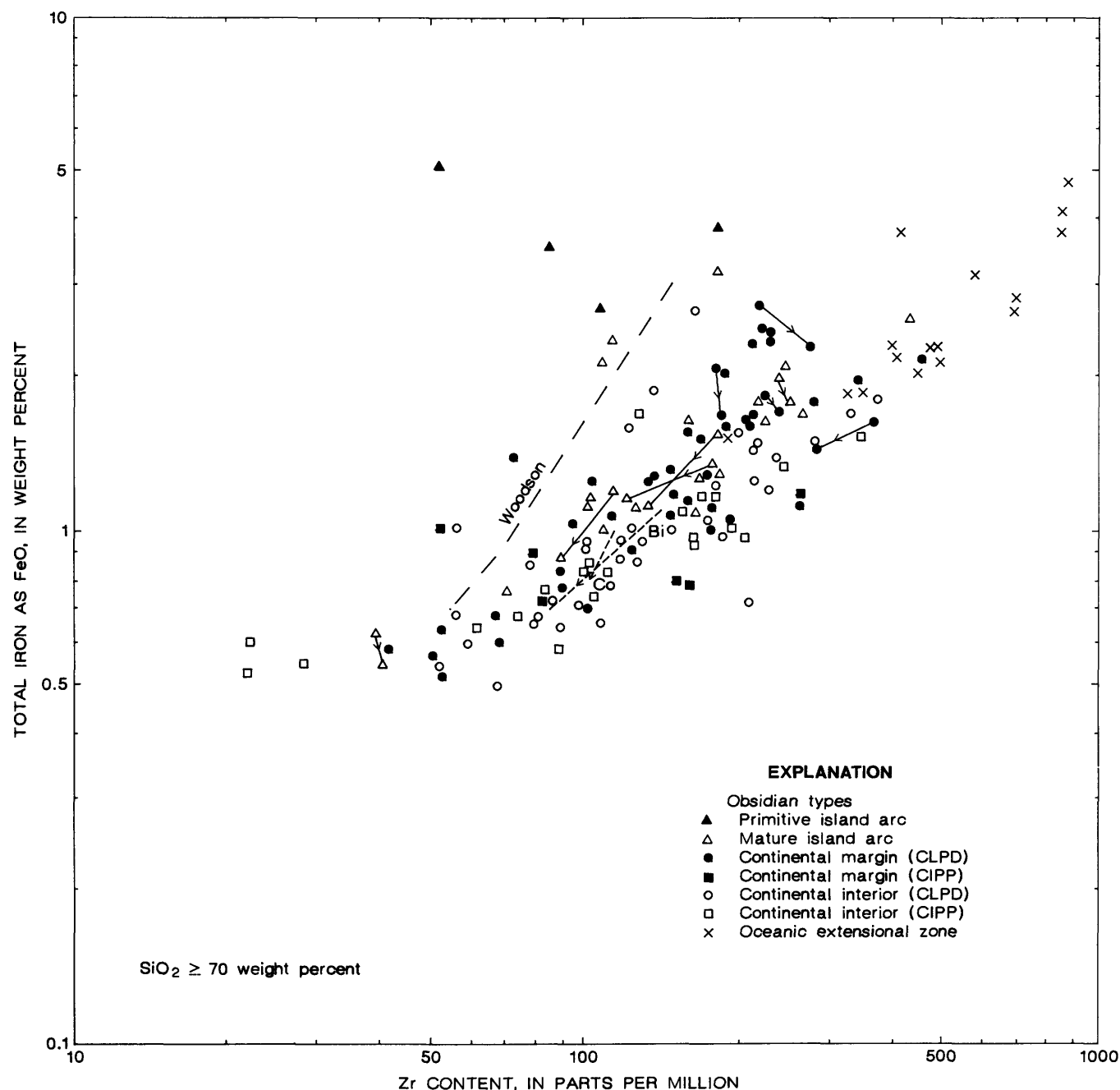


FIGURE 60.—Zr content versus total iron as FeO for obsidians and comparative rocks. Data sources are same as for figure 5. Solid tielines represent rock-glass pairs, arrows point toward glass separate. Dashed lines represent CIPP systems: Bishop Tuff, Bi (Hildreth, 1981); Coso Range, Co (Bacon and others, 1981). Arrows indicate direction of liquid fractionation.

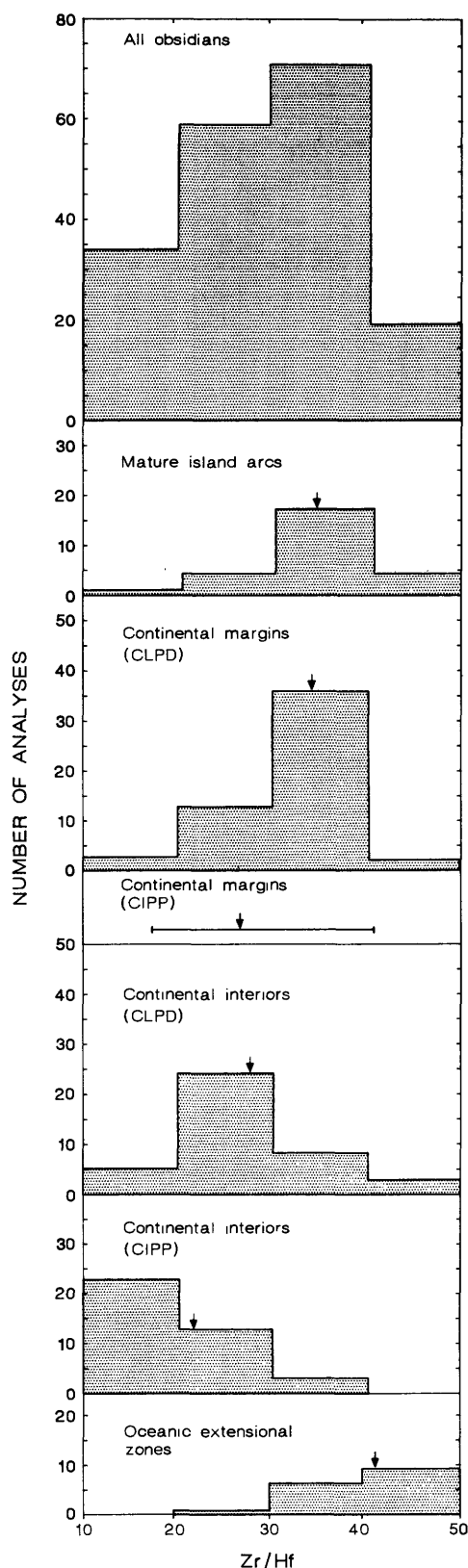


FIGURE 61.—Distribution of Zr/Hf ratio in obsidians. Obsidians of continental margins (CIPP types) are shown as ranges only. Arrows indicate average values. Data from appendix I.

#### RARE-EARTH ELEMENTS AND YTTRIUM

The established procedure is to discuss Y with the HREE (Herrmann, 1970) and is fully justified for the rhyolites by the near-perfect correlation of Y and the HREE (app. VI). Ranges and averages in the different rhyolite groups are presented in tables 7–9 and summarized in table 15. For the sake of simplicity, Ce and Yb are used to show variations in the LREE and HREE, respectively, in the following discussion, whereas Eu is treated separately.

The greatest REE abundances occur in the obsidians of oceanic extensional zones. As a group, they are marked by LREE enrichment, between 100 and 300 times chondritic.  $Ce_N/Yb_N$  ratios range from 2.2 to 6.0, the lowest values found in the rocks from the Salton Sea (Nos. 73–75). There are marked negative Eu anomalies (average  $Eu/Eu^*=0.48$ ).

In contrast, the lowest REE abundances occur in the obsidians of primitive island arcs. The chondrite-normalized pattern is characteristically flat ( $Ce_N/Yb_N \sim 1$ ) and, with the exception of a sample from Fiji (app. V, sample H), the Eu anomaly is either absent or negative and small.

There is a transition from early arc REE character to that in obsidians of mature island arcs. Masuda and others (1975) present data on a calcic rhyolite from Mashu, Hokkaido, which has a flat pattern, with  $Ce_N/Yb_N < 1$  and no Eu anomaly (fig. 62). A similar pattern has been recorded for a calcic rhyolite from Honsyu by Yajima and others (1972). The analyzed specimens in the data bank are slightly more fractionated: the average  $Ce_N/Yb_N$  value is 1.97, and there is a distinct negative Eu anomaly ( $Eu/Eu^*_{avg}=0.64$ ).

Such patterns are themselves transitional to the calc-alkalic rocks of mature island arcs, marked by increased LREE enrichment, to 60 times chondritic, higher  $Ce_N/Yb_N$  values (average 2.75), and larger negative Eu anomalies (average  $Eu/Eu^*=0.46$ ).

An increasingly fractionated stage is represented by the CLPD rocks of the continental margins. Although there is considerable overlap in REE abundances with the arc rocks, the average obsidian has a higher  $Ce_N/Yb_N$  ratio (4.46) but a similar Eu deficiency ( $Eu/Eu^*=0.43$ ). CLPD obsidians of the continental interiors show an even more fractionated character, with higher average LREE abundances ( $Ce_N$  up to 209), increased LREE enrichment (average  $Ce_N/Yb_N=5.08$ ), and a very substantial negative Eu anomaly ( $Eu/Eu^*=0.20$ ). There are also larger ranges of these values within the group.

The transition from primitive island arc to cratonic continental interior involves, therefore, (1) increasing LREE enrichment, (2) increasing development of

TABLE 15.—Rare-earth element characteristics of obsidians

Obsidian group	Ce <sub>N</sub> <sup>+</sup>		Ce <sub>N</sub> /Yb <sub>N</sub>		Eu/Eu*	
	Range	Average	Range	Average	Range	Average
Primitive island arcs -----	13–26	19	0.7–1.7	1.3	0.38–0.97	0.74
Mature island arcs						
Calcic -----	28–49	36	1.5–3.3	1.9	.53–0.75	.62
Calc alkalic -----	19–90	52	1.8–5.6	2.8	.20–0.78	.46
Continental margins						
CLPD -----	20–161	58	1.7–5.2	4.4	.10–0.75	.43
CIPP -----	47–81	58	1.1–4.2	2.5	.04–0.18	.12
Continental interiors						
CLPD -----	20–210	95	2.4–27	5.1	.05–0.56	.20
CIPP -----	3–150	55	.55–4.9	1.5	.01–0.24	.04
Oceanic extensional zones -----	89–200	148	2.0–6.0	3.6	.32–6.8	.48

\*N indicates chondrite normalized value

negative Eu anomalies, and (3) increasing ranges within groups.

Data for rock-glass pairs indicate slight enrichment of Ce and Yb in rocks with SiO<sub>2</sub> less than 75 percent. The data for this part of the Woodson granodiorite compositional range are so scattered that a meaningful trend cannot be drawn. At the

high-SiO<sub>2</sub> end, Ce is depleted rapidly with increasing fractionation. Ce depletion is also shown in the Okushiri glass (Nos. 186, 187). In high-SiO<sub>2</sub> CLPD rocks, LREE depletion is probably achieved by fractionation of accessory phases such as monazite and allanite (see Miller and Mittlefehldt, 1982; Mittlefehldt and Miller, 1983, for review).

Analyses of the rock-glass pairs and the Woodson rocks show slight depletion of Eu in the residual liquids of rocks with SiO<sub>2</sub> less than 75 percent but very strong depletion in more SiO<sub>2</sub>-rich rocks. The Eu depletion presumably reflects plagioclase control, either during crystal fractionation or as a residual phase during melting of the source rocks.

CIPP has a striking and characteristic effect on REE distribution. The LREE are down-elements and the HREE up-elements, the cross-over point being between Nd and Sm (fig. 63). Eu is highly depleted. The chondrite-normalized patterns thus tend toward being dagger-shaped, flat with a substantial negative Eu anomaly. The Ce/Yb ratios are notably lower than in CLPD rocks of the same rhyolite group. In individual CIPP systems, the magnitude of the Eu anomaly increases strongly and almost linearly with decreasing Ce/Yb ratio (Hildreth, 1981, fig. 8). The relation between Ce/Yb and Eu/Eu\* in CIPP obsidians is scattered because of within-group variations in REE abundances, but is still positive (fig. 64).

Within-group variations in the REE are substantial; at constant SiO<sub>2</sub>, Ce and Yb can vary by a factor of 4–5 in CLPD rocks. In a gross way, the LREE are highest in those rocks with relatively high FeO, Zr, and Hf, such as the Yellowstone obsidians and rhyolites of oceanic extensional zones. The HREE from Tb–Lu do not show this affiliation, their strongest correlations ( $r > 0.60$ ) being with Nb, Ta, Be, F, Sn, and Zn. The correlation with those elements (table

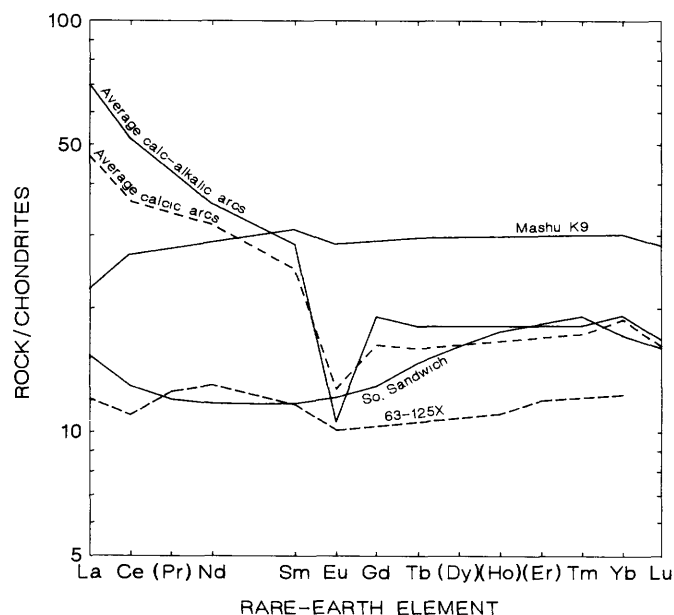


FIGURE 62.—Chondrite-normalized rare-earth-element patterns for rhyolites of island arcs. Data sources: South Sandwich pumice (app. II, No. 220); Mashu K9, dacite, Mashu Volcano, Hokkaido (Masuda and others, 1975); 63–125X, alkali-poor dacite, Louisehoj Formation, St. Thomas (Donnelly and Rogers, 1980, fig. 5). Averages of obsidians from island arcs (table 8). Chondrite rare-earth-element values from Haskin and others (1968). Rare-earth elements in parentheses are not used in construction of curves, owing to lack of data.

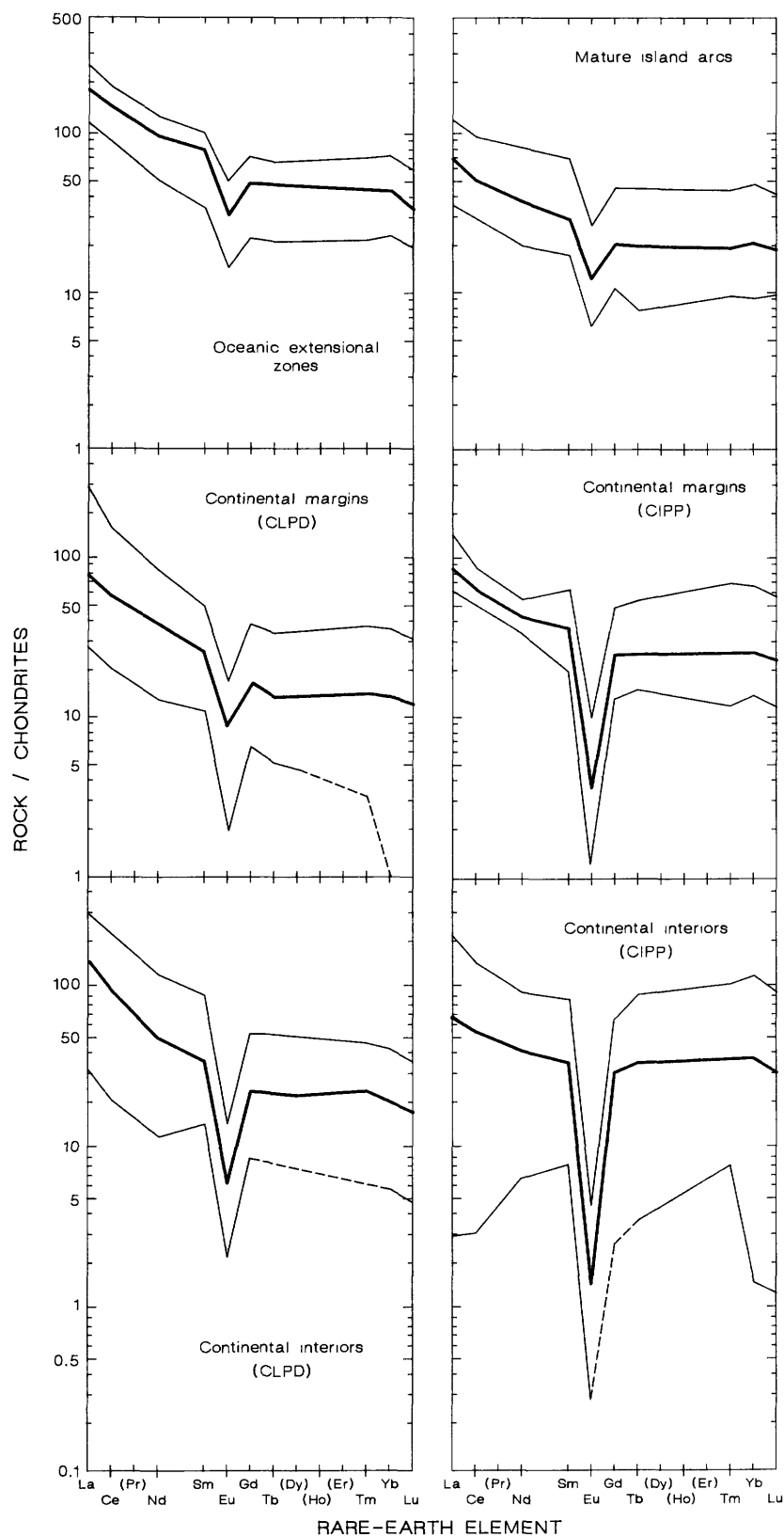


FIGURE 63.—Chondrite-normalized rare-earth-element (REE) patterns for obsidians of various obsidian groups (dashed where uncertain). Range is indicated by lighter lines and average by heavier line in each case. Dashed lines indicate uncertainty. Chondrite REE values from Haskin and others (1968).



TABLE 17.—*Attempt to isolate, for each element, those factors causing compositional variations in the obsidians, on a SiO<sub>2</sub>-normalized basis*

[Question marks denote uncertainty, usually due to quality of analytical data. Abbreviations: PIA, primitive island arcs; C-MIA, calcic obsidians of mature island arcs; C-A-MIA, calc-alkalic obsidians of mature island arcs; CM, continental margins; CI, continental interiors; OE, oceanic extensional zones]

Element	Total concentration range	Maximum range within-group	Variation due to tectonic setting	Variation related to CLPD	Variation related to CIPP
Al <sub>2</sub> O <sub>3</sub> -----	0.4	0.1	PIA+OE<MIA+CM+CI	Slight	Slight
FeO <sub>t</sub> -----	×10	×3–4	PIA+OE>C-MIA> C-A-MIA+CM+CI	Slight	Modest
MgO -----	×10 <sup>3</sup>	×<10	PIA+C-MIA>CM+CI	Very strong	Very strong
CaO -----	×30	×2–3	PIA+MIA>CM+CI	Very strong	Very strong
Na <sub>2</sub> O -----	×2	×2	Little	Modest	Strong
K <sub>2</sub> O -----	×5	×1.5–2	PIA<MIA<CM+CI	Modest	Slight
TiO <sub>2</sub> -----	×45	×4	MIA>CM+CI	Strong	Strong
P <sub>2</sub> O <sub>5</sub> -----	10 <sup>2</sup>	×10	Modest strong	Strong	
MnO -----	×10	5–10	None	Modest→strong	Strong
Cl -----	×10	×3	OE>MIA>CM+CI	Modest	Modest
F -----	×30	×3	OE>CI>CM+MIA	Modest	Modest→very strong
Ba -----	×10 <sup>3</sup>	×2	PIA<C-MIA<C-A-MIA<CM<CI	Low	Very strong
Co -----	×40	?	None?	Strong	Strong
Cs -----	×20	8–9	PIA?<MIA+CM+CI<OE	Modest	Strong
Nb, Ta -----	×400	×2	PIA<MIA<CM<CI	Slight	Strong
Pb -----	×25	×2–3	IA<CM+MIA+CI	Modest	Strong
Rb -----	×75	×2	PIA<MIA+CM<CI	Modest	Strong
Sb -----	×10	?	OE+CI<CM+MIA?	?	Modest→strong?
Sc -----	×20	×4	MIA>CM+CI	Strong	Modest
Sr -----	×10 <sup>3</sup>	×3–4	PIA<MIA+CM<CI	Strong	Very strong
Th, U -----	×80	×3–4	PIA<C-MIA<C-A-MIA<CM<CI	Modest	Strong
Zn -----	×35	×4	OE>MIA+CM+CI	Modest	Modest
Zr, Hf -----	×40	×4	Zr: OE>MIA+CM+CI	Modest	Modest
			Hf: OE>CI>CM+MIA	Modest	
LREE -----	×10	×7	PIA<C-MIA<C-A-MIA<CM<CI<OE	Modest→strong	Strong
Eu -----	×10	×6	MIA>CM>CI	Strong	Strong
HREE -----	×20	×6	MIA+CM<CI+OE	Modest	Strong

and are, with the possible exception of Sc, down-elements in CIPP systems.

2. Be, Sn, Li, W, Rb, Th, U, Pb, Nb, Ta, HREE, Y, and F, ±Zn. These elements are all concentrated in residual liquids during crystal-liquid processes, are enriched in continental-interior rhyolites, as opposed to subduction-related rhyolites, and are up-elements in CIPP systems. This similarity has led to correlations greater than 0.60 between most pairs. The role of F may be especially important in this group. For example, the average Be/F and Sn/F ratios for each of the main rhyolite groups (excluding primitive island arcs, for which no data are available) lie within the narrow limits 0.0043±0.0008 and 0.0044±0.0006, respectively. A possible interpretation is that Be and Sn contents are directly related to the contents of F

in the magma, perhaps as a result of complexing, independently of the degree of crustal maturity.

(3) FeO<sub>t</sub>, Na<sub>2</sub>O, Cl, Hf, Zr, LREE, and Eu, ±Zn. Some of the correlation coefficients in this group are less than 0.60, but, for each element, the highest correlations shown are usually for other members of the group. Na<sub>2</sub>O, Cl, Hf, and Zn are usually up-elements, and the LREE and Eu down-elements, in CIPP sub-alkalic systems, whereas FeO<sub>t</sub> and Zr show controls by CIPP and crystal-liquid processes. Such dissimilar behavior contributes to the lowering of the values of the correlation coefficient. The most significant correlations between the members of this group are found in base-level compositions, and the controlling factor may be the presence of Cl acting as a ligand in halide complexes.

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## APPENDIXES I–VII

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## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians

Country/State-----	ALASKA							OREGON			
Volcanic field/region---	Umnak Island		Katmai	Wrangell Mountains			Koyukuk Valley	Three Sisters		Crater Lake	
Locality-----	SW. Umnak	Okmok	Novarupta	Capital Mountain	Ptarmigan Lake	Indian River		South Sister		The Watchman	
Specimen-----	1	2	3	4	5	6	7	8	9	10	11
Collection No. (RLS)---	190	56	214	39	196	45	46	187	189	199	8-3Av
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	76.1	73.1	75.9	71.0	71.6	75.4	77.3	72.6	72.8	73.1	66.8
Al <sub>2</sub> O <sub>3</sub> -----	12.71	13.33	12.55	15.13	15.37	13.22	12.41	14.21	14.34	14.02	16.13
Fe <sub>2</sub> O <sub>3</sub> -----	.23	.62	.72	.82	.70	.56	.44	.84	.76	.46	.54
FeO-----	.93	2.06	.93	.91	.82	.65	.26	1.31	1.41	1.30	3.00
MgO-----	.15	.08	.34	.38	.35	.20	.04	.53	.55	.39	1.33
CaO-----	1.04	1.23	1.16	1.29	1.24	.84	.39	1.97	1.90	1.58	3.57
Na <sub>2</sub> O-----	3.59	4.68	4.32	5.27	5.26	4.32	4.05	4.69	4.64	4.54	4.84
K <sub>2</sub> O-----	3.91	3.88	2.94	3.68	3.61	4.18	4.52	3.08	3.02	3.20	2.32
H <sub>2</sub> O+-----	.42	.05	.14	.15	.11	.11	.06	.25	.12	.08	.51
TiO <sub>2</sub> -----	.13	.18	.21	.34	.31	.21	.10	.34	.34	.31	.64
P <sub>2</sub> O <sub>5</sub> -----	.01	.02	.02	.07	.05	.03	.01	.05	.05	.04	.11
MnO-----	.05	.10	.07	.11	.12	.05	.07	.07	.07	.05	.08
Cl*-----	.09	.19	.10	.05	.04	.10	.08	.06	.05	.07	.07
Cl**-----	.09	.18	.08	.03	--	.09	.06	.05	.06	--	--
F-----	.03	.06	.08	.06	.05	.04	.12	.03	.03	.04	.06
F**-----	.03	.06	.06	.05	--	.04	.11	.03	.03	--	--
Subtotal-----	99.39	99.58	99.46	99.25	99.63	99.91	99.84	100.03	100.09	99.18	100.00
Less O=(F,Cl) <sub>2</sub> -----	.03	.07	.05	.03	.03	.04	.06	.02	.02	.03	.04
Total-----	99.36	99.51	99.41	99.22	99.60	99.87	99.78	100.01	100.07	99.15	99.96
FeO <sup>1</sup> -----	1.14	2.62	1.58	1.65	1.45	1.15	.66	2.07	2.09	1.71	3.49
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	.80	.77	.56	.53	.54	.54	.37	.61	.65	.74	.85
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	.92	1.21	1.47	1.43	1.46	1.03	.90	1.52	1.54	1.42	2.09
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	.80	.89	.82	.84	.82	.88	.93	.78	.76	.78	.65
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	.95	1.06	.99	.99	.96	1.00	.99	1.03	1.00	.98	1.05
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	.14	.14	.16	.14	.14	.10	.05	.25	.25	.20	.50
Cl/F <sup>1†</sup> -----	3.3	3.2	1.4	.79	.83	2.5	.60	1.9	2.1	1.9	1.2
CIPW norms											
Q-----	37.63	27.54	36.48	23.07	24.00	32.15	35.69	28.35	28.84	30.17	19.01
or-----	23.37	23.09	17.52	22.00	21.46	24.79	26.82	18.26	17.87	19.10	13.80
ab-----	30.73	39.89	36.86	45.04	44.76	36.68	34.41	39.81	39.31	38.81	41.22
an-----	5.15	3.93	5.67	6.00	5.86	3.99	1.88	8.65	9.11	7.65	15.53
C-----	.71	--	.20	.30	.68	.13	.17	--	.10	.31	--
ac-----	--	--	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--	--	--
wo }-----	--	.87	--	--	--	--	--	.34	--	--	.65
en } di-----	--	.06	--	--	--	--	--	.17	--	--	.29
fs }-----	--	.91	--	--	--	--	--	.17	--	--	.36
en } hy-----	.38	.14	.85	.96	.88	.50	.10	1.15	1.37	.98	3.04
fs }-----	1.41	2.27	.90	.64	.64	.48	.08	1.12	1.53	1.60	3.82
mt-----	.34	.91	1.05	1.20	1.02	.82	.64	1.22	1.10	.67	.79
il-----	.25	.34	.40	.65	.59	.40	.19	.65	.65	.60	1.22
ap-----	.02	.05	.05	.16	.12	.07	.02	.12	--	.09	.26



	1	2	3	4	5	6	7	8	9	10	11
Trace elements (ppm)											
Ba-----	925.	1285.	952.	1085.	1070.	670.	33.	835.	815.	980.	685.
Be-----	1.6	3.2	1.6	2.5	--	2.2	5.4	1.5	1.4	--	--
Co-----	.9	.5	1.6	.4	.4	.9	< .3	3.0	3.1	2.2	11.2 <sup>3</sup>
Cr-----	<2.0	<7.0	1.6	1.7	<2.0	<5.0	<4.0	2.0	2.2	<3.0	153.0 <sup>3</sup>
Cs-----	11.4	6.9	2.3	1.8	2.3	3.0	3.4	3.0	2.8	2.9	3.2
Hf-----	3.4	10.9	4.9	7.5	7.6	4.2	4.3	4.7	4.5	4.8	5.9
Li-----	68.	44.	35.	29.	--	36.	47.	30.	32.	--	--
Mo-----	2.3	4.2	2.5	5.0	--	4.9	8.2	2.8	2.8	--	--
Nb**-----	5.2	13.	5.3	19.	--	14.	30.	13.	11.	--	--
Nb***-----	6.	16.	5.	17.	--	13.	34.	12.	10.	12.	7.
Pb-----	22.	44.	9.	30.	19.	15.	39.	21.	18.	12.	12.
Rb**-----	162.	96.	64.	93.	97.	109.	169.	76.	70.	74.	52.
Rb***-----	170.	100.	66.	105.	100.	100.	170.	84.	79.	77.	53.
Sb-----	2.3	1.7	1.2	.7	.8	.7	1.1	.5	< .8	.6	1.4
Sc-----	2.0	6.4	8.4	2.4	2.6	2.3	1.8	3.8	3.8	3.8	9.0
Sn-----	3.4	3.6	1.0	1.3	--	1.0	2.5	1.5	1.5	--	--
Sr-----	105.	97.	86.	305.	255.	100.	2.	255.	250.	215.	444.
Ta-----	.55	1.03	.44	1.24	1.37	1.30	2.40	.82	.89	.96	2.41 <sup>3</sup>
Th-----	15.5	10.1	5.0	11.6	12.5	11.8	40.1	7.3	7.4	8.3	5.4
U-----	7.2	4.5	2.1	4.1	4.1	5.6	14.4	3.0	3.2	3.3	2.3
W-----	2.2	2.0	1.3	.74	--	1.1	1.9	1.1	1.3	--	--
Y-----	21.	85.	48.	24.	32.	14.	30.	23.	25.	23.	25.
Zn-----	20.	108.	31.	52.	56.	30.	31.	41.	37.	34.	42.
Zr-----	100.	420.	157.	360.	286.	157.	106.	171.	178.	183.	218.
La-----	21.	37.	19.	38.	43.	25.	30.	21.	21.	22.	21.
Ce-----	38.	79.	39.	71.	78.	36.	47.	39.	39.	40.	43.
Nd-----	17.	46.	20.	30.	33.	16.	14.	17.	17.	17.	24.
Sm-----	3.0	11.8	5.6	5.5	5.7	3.0	3.0	2.9	2.9	3.4	4.8
Eu-----	.40	1.65	.78	1.11	1.07	.38	.14	.63	.62	.63	1.04
Gd-----	<3.0	10.5	6.1	3.8	3.7	1.8	2.9	2.9	2.6	3.5	4.6
Tb-----	< .30	2.0	1.14	.62	.72	.39	.59	.41	.43	.43	.55
Tm-----	.27	1.3	.55	.37	.45	.26	.44	.33	.21	.26	.36
Yb-----	1.7	8.9	4.6	2.6	2.8	2.0	3.9	1.8	1.8	2.0	2.6
Lu-----	.27	1.30	.67	.38	.43	.30	.59	.29	.29	.33	.36
Nb/Ta-----	10.2	14.1	11.7	14.5	--	10.4	13.3	15.2	11.8	12.5	--
K/Rb-----	191.	322.	370.	290.	300.	347.	221.	304.	317.	345.	363.
Rb/Sr-----	1.6	1.0	.77	.34	.39	1.0	85.	.33	.32	.36	.12
Ca/Sr-----	71.	91.	112.	35.	35.	70.	1394.	55.	54.	53.	58.
Th/U-----	2.2	2.2	2.4	2.8	3.1	2.1	2.8	2.4	2.3	2.5	2.4
Zr/Hf-----	29.	39.	32.	48.	38.	37.	25.	36.	40.	38.	37.
Ce/Yb-----	22.4	8.9	8.5	27.3	27.9	18.0	12.1	21.7	21.7	20.0	16.5
Eu/Eu*-----	--	.46	.41	.75	.72	.50	.14	.67	.69	.57	.68

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	OREGON											
Volcanic field/region---	Crater Lake										Newberry Volcano	
Locality-----	The Watchman	Grouse Hill		Llao Rock		Redcloud Cliff		Cleetwood	Cloudcap	Llao Rock	Lost Lake	East Lake
Specimen-----	12	13	14	15	16	17	18	19	20	21	22	23
Collection No. (RLS)---	8-3Av-G	9-2v	9-2v-G	9-16v	9-16v-G	9-19v	9-19v-G	222	223	224	144	156
Chemical analyses (weight percent)												
SiO <sub>2</sub> -----	71.9	70.4	73.6	70.3	73.1	71.2	74.4	70.2	71.0	71.5	72.7	73.4
Al <sub>2</sub> O <sub>3</sub> -----	14.33	15.21	14.21	15.00	13.67	14.75	13.42	15.01	14.88	15.11	14.33	13.87
Fe <sub>2</sub> O <sub>3</sub> -----	.13	1.01	1.67	.09	.70	.84	1.41	1.11	.88	.96	.50	.56
FeO-----	2.06	1.84	1.20	1.77	1.10	1.58	1.07	1.51	1.63	1.58	1.53	1.33
MgO-----	.46	.78	.33	.76	.30	.64	.24	.70	.65	.62	.15	.21
CaO-----	1.71	2.48	1.35	2.29	1.28	2.05	1.07	2.12	2.13	2.06	.81	.96
Na <sub>2</sub> O-----	4.88	4.97	5.00	4.93	4.98	4.93	4.78	5.34	4.97	5.38	5.14	4.80
K <sub>2</sub> O-----	3.13	2.50	2.98	2.56	3.07	2.73	3.29	2.47	2.71	2.49	4.01	4.19
H <sub>2</sub> O+-----	.49	.14	.17	1.10	.88	.33	.30	.19	.17	.10	.08	.07
TiO <sub>2</sub> -----	.49	.54	.36	.53	.32	.45	.28	.50	.48	.49	.23	.26
P <sub>2</sub> O <sub>5</sub> -----	.09	.10	.07	.10	.07	.08	.05	.09	.08	.09	.03	.04
MnO-----	.06	.07	.05	.07	.05	.07	.05	.07	.07	.07	.06	.06
Cl*-----	.09	.01	--	.17	--	.13	.16	.11	.10	.11	.10	.08
Cl**-----	--	--	--	--	--	--	--	.14	.11	.13	.10	.07
F*-----	.07	.05	--	.06	--	.06	.08	.06	.06	.06	.07	.07
F**-----	--	--	--	--	--	--	--	.05	.05	.05	.06	.06
Subtotal-----	99.89	100.10	100.99	99.73	99.52	99.84	100.60	99.50	99.82	100.63	99.74	99.90
Less O=(F,Cl) <sub>2</sub> -----	.05	.02	--	.06	--	.05	.07	.05	.05	.05	.05	.05
Total-----	99.84	100.08	100.99	99.67	99.52	99.79	100.53	99.45	99.77	100.58	99.69	99.85
FeO <sup>1</sup> -----	2.18	2.75	2.70	1.85	1.73	2.34	2.34	2.51	2.42	2.44	1.98	1.83
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	.94	.65	.42	.95	.61	.65	.43	.58	.65	.62	.75	.70
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.56	1.99	1.68	1.93	1.62	1.81	1.45	2.16	1.83	2.16	1.28	1.15
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	.80	.72	.81	.73	.84	.75	.85	.76	.75	.76	.89	.90
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.01	1.01	.98	1.01	.99	1.00	1.00	1.02	1.01	1.01	1.00	1.02
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	.21	.33	.17	.31	.16	.27	.13	.27	.28	.26	.09	.11
Cl/F <sup>1†</sup> -----	1.3	.15	--	2.8	--	2.0	2.1	2.3	1.8	2.2	1.5	1.2
CIPW norms												
Q-----	26.28	24.94	29.54	25.37	29.34	26.41	31.28	24.09	25.82	24.86	24.74	26.64
or-----	18.64	14.79	17.47	15.37	18.39	16.24	19.43	14.73	16.10	14.66	23.82	24.84
ab-----	41.61	42.10	41.97	42.40	42.72	42.00	40.42	45.59	42.28	45.37	43.72	40.75
an-----	7.96	11.66	6.19	10.88	5.96	9.71	4.98	9.78	10.10	9.60	3.84	3.94
C-----	.02	.06	.47	.20	--	.15	.17	--	.09	.03	.13	--
ac-----	--	--	--	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--	--	--	--
wo }-----	--	--	--	--	.01	--	--	.10	--	--	--	.24
en } di-----	--	--	--	--	.00	--	--	.06	--	--	--	.06
fs }-----	--	--	--	--	.00	--	--	.04	--	--	--	.19
en } hy-----	1.15	1.95	.82	1.92	.76	1.61	.60	1.7	1.63	1.54	.38	.46
fs }-----	3.00	1.79	.32	2.47	1.02	1.61	.43	1.13	1.61	1.42	2.14	1.47
mt-----	.19	1.47	2.40	.13	1.03	1.23	2.04	1.62	1.28	1.39	.73	.82
il-----	.94	1.03	.68	1.02	.62	.86	.53	.96	.92	.93	.44	.50
ap-----	.21	.23	.16	.24	.16	.19	.12	.21	.19	.21	.07	.09

	12	13	14	15	16	17	18	19	20	21	22	23
Trace elements (ppm)												
Ba-----	847.	790.	786.	748.	802.	798.	817.	782.	821.	820.	895.	910.
Be-----	--	--	--	--	--	--	--	3.3	2.0	2.0	2.9	2.9
Co-----	6.1 <sup>3</sup>	4.5	2.1	4.3	1.9	3.8	1.6	3.8	4.0	3.4	0.8	1.4
Cr-----	92.3	--	1.3	2.2	<2.0	--	2.0	2.5	3.0	1.1	<5.0	2.3
Cs-----	4.4	1.8	2.1	4.0	4.7	4.1	5.0	3.1	4.1	3.4	5.0	5.1
Hf-----	7.5	5.7	6.4	6.1	6.8	6.4	5.9	5.8	6.5	5.9	8.6	7.5
Li-----	--	--	--	--	--	--	--	28.	35.	35.	43.	47.
Mo-----	--	--	--	--	--	--	--	1.6	1.8	1.6	3.9	3.3
Nb**-----	--	--	--	--	--	--	--	6.8	6.8	6.4	19.	19.
Nb***-----	9.	8.	9.	8.	8.	9.	8.	8.	8.	8.	22.	20.
Pb-----	14.	12.	14.	13.	14.	16.	18.	13.	11.	13.	17.	28.
Rb**-----	60.	61.	67.	61.	76.	67.	79.	56.	71.	60.	111.	150.
Rb***-----	72.	60.	75.	63.	80.	70.	84.	52.	65.	56.	122.	136.
Sb-----	1.9	.8	--	.9	--	0.9	0.9	1.2	--	--	<0.5	0.4
Sc-----	6.1	7.7	5.4	7.5	5.4	6.9	4.4	6.6	7.4	6.5	5.5	4.9
Sn-----	--	--	--	--	--	--	--	1.1	1.6	1.2	4.0	4.3
Sr-----	248.	344.	205.	327.	195.	300.	158.	402.	291.	326.	50.	75.
Ta-----	32.33	.56	.55	.61	.59	.54	.57	.52	.60	.50	1.82	1.46
Th-----	7.0	5.6	6.6	6.0	7.3	6.4	7.4	4.9	6.1	5.1	11.2	11.9
U-----	3.3	2.6	3.3	2.9	3.6	3.3	3.3	2.3	3.0	2.5	4.9	4.2
W-----	--	--	--	--	--	--	--	.60	.66	.50	1.7	2.1
Y-----	32.	22.	23.	28.	30.	27.	30.	24.	27.	25.	50.	49.
Zn-----	39.	31.	26.	35.	35.	36.	30.	42.	34.	43.	48.	46.
Zr-----	285.	217.	232.	225.	236.	226.	214.	220.	233.	228.	337.	280.
La-----	24.	18.	17.	22.	25.	22.	25.	22.	22.	21.	32.	30.
Ce-----	52.	35.	33.	45.	49.	45.	49.	42.	45.	43.	64.	64.
Nd-----	28.	20.	18.	26.	27.	26.	25.	22.	27.	23.	28.	25.
Sm-----	5.6	4.2	4.3	5.6	5.5	5.2	5.4	4.6	5.4	4.8	7.1	6.5
Eu-----	.93	.96	.89	.99	.86	.92	.74	.93	.97	.94	.79	.75
Gd-----	5.6	4.1	4.1	4.8	5.2	5.6	5.0	4.3	5.3	4.5	5.6	5.6
Tb-----	.80	.58	.52	.70	.66	.65	.75	.69	.82	.73	.90	1.08
Tm-----	.37	.40	.45	.54	.55	.43	.45	.31	.38	.35	.89	.78
Yb-----	3.1	2.3	2.4	2.7	2.9	2.7	2.8	2.3	2.7	2.7	4.9	4.6
Lu-----	.44	.36	.36	.40	.42	.40	.42	.34	.39	.36	.72	.62
Nb/Ta-----	--	14.3	16.4	13.1	13.6	16.7	14.0	14.2	12.3	14.4	11.3	13.4
K/Rb-----	361.	346.	330.	337.	319.	324.	325.	394.	346.	369.	273.	256.
Rb/Sr-----	.29	.17	.37	.19	.41	.23	.53	.13	.22	.17	2.4	1.8
Ca/Sr-----	49.	52.	47.	50.	47.	49.	48.	38.	52.	45.	116.	92.
Th/U-----	2.1	2.2	2.0	2.1	2.0	1.9	2.2	2.1	2.0	2.0	2.3	2.8
Zr/Hf-----	38.	38.	36.	37.	35.	35.	36.	38.	36.	39.	39.	37.
Ce/Yb-----	16.8	15.2	13.8	16.7	16.9	16.7	17.5	18.3	16.7	15.9	13.1	13.9
Eu/Eu*-----	.51	.71	.64	.59	.50	.60	.44	.64	.56	.62	.38	.38

See footnotes at end of table.

APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

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CHEMISTRY OF THE SUBALKALIC SILICIC OBSIDIANS

Country/State-----	OREGON										
Volcanic field/region---	Southeast Oregon										
Locality-----	East Butte	Quartz Mountain	Cougar Mountain	Glass Buttes	Riley	Horse Mountain	Drewes Ranch	Tucker Hill	McComb Butte	Orijana Canyon	Beatys Butte
Specimen-----	24	25	26	27	28	29	30	31	32	33	34
Collection No. (RLS-)---	159	157	162	158	154	54	163	161	155	164	160
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	74.9	74.3	77.3	76.6	73.8	76.4	76.3	76.7	76.3	76.9	74.0
Al <sub>2</sub> O <sub>3</sub> -----	13.71	13.34	12.66	13.11	13.23	10.82	12.64	13.23	13.30	11.92	13.78
Fe <sub>2</sub> O <sub>3</sub> -----	.46	.35	.37	.28	.71	1.23	.30	.15	.18	.45	.36
FeO-----	1.22	1.17	.75	.60	1.55	1.52	.41	.50	.41	.41	.77
MgO-----	.05	.05	.03	.09	.08	< .005	.03	.05	.05	.04	.15
CaO-----	1.00	.84	.64	.85	.50	.17	.49	.78	.91	.27	1.16
Na <sub>2</sub> O-----	4.57	4.55	4.34	3.90	4.99	4.74	4.04	4.02	3.95	3.82	3.71
K <sub>2</sub> O-----	3.74	4.03	3.65	4.28	4.60	4.48	4.46	4.48	4.57	4.95	4.93
H <sub>2</sub> O+-----	.14	.09	.09	.11	.07	.08	.19	.09	.11	.13	.11
TiO <sub>2</sub> -----	.12	.12	.07	.12	.23	.18	.06	.06	.06	.13	.17
P <sub>2</sub> O <sub>5</sub> -----	.01	.01	.01	.02	.02	.01	.01	.01	.01	.01	.03
MnO-----	.05	.05	.05	.05	.10	.08	.07	.07	.07	.09	.06
Cl*-----	.06	.07	.06	.03	.09	.10	.04	.04	.02	.06	.03
Cl**-----	.05	.06	.05	.02	.07	.09	.04	.04	.04	.05	.02
F*-----	.05	.07	.06	.04	.07	.09	.04	.11	.04	.09	.02
F**-----	.05	.06	.02	.03	.07	.09	.03	.10	.03	.08	.02
Subtotal-----	100.08	99.04	100.08	100.08	100.03	99.90	99.08	100.29	99.99	99.27	99.28
Less O=(F,Cl) <sub>2</sub> -----	.03	.04	.04	.02	.05	.06	.03	.05	.02	.05	.02
Total-----	100.05	99.00	100.04	100.06	99.98	99.84	99.05	100.24	99.97	99.22	99.26
FeO <sup>1</sup> -----	1.63	1.49	1.08	0.85	2.19	2.63	0.68	0.64	0.57	0.82	1.09
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	.73	.77	.67	.68	.69	.55	.58	.77	.69	.48	.68
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.22	1.13	1.19	.91	1.08	1.06	.91	.90	.86	.77	.75
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	.84	.89	.88	.84	1.00	1.17	.91	.87	.86	.97	.83
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	.98	1.00	.97	.96	1.06	1.20	.98	.97	.98	1.01	.98
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	.12	.10	.08	.10	.05	.02	.06	.09	.11	.03	.13
Cl/F <sup>1+</sup> -----	1.1	1.0	.83	.61	1.1	1.1	1.0	.38	.74	.65	1.2
CIPW norms											
Q-----	31.07	30.13	36.27	35.32	25.63	34.43	34.84	34.06	33.30	35.44	30.77
or-----	22.14	24.10	21.60	25.32	27.23	26.57	26.67	26.46	27.24	29.55	29.39
ab-----	38.74	38.97	36.77	33.03	42.30	30.83	34.60	34.00	33.54	32.65	31.67
an-----	4.90	4.12	3.11	4.09	.12	--	2.39	3.80	4.17	.77	5.61
C-----	.35	--	.43	.57	--	--	.30	.37	--	--	.31
ac-----	--	--	--	--	--	3.57	--	--	--	--	--
ns-----	--	--	--	--	--	1.25	--	--	--	--	--
wo } di-----	--	.01	--	--	.94	.33	--	--	.12	.22	--
en } di-----	--	.00	--	--	.09	.00	--	--	.01	.05	--
fs } di-----	--	.01	--	--	.94	.37	--	--	.12	.18	--
en } hy-----	.13	.13	.08	.22	.11	.00	.08	.12	.12	.05	.38
fs } hy-----	1.76	1.76	1.05	.77	1.13	2.28	.54	.83	.53	.16	.96
mt-----	.67	.51	.54	.41	1.03	.00	.44	.22	.22	.66	.53
il-----	.23	.23	.13	.23	.44	.34	.12	.11	.15	.25	.33
ap-----	.02	.02	.02	.05	.05	.02	.02	.02	.02	.02	.07

	24	25	26	27	28	29	30	31	32	33	34
Trace elements (ppm)											
Ba-----	950.	995.	1250.	1370.	1200.	42.	31.	305.	380.	13.	985.
Be-----	2.5	2.6	2.2	1.3	3.4	4.7	3.1	3.3	3.3	4.4	2.0
Co-----	.3	.4	.1	.3	.4	< .4	.1	.2	.1	< .2	.9
Cr-----	<5.0	<4.0	<4.0	<4.0	<5.0	<7.0	<4.0	<4.0	<3.0	3.5	<3.0
Cs-----	5.8	6.2	3.7	3.4	4.8	5.6	4.3	4.4	4.3	4.7	2.8
Hf-----	5.9	5.5	4.6	3.4	11.5	15.0	3.5	3.0	2.9	6.7	4.0
Li-----	60.	68.	42.	36.	37.	44.	46.	49.	59.	75.	40.
Mo-----	2.1	2.2	3.2	3.0	4.5	5.5	4.1	6.5	3.1	7.1	4.0
Nb**-----	13.	11.	10.	11.	24.	39.	12.	9.6	12.	36.	14.
Nb***-----	11.	12.	10.	8.	30.	37.	--	8.	11.	38.	17.
Pb-----	26.	21.	19.	21.	21.	32.	26.	19.	30.	19.	19.
Rb**-----	122.	128.	92.	97.	116.	114.	127.	108.	91.	141.	122.
Rb***-----	127.	132.	103.	102.	110.	140.	133.	110.	102.	130.	125.
Sb-----	.6	.6	.4	.2	.5	2.2	.4	< .5	.3	1.2	.4
Sc-----	4.7	3.6	3.9	2.7	6.6	.53	3.0	2.4	2.2	3.8	1.8
Sn-----	3.9	4.3	2.7	1.4	3.2	4.0	1.4	2.9	1.1	4.0	.7
Sr-----	80.	70.	40.	73.	10.	2.	9.	50.	80.	2.	173.
Ta-----	.95	1.07	.95	.76	1.65	2.36	1.24	1.19	1.33	2.62	1.08
Th-----	10.5	11.5	6.9	8.4	9.0	12.5	10.8	7.8	6.3	9.8	7.2
U-----	4.0	4.4	2.8	3.2	3.4	4.9	4.8	4.2	3.8	5.1	3.0
W-----	1.6	1.8	1.3	1.1	2.0	1.7	1.4	1.4	1.3	2.5	.7
Y-----	52.	48.	61.	27.	80.	120.	27.	29.	28.	108.	12.
Zn-----	62.	56.	64.	20.	89.	195.	24.	27.	21.	95.	24.
Zr-----	188.	168.	112.	88.	447.	710.	66.	52.	65.	149.	146.
La-----	27.	27.	18.	27.	36.	62.	16.	13.	9.	20.	23.
Ce-----	55.	56.	42.	49.	78.	124.	33.	25.	18.	55.	38.
Nd-----	25.	23.	20.	18.	35.	70.	14.	9.	8.	30.	11.
Sm-----	6.6	6.4	6.4	3.7	9.0	15.5	4.3	3.3	2.1	10.5	2.3
Eu-----	.75	.65	.68	.54	1.00	1.16	.13	.30	.34	.61	.42
Gd-----	5.5	5.3	6.6	3.7	7.3	14.1	3.5	2.9	1.8	10.8	1.9
Tb-----	1.09	1.13	1.21	.69	1.53	2.71	.70	.58	.53	2.25	.36
Tm-----	.74	.74	.84	.41	1.10	1.74	.43	.39	.27	1.82	.23
Yb-----	4.8	4.7	5.7	2.8	6.9	11.6	3.0	2.7	2.4	11.7	1.4
Lu-----	.66	.65	.76	.41	.98	1.65	.44	.38	.34	1.66	.21
Nb/Ta-----	12.6	10.8	10.5	12.5	16.4	16.1	9.7	7.4	8.7	14.1	14.4
K/Rb-----	244.	253.	294.	348.	347.	266.	278.	338.	372.	316.	327.
Rb/Sr-----	15.9	1.9	2.6	1.4	11.0	70.0	14.8	2.2	1.3	65.0	.72
Ca/Sr-----	89.	86.	114.	83.	357.	608.	389.	112.	81.	965.	48.
Th/U-----	2.6	2.6	2.5	2.6	2.7	2.6	2.3	1.9	1.7	1.9	2.4
Zr/Hf-----	32.	31.	24.	26.	39.	47.	19.	17.	22.	22.	37.
Ce/Yb-----	11.5	11.9	7.4	17.5	11.3	10.7	11.0	9.3	7.5	4.7	27.1
Eu/Eu*-----	.38	.34	.32	.45	.38	.24	.10	.30	.54	.18	.61

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	CALIFORNIA											
Volcanic field/region---	Warner Mountains				Medicine Lake Highlands				Sonoma Volcanic Field		Clear Lake Volcanic Field	
Locality-----	Sugar Hill		Buck Mountain		Boyd Creek	Grasshopper Flat	Little Glass Mountain	Big Glass Mountain		Napa Glass Mountain	Bonanza Springs	Camel Back Ridge
Specimen-----	35	36	37	38	39	40	41	42	43	44	45	46
Collection No. (RLS)---	51	52	40	41	44	142	143	141	RGM-1	43	153	149
Chemical analyses (weight percent)												
SiO <sub>2</sub> -----	76.5	73.0	75.8	75.7	75.7	75.2	74.0	73.3	73.44	76.3	75.1	75.7
Al <sub>2</sub> O <sub>3</sub> -----	12.67	14.37	13.27	13.16	13.35	13.34	14.02	13.99	13.74	12.62	13.23	13.10
Fe <sub>2</sub> O <sub>3</sub> -----	.38	.50	.37	.37	.40	.40	.42	.41	.50	.51	.18	.19
FeO-----	.55	.70	.38	.39	.39	.86	1.25	1.29	1.24	.71	1.09	1.12
MgO-----	.10	.13	.08	.08	.07	.19	.26	.26	.29	.01	.08	.19
CaO-----	.67	.71	.81	.82	.80	.85	1.21	1.23	1.18	.37	.90	1.00
Na <sub>2</sub> O-----	3.65	4.63	3.98	3.96	3.87	3.97	4.06	4.12	4.18	4.31	3.79	3.43
K <sub>2</sub> O-----	4.77	4.91	4.54	4.49	4.59	4.57	4.34	4.33	4.34	4.50	4.33	4.67
H <sub>2</sub> O+-----	.11	.15	.17	.04	.09	.08	.08	.08	.34	.22	.07	.11
TiO <sub>2</sub> -----	.13	.21	.09	.10	.09	.22	.28	.29	.27	.08	.09	.26
P <sub>2</sub> O <sub>5</sub> -----	.02	.02	.01	.01	.02	.03	.05	.05	.05	.01	.02	.03
MnO-----	.05	.08	.06	.06	.06	.04	.04	.04	.04	.03	.04	.03
Cl*-----	.04	.10	.05	.04	.04	.06	.06	.05	.07	.07	.06	.04
Cl**-----	.03	.08	.03	.03	.03	.06	.06	.06	.06	.06	.05	.04
F*-----	.03	.04	.03	.03	.03	.05	.04	.04	.04	.07	.07	.07
F**-----	.03	.04	.02	.02	.02	.04	.03	.04	.04	.06	.07	.06
Subtotal-----	99.67	99.54	99.63	99.25	99.50	99.86	100.11	99.49	99.72	99.81	99.05	99.94
Less O=(F,Cl) <sub>2</sub> -----	.02	.04	.02	.02	.02	.03	.03	.03	.03	.04	.04	.04
Total-----	99.65	99.50	99.61	99.23	99.48	99.83	100.08	99.46	99.69	99.77	99.01	99.90
FeO <sup>1</sup> -----	.90	1.15	.71	.72	.75	1.22	1.63	1.66	1.69	1.17	1.25	1.29
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	.59	.58	.51	.51	.49	.68	.75	.76	.71	.58	.86	.85
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	.77	.94	.88	.88	.84	.87	.94	.95	.96	.96	.88	.73
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	.88	.90	.86	.86	.85	.86	.81	.82	.84	.95	.83	.82
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	.98	.99	.97	.98	.96	.98	.97	.98	1.00	1.00	.95	.95
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	.08	.07	.10	.10	.10	.10	.14	.15	.14	.04	.11	.12
Cl/F <sup>1</sup> -----	1.3	2.3	1.5	1.4	1.4	1.4	1.6	1.4	1.6	1.0	.76	.61
CIPW norms												
Q-----	35.41	25.50	33.49	33.76	33.93	32.27	30.25	29.35	29.23	33.04	34.08	34.94
or-----	28.33	29.23	26.99	26.76	27.30	27.10	25.66	25.77	25.84	26.74	25.89	27.67
ab-----	31.04	39.47	33.88	33.80	32.96	33.70	34.38	35.11	35.63	36.67	32.44	29.11
an-----	3.21	3.42	3.98	4.04	3.86	4.03	5.68	5.82	5.57	1.78	4.39	4.78
C-----	.33	.20	.36	.32	.61	.39	.56	.41	.14	.01	.73	.66
ac-----	--	--	--	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--	--	--	--
wo } di-----	--	--	--	--	--	--	--	--	--	--	--	--
en } di-----	--	--	--	--	--	--	--	--	--	--	--	--
fs } di-----	--	--	--	--	--	--	--	--	--	--	--	--
en } hy-----	.25	.33	.20	.20	.18	.48	.65	.65	.73	.03	.20	.48
fs } hy-----	.58	.68	.36	.36	.35	.96	1.56	1.64	1.50	.81	1.80	1.53
mt-----	.55	.73	.54	.54	.58	.58	.61	.60	.73	.74	.26	.28
il-----	.25	.40	.17	.19	.17	.42	.53	.56	.52	.15	.17	.50
ap-----	.05	.05	.02	.02	.05	.07	.12	.12	.12	.02	.05	.07

	35	36	37	38	39	40	41	42	43	44	45	46
Trace elements (ppm)												
Ba-----	680.	1340.	635.	745.	690.	790.	850.	885.	810.	415.	1200.	655.
Be-----	2.6	3.0	3.0	2.7	2.8	2.5	2.6	2.7	--	3.7	2.5	2.3
Co-----	.5	.4	.2	.2	.2	1.2	1.9	2.1	1.9	< .3	.7	1.4
Cr-----	<6.0	<7.0	<5.0	<5.0	<4.0	<4.0	<5.0	<5.0	3.3	<5.0	1.6	2.3
Cs-----	3.2	2.1	2.4	3.0	2.6	7.8	10.1	10.5	9.7	13.5	9.7	14.8
Hf-----	3.5	5.5	3.1	3.7	3.2	5.0	5.6	5.7	5.7	6.4	3.9	5.5
Li-----	32.	25.	42.	41.	42.	52.	64.	61.	--	110.	69.	75.
Mo-----	4.4	4.6	4.4	4.2	4.5	3.8	2.9	2.8	--	1.7	.58	.75
Nb**-----	16.	18.	15.	14.	15.	9.2	9.6	9.1	9.4	13.	11.	14.
Nb***-----	17.	18.	16.	16.	16.	7.	--	9.	10.	16.	14.	14.
Pb-----	18.	27.	27.	32.	34.	22.	18.	22.	22.	49.	27.	21.
Rb**-----	119.	102.	104.	121.	111.	146.	155.	147.	148.	175.	154.	201.
Rb***-----	135.	118.	122.	120.	115.	142.	155.	156.	154.	200.	157.	210.
Sb-----	1.1	.4	.4	.6	< .7	1.5	.6	.7	1.2	1.3	.7	1.2
Sc-----	2.5	4.2	1.7	2.0	1.8	3.6	4.3	4.5	4.36		5.7	4.6
Sn-----	1.7	1.8	1.2	1.0	1.4	3.0	3.0	3.7	--	5.8	2.7	5.7
Sr-----	50.	63.	70.	70.	70.	72.	115.	115.	115.	5.	97.	73.
Ta-----	1.45	1.17	1.16	1.50	1.16	1.09	1.10	1.00	1.03	1.02	.97	1.31
Th-----	14.5	10.2	9.8	11.7	10.1	13.9	14.9	14.8	14.6	17.1	15.6	21.7
U-----	5.6	3.8	4.1	4.7	4.1	6.2	6.7	6.5	5.9	7.0	5.6	6.8
W-----	1.1	1.5	.80	.78	.84	1.6	1.4	2.1	--	2.2	2.7	3.5
Y-----	16.	26.	12.	21.	20.	20.	25.	23.	28.	37.	28.	33.
Zn-----	22.	37.	23.	25.	20.	25.	32.	30.	28.	62.	42.	24.
Zr-----	122.	262.	100.	100.	101.	170.	208.	206.	212.	260.	102.	136.
La-----	27.	35.	23.	30.	25.	25.	24.	23.	24.	30.	31.	31.
Ce-----	48.	63.	36.	51.	37.	50.	46.	44.	45.	47.	66.	64.
Nd-----	17.	24.	13.	17.	13.	20.	17.	17.	20.	24.	28.	25.
Sm-----	3.2	4.7	2.7	3.4	2.8	5.1	4.5	4.8	4.3	6.1	5.5	5.2
Eu-----	.36	.80	.37	.50	.33	.41	.57	.58	.59	.18	.37	.33
Gd-----	2.9	3.2	1.9	2.5	1.7	3.7	3.8	3.6	4.0	4.3	6.0	5.0
Tb-----	.46	.70	.38	.37	.39	.68	.68	.76	.62	1.04	1.06	.96
Tm-----	.33	.56	.26	.36	.23	.56	.40	.46	.39	.57	.35	.56
Yb-----	2.6	3.0	1.9	2.2	1.9	3.2	2.5	2.6	2.5	4.4	2.8	3.5
Lu-----	.37	.45	.29	.34	.29	.47	.39	.39	.39	.61	.36	.46
Nb/Ta-----	11.4	15.4	13.4	10.0	13.4	7.4	8.7	9.1	9.4	14.2	12.9	10.7
K/Rb-----	293.	345.	309.	311.	331.	267.	232.	230.	234.	187.	229.	185.
Rb/Sr-----	2.7	1.9	1.7	1.7	1.6	2.0	1.4	1.4	1.3	40.	6.2	2.9
Ca/Sr-----	96.	81.	83.	84.	82.	84.	75.	76.	73.	529.	66.	98.
Th/U-----	2.6	2.7	2.4	2.5	2.4	2.2	2.2	2.3	2.5	2.4	2.8	3.2
Zr/Hf-----	35.	48.	32.	27.	32.	34.	37.	36.	37.	41.	26.	25.
Ce/Yb-----	18.5	21.0	19.0	23.2	19.5	15.6	18.4	16.9	18.0	10.7	23.6	18.3
Eu/Eu*-----	.39	.63	.51	.58	.46	.32	.42	.42	.43	.11	.20	.20

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

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CHEMISTRY OF THE SUBALKALIC SILICIC OBSIDIANS

Country/State-----	CALIFORNIA											
Volcanic field/region---	Clear Lake Volcanic Field		Mono Craters		Inyo Craters	Long Valley Caldera			Big Pine	Northern Coso	Coso Volcanic Field	
Locality-----	Thurston Canyon	Borax Lake	Northwest Coulee	Panum Dome	Obsidian Dome	Early rhyolite sequence		Hot Creek flow	Big Pine flow	Olancha		
Specimen----- Collection No. (RLS)---	47 7	48 150	49 148	50 147	51 MC73-1A	52 M72-8	53 M72-21	54 M72-62	55 9	56 5	57 CD-3	58 CD-4A
Chemical analyses (weight percent)												
SiO <sub>2</sub> -----	75.18	77.2	76.4	76.5	72.94	74.26	74.48	75.54	75.65	75.93	76.9	76.9
Al <sub>2</sub> O <sub>3</sub> -----	13.23	12.49	12.58	12.51	14.22	13.54	13.55	13.24	13.30	12.73	12.41	12.77
Fe <sub>2</sub> O <sub>3</sub> -----	.28	.21	.34	.33	.47	.35	.35	.38	.38	.35	.50	.43
FeO-----	1.04	.73	.74	.76	1.15	.95	.91	.65	.34	.45	.54	.56
MgO-----	.22	.07	.02	.02	.09	.19	.14	.10	.05	.05	< .01	< .01
CaO-----	1.02	.61	.52	.52	.74	.90	.84	.64	.53	.46	.35	.39
Na <sub>2</sub> O-----	3.52	3.52	3.92	3.96	4.28	3.67	3.85	3.99	4.55	4.51	4.45	4.58
K <sub>2</sub> O-----	4.83	4.69	4.57	4.59	5.26	5.15	5.14	4.92	4.43	4.24	4.40	4.19
H <sub>2</sub> O+-----	.20	.15	.23	.25	.21	.28	.38	.26	.28	.87	.19	.21
TiO <sub>2</sub> -----	.24	.09	.07	.07	.13	.19	.15	.11	.07	.05	.06	.06
P <sub>2</sub> O <sub>5</sub> -----	.03	.01	.01	.01	.01	.02	.03	.02	.02	.02	< .01	< .01
MnO-----	.03	.03	.05	.05	.05	.04	.04	.04	.11	.10	.018	.019
Cl*-----	--	.03	.06	.06	--	--	--	--	--	--	--	.10
Cl**-----	.04	.02	.07	.07	--	.03	--	--	.06	.04	--	--
F*-----	--	.06	.07	.07	--	--	--	--	--	--	--	.21
F**-----	.07	.08	.07	.07	--	--	--	--	.07	.08	.19	.19
Subtotal-----	99.93	99.90	99.59	99.71	99.55	99.57	99.86	99.89	99.84	99.88	100.01	100.41
Less O=(F,Cl) <sub>2</sub> -----	0.04	0.04	0.05	0.04	--	--	--	--	0.04	0.04	0.08	0.11
Total-----	99.89	99.86	99.54	99.67	99.55	99.57	99.86	99.89	99.80	99.84	99.93	100.30
FeO <sup>1</sup> -----	1.29	0.92	1.04	1.06	1.57	1.27	1.23	0.99	0.68	0.77	0.99	0.95
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.79	0.78	0.69	0.70	0.71	0.73	0.72	0.63	0.47	0.56	0.52	0.57
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.73	0.75	0.86	0.86	0.81	0.71	0.75	0.81	1.03	1.06	1.01	1.09
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.83	0.87	0.91	0.92	0.90	0.86	0.88	0.90	0.92	0.94	0.97	0.95
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.97	0.96	0.98	0.99	0.99	0.98	0.99	0.99	1.00	1.01	1.03	1.00
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.12	0.07	0.06	0.06	0.08	0.10	0.09	0.07	0.06	0.05	0.04	0.04
Cl/F <sup>1†</sup> -----	0.57	0.35	0.93	0.93	--	--	--	--	0.86	0.50	--	0.51
CIPW norms												
Q-----	33.31	37.03	34.78	34.52	25.66	30.72	30.10	31.81	31.07	32.58	33.51	33.15
or-----	28.65	27.81	27.22	27.31	31.29	30.66	30.53	29.18	26.33	25.34	26.10	24.79
ab-----	29.90	29.89	33.43	33.74	36.46	31.29	32.75	33.89	38.72	38.59	37.79	38.79
an-----	4.88	2.97	2.53	2.53	3.63	4.37	3.99	3.06	2.51	1.99	0.90	1.91
C-----	0.43	0.54	0.27	0.11	0.17	0.34	0.20	.024	0.11	--	--	--
ac-----	--	--	--	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--	--	--	--
wo }-----	--	--	--	--	--	--	--	--	--	0.08	0.33	0.01
en } di-----	--	--	--	--	--	--	--	--	--	0.01	0.00	0.00
fs }-----	--	--	--	--	--	--	--	--	--	0.07	0.37	0.01
en } hy-----	0.55	0.18	0.05	0.05	0.23	0.48	0.35	0.25	0.13	0.11	0.00	0.00
fs }-----	1.34	1.08	1.06	1.11	1.61	1.23	1.22	0.78	0.40	0.58	0.15	0.60
mt-----	0.41	0.31	0.50	0.48	0.69	0.51	0.51	0.55	0.55	0.51	0.73	0.62
il-----	0.46	0.17	0.13	0.13	0.25	0.36	0.29	0.21	0.13	0.10	0.11	0.11
ap-----	0.07	0.02	0.02	0.02	0.02	0.05	0.07	0.05	0.05	0.05	0.02	0.00



	47	48	49	50	51	52	53	54	55	56	57	58
Trace elements (ppm)												
Ba-----	649.	60.	20.	<50.	--	--	--	--	12.	9.	8.	5.4
Be-----	2.5	3.1	3.8	3.8	--	--	--	--	7.3	9.1	--	11.
Co-----	1.3	0.4	0.2	0.2	0.4	0.8	0.6	0.4	<0.3	<0.4	0.1	0.1
Cr-----	1.1	2.1	1.7	<4.0	2.3	1.7	1.9	2.5	1.6	<5.0	0.0	<0.7
Cs-----	14.0	14.0	5.2	5.3	4.0	4.7	4.7	3.5	4.4	9.0	7.0	7.1
Hf-----	5.3	3.6	4.2	4.3	6.5	4.8	4.9	4.2	4.2	4.3	6.0	6.1
Li-----	81.	95.	42.	42.	--	--	--	--	64.	110.	--	180.
Mo**-----	0.61	0.96	2.5	2.6	--	--	--	--	5.3	2.0	--	--
Nb-----	12.	16.	23.	22.	--	--	--	--	40.	45.	--	--
Nb***-----	14.	18.	28.	25.	--	--	--	--	50.	59.	75.	71.
Pb-----	20.	25.	28.	21.	--	--	--	--	30.	32.	34.	38.
Rb**-----	193.	218.	175.	178.	170.	148.	143.	123.	208.	265.	297.	313.
Rb***-----	223.	227.	190.	193.	--	--	--	--	206.	278.	330.	325.
Sb-----	0.7	0.8	0.8	0.9	0.7	0.9	1.0	1.0	1.4	2.7	0.9	0.9
Sc-----	4.3	4.1	1.8	1.9	3.1	2.1	2.1	1.07	3.3	2.0	0.99	0.99
Sn-----	6.0	7.9	3.1	3.1	--	--	--	--	3.0	5.7	--	11.
Sr-----	72.	9.	7.	8.	--	--	--	--	8.	4.	2.8	3.2
Ta-----	1.21	1.25	1.95	1.97	1.73	1.34	1.37	1.66	3.80	6.55	7.00	6.66
Th-----	22.2	15.6	18.7	18.9	21.2	15.8	16.0	14.2	21.8	26.8	34.3	34.3
U-----	7.3	6.6	5.2	5.2	6.2	5.2	5.5	4.1	7.2	9.3	12.3	12.5
W-----	3.5	3.3	2.1	2.2	--	--	--	--	2.4	2.7	--	--
Y-----	45.	47.	28.	26.	--	--	--	--	40.	54.	--	72.
Zn-----	25.	34.	36.	41.	--	--	--	--	38.	39.	55.	59.
Zr-----	173.	78.	103.	105.	--	--	--	--	73.	83.	105.	105.
La-----	31.	21.	23.	24.	90.	42.	43.	42.	11.	9.	16.	16.
Ce-----	55.	48.	48.	52.	142.	64.	68.	65.	28.	22.	40.	39.
Nd-----	26.	24.	22.	19.	51.	23.	24.	22.	13.	9.	25.	21.
Sm-----	5.6	5.6	5.1	4.4	8.0	3.4	3.6	3.2	4.0	3.7	6.9	6.8
Eu-----	0.30	0.08	0.13	0.13	0.36	0.43	0.40	0.25	0.31	0.06	0.02	0.02
Gd-----	4.4	6.1	4.5	4.9	9.5	4.7	5.4	6.6	4.0	4.2	--	--
Tb-----	0.86	1.19	0.73	0.75	0.76	0.37	0.41	0.38	0.71	0.72	1.67	1.60
Tm-----	0.37	0.59	0.32	0.45	0.35	0.14	0.21	0.28	0.39	<0.30	1.03	1.05
Yb-----	3.3	3.9	2.7	2.8	3.0	1.7	1.8	1.6	3.1	4.0	7.5	7.4
Lu-----	0.48	0.51	0.37	0.39	0.44	0.27	0.28	0.23	0.46	0.58	0.99	1.07
Nb/Ta-----	10.7	13.6	13.1	11.9	--	--	--	--	11.8	7.9	10.7	10.7
K/Rb-----	180.	172.	200.	197.	257.	289.	298.	332.	179.	127.	111.	107.
Rb/Sr-----	3.1	25.2	27.1	24.1	--	--	--	--	25.8	69.5	118.	102.
Ca/Sr-----	101.	484.	531.	465.	--	--	--	--	474.	822.	893.	871.
Th/U-----	3.1	2.4	3.6	3.6	3.4	3.2	2.9	3.5	3.0	2.9	2.8	2.7
Zr/Hf-----	33.	22.	25.	24.	--	--	--	--	17.	19.	18.	17.
Ce/Yb-----	16.7	12.3	17.8	18.6	47.3	37.7	37.8	40.6	9.0	5.5	5.3	5.3
Eu/Eu*-----	0.19	0.04	0.08	0.09	0.13	0.33	0.28	0.17	0.24	0.05	0.01	0.01

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	CALIFORNIA											
Volcanic field/region---	Coso Volcanic Field											
Specimen-----	59	60	61	62	63	64	65	66	67	68	69	70
Collection No. (RLS)---	CD-5	CD-17	CD-22	CD-7	CD-20	CD-23	CD-30	CD-33	CD-8	CD-12	CD-14	CD-18
Chemical analyses (weight percent)												
SiO <sub>2</sub> -----	76.6	76.2	76.9	76.9	76.2	76.4	76.5	76.7	77.0	76.6	77.0	76.8
Al <sub>2</sub> O <sub>3</sub> -----	12.41	12.57	12.39	12.68	12.56	12.56	12.57	12.45	12.06	12.42	12.54	12.41
Fe <sub>2</sub> O <sub>3</sub> -----	0.40	0.40	0.64	0.40	0.56	0.35	0.31	0.40	0.38	0.69	0.43	0.28
FeO-----	0.58	0.53	0.39	0.44	0.44	0.60	0.65	0.63	0.57	0.30	0.50	0.55
MgO-----	<0.01	<0.02	0.02	<0.01	0.02	0.02	0.02	0.02	0.02	<0.01	0.03	0.03
CaO-----	0.35	0.39	0.35	0.32	0.43	0.44	0.42	0.41	0.31	0.36	0.38	0.42
Na <sub>2</sub> O-----	4.52	4.31	4.55	4.58	4.07	4.32	4.32	4.34	4.44	4.36	4.32	4.40
K <sub>2</sub> O-----	4.15	4.50	4.18	4.30	4.87	4.58	4.58	4.61	4.41	4.24	4.37	4.38
H <sub>2</sub> O+-----	0.29	0.22	0.08	0.14	0.51	0.28	0.37	0.19	0.23	0.38	0.27	0.22
TiO <sub>2</sub> -----	0.07	0.06	0.06	0.05	0.09	0.09	0.07	0.09	0.06	0.08	0.04	0.07
P <sub>2</sub> O <sub>5</sub> -----	0.03	0.01	0.02	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
MnO-----	0.019	0.017	0.020	0.020	0.019	0.016	0.018	0.016	0.021	0.021	0.023	0.018
Cl <sup>*</sup> -----	0.10	0.06	--	0.05	--	0.07	0.08	0.07	--	0.06	--	0.08
Cl <sup>**</sup> -----	--	--	--	--	--	--	--	--	--	--	--	--
F-----	0.20	0.27	--	0.25	--	0.16	0.11	0.11	--	0.16	--	0.14
F <sup>**</sup> -----	0.19	0.17	0.18	0.25	0.11	0.14	0.12	0.12	0.13	0.13	0.12	0.13
Subtotal-----	99.72	99.51	99.78	100.13	99.88	99.88	100.04	100.05	99.63	99.80	100.02	99.80
Less O=(F,Cl) <sub>2</sub> -----	0.10	0.11	0.08	0.12	0.05	0.08	0.07	0.06	0.05	0.08	0.05	0.08
Total-----	99.62	99.40	99.70	100.01	99.83	99.80	99.97	99.99	99.58	99.72	99.97	99.72
FeO <sup>1</sup> -----	0.94	0.89	0.97	0.80	0.94	0.92	0.93	0.99	0.91	0.92	0.89	0.80
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.59	0.57	0.38	0.52	0.44	0.63	0.68	0.61	0.67	0.30	0.54	0.66
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.09	0.96	1.09	1.07	0.84	0.94	0.94	0.94	1.01	1.03	0.99	1.01
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.96	0.95	0.97	0.96	0.95	0.96	0.96	0.97	1.00	0.95	0.94	0.97
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.01	1.01	1.02	1.01	1.02	1.02	1.02	1.03	1.05	1.00	1.00	1.03
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.05
Cl/F <sup>1†</sup> -----	0.49	0.26	--	0.20	--	0.45	0.68	0.56	--	0.41	--	0.56
CIPW norms												
Q-----	33.81	33.20	33.94	33.08	33.19	32.84	32.86	32.94	33.89	34.56	34.17	33.59
or-----	24.74	26.86	24.82	25.49	28.99	27.23	27.21	27.33	26.25	25.29	25.92	26.05
ab-----	38.58	36.84	38.69	38.88	34.70	36.78	36.75	36.85	37.76	37.24	36.69	37.47
an-----	1.33	1.68	1.04	1.35	1.63	1.36	1.39	0.88	--	1.80	1.89	1.18
C-----	--	(4)	--	--	--	--	--	--	--	--	0.01	--
ac-----	--	--	--	--	--	--	--	--	0.08	--	--	--
ns-----	--	--	--	--	--	--	--	--	--	--	--	--
wo } di-----	0.09	0.09	0.17	0.10	0.22	0.35	0.27	0.49	0.65	--	--	0.38
en } di-----	0.00	0.00	0.05	0.00	0.04	0.03	0.02	0.04	0.05	--	--	0.04
fs } di-----	0.11	0.09	0.13	0.12	0.19	0.36	0.28	0.51	0.67	--	--	0.38
en } hy-----	0.00	0.02	--	0.00	0.01	0.02	0.03	0.02	0.00	--	0.08	0.04
fs } hy-----	0.56	0.49	--	0.32	0.04	0.34	0.58	0.21	0.03	--	0.54	0.33
mt-----	0.59	0.59	0.93	0.58	0.82	0.51	0.45	0.58	0.52	0.81	0.63	0.41
il-----	0.13	0.12	0.12	0.10	0.17	0.17	0.13	0.17	0.12	0.15	0.08	0.13
ap-----	0.07	0.02	0.05	--	--	--	0.02	0.00	0.00	0.00	0.00	0.00

	59	60	61	62	63	64	65	66	67	68	69	70
Trace elements (ppm)												
Ba-----	6.0	--	6.	<2.	--	32.	--	55.	--	--	--	--
Be-----	--	--	--	13.	--	8.9	--	6.5	--	--	--	--
Co-----	0.1	0.2	0.1	0.1	0.2	0.2	0.3	0.2	0.1	0.1	0.1	0.1
Cr-----	<1.1	<1.0	<1.3	<0.5	<1.2	<1.6	0.4	<1.7	<1.3	<1.1	<1.1	<1.1
Cs-----	6.9	7.2	7.2	9.2	6.7	6.5	4.5	4.4	5.8	6.0	6.2	6.3
Hf-----	5.7	5.9	5.9	6.2	5.1	5.3	5.6	5.1	4.9	5.0	4.9	5.1
Li-----	120.	--	--	150.	--	89.	--	76.	--	--	--	--
Mo-----	--	--	--	--	--	--	--	--	--	--	--	--
Nb**-----	--	--	--	--	--	--	--	--	--	--	--	--
Nb***-----	77.	80.	78.	88.	--	57.	52.	49.	53.	47.	50.	51.
Pb-----	31.	39.	33.	36.	21.	31.	23.	26.	36.	28.	29.	30.
Rb-----	295.	302.	312.	353.	285.	258.	205.	201.	222.	229.	232.	236.
Rb***-----	315.	335.	320.	370.	270.	270.	195.	210.	250.	235.	230.	240.
Sb-----	1.2	1.0	1.0	1.3	0.9	1.0	0.8	0.6	0.9	0.9	1.0	1.0
Sc-----	0.97	0.95	1.00	0.87	0.76	0.80	0.90	0.85	0.50	0.51	0.55	0.53
Sn-----	--	--	--	13.	--	9.6	--	6.7	--	--	--	--
Sr-----	3.7	--	2.2	1.4	--	6.8	--	10.2	--	--	--	--
Ta-----	6.97	7.54	7.00	8.99	6.33	5.52	4.29	4.02	5.16	5.43	5.48	5.81
Th-----	34.7	34.7	34.8	42.1	32.5	31.6	26.3	25.3	28.4	29.2	29.0	29.9
U-----	13.4	15.4	11.2	16.7	14.8	9.3	8.1	7.8	12.1	12.9	12.8	13.6
W-----	--	--	--	--	--	--	--	--	--	--	--	--
Y-----	76.	70.	75.	--	--	--	47.	47.	59.	55.	62.	57.
Zn-----	53.	57.	57.	53.	43.	44.	49.	45.	44.	44.	45.	46.
Zr-----	100.	100.	100.	100.	115.	110.	140.	135.	95.	90.	95.	90.
La-----	16.	16.	17.	13.	30.	32.	44.	41.	17.	17.	17.	19.
Ce-----	38.	37.	40.	32.	56.	61.	78.	74.	36.	37.	37.	38.
Nd-----	23.	25.	23.	22.	33.	27.	34.	31.	21.	25.	23.	27.
Sm-----	7.0	6.6	7.0	6.9	5.9	6.2	6.7	6.6	4.8	4.9	4.9	5.0
Eu-----	<0.03	<0.03	0.04	<0.03	0.11	0.09	0.13	0.15	0.07	0.06	0.08	0.08
Gd-----	--	--	--	--	--	--	--	--	--	--	--	--
Tb-----	1.57	1.63	1.58	1.83	1.28	1.20	1.12	1.06	1.06	1.06	1.20	1.11
Tm-----	1.10	1.10	1.11	1.32	0.92	0.80	0.64	0.72	0.75	0.81	0.76	0.82
Yb-----	7.2	7.3	7.4	9.0	5.9	6.1	5.2	4.9	5.5	5.6	5.5	5.7
Lu-----	0.99	0.97	0.98	1.20	0.80	0.82	0.67	0.62	0.72	0.77	0.75	0.77
Nb/Ta-----	11.1	10.6	11.1	9.8	--	10.3	12.1	12.2	10.3	8.7	9.1	8.8
K/Rb-----	109.	112.	108.	96.	150.	141.	195.	182.	146.	150.	158.	151.
Rb/Sr-----	85.1	--	146.	264.	--	39.7	--	20.6	--	--	--	--
Ca/Sr-----	6.8	--	1137.	1634.	--	463.	--	287.	--	--	--	--
Th/U-----	2.6	2.3	3.1	2.5	2.2	3.4	3.3	3.2	2.4	2.3	2.3	2.2
Zr/Hf-----	18.	17.	17.	16.	23.	21.	25.	26.	19.	18.	19.	18.
Ce/Yb-----	5.3	5.1	5.4	3.6	9.5	10.0	15.0	15.1	6.6	6.6	6.7	6.7
Eu/Eu*-----	--	--	0.02	--	0.05	0.04	0.06	0.08	0.04	0.04	0.04	0.05

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	CALIFORNIA					NEVADA					
Volcanic field/region---	Coso Volcanic Field		Salton Sea			Northwest Nevada				West-central Nevada	
Locality-----			Obsidian Butte	Red Island	Mullet Island	Cow Creek	Rocky Canyon	Trinity Range	McGee Mountain	Clayton Ridge	Gilbert District
Specimen-----	71	72	73	74	75	76	77	78	79	80	81
Collection No. (RLS)---	CD-19	CD-21A	49	50	212	21	29	31	74	226	202
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	77.5	76.4	73.8	74.2	75.4	76.16	74.69	74.73	77.1	76.6	77.3
Al <sub>2</sub> O <sub>3</sub> -----	12.57	12.43	12.81	12.95	12.34	12.86	13.46	13.59	12.48	12.69	12.39
Fe <sub>2</sub> O <sub>3</sub> -----	0.26	0.32	0.70	0.74	0.65	0.30	0.40	0.42	0.47	0.38	0.51
FeO-----	0.54	0.50	1.65	1.56	1.34	0.77	0.95	1.01	0.39	0.41	0.20
MgO-----	0.02	<0.02	0.16	0.13	0.03	0.08	0.19	0.04	0.05	0.02	0.05
CaO-----	0.41	0.37	0.85	0.81	0.48	0.67	0.90	0.76	0.37	0.47	0.45
Na <sub>2</sub> O-----	4.25	4.44	4.75	4.72	4.77	3.68	3.86	4.05	4.05	4.00	4.12
K <sub>2</sub> O-----	4.56	4.36	4.10	4.15	4.27	4.85	4.78	4.68	4.61	4.60	4.59
H <sub>2</sub> O+-----	0.17	0.31	0.09	0.08	0.12	0.16	0.25	0.31	0.09	0.31	0.08
TiO <sub>2</sub> -----	0.06	0.05	0.21	0.19	0.11	0.11	0.18	0.03	0.12	0.07	0.09
P <sub>2</sub> O <sub>5</sub> -----	<0.01	<0.01	0.02	0.02	<0.05	0.02	--	--	0.01	<0.005	<0.005
MnO-----	0.020	0.019	0.06	0.05	0.06	0.05	--	--	0.05	0.10	0.07
Cl-----	--	0.08	0.34	0.34	0.35	--	--	--	0.07	0.09	0.07
Cl**-----	--	--	0.31	0.32	0.36	0.05	0.05	0.08	0.06	0.12	0.07
F-----	--	0.14	0.13	0.14	0.15	--	--	--	0.06	0.14	0.06
F**-----	0.12	0.12	0.12	0.12	0.15	0.05	0.04	0.05	0.06	0.13	0.056
Subtotal-----	99.80	99.41	99.66	100.06	100.08	99.81	99.75	99.75	99.92	99.90	99.98
Less O=(F,Cl) <sub>2</sub> -----	0.05	0.08	0.13	0.13	0.14	0.03	0.03	0.04	0.04	0.08	0.04
Total-----	99.75	99.33	99.53	99.93	99.94	99.78	99.72	99.71	99.88	99.82	99.94
FeO <sup>1</sup> -----	0.77	0.79	2.28	2.23	1.93	1.04	1.31	1.39	0.81	0.75	0.66
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.68	0.61	0.70	0.68	0.67	0.72	0.70	0.71	0.45	0.52	0.28
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.93	1.02	1.16	1.14	1.12	0.76	0.81	0.87	0.88	0.87	0.90
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.95	0.97	0.96	0.95	1.01	0.88	0.86	0.86	0.93	0.91	0.95
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.01	1.02	1.08	1.06	1.08	0.97	0.98	0.96	0.99	0.98	1.01
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.05	0.04	0.10	0.09	0.05	0.08	0.10	0.09	0.04	0.05	0.05
Cl/F <sup>1</sup> -----	--	0.61	2.6	2.5	2.4	1.0	1.3	1.6	1.0	0.80	1.3
CIPW norms											
Q-----	34.09	33.35	28.27	28.63	30.15	34.36	31.41	31.13	35.07	34.69	34.91
or-----	26.90	26.05	24.45	24.64	25.37	28.79	28.41	27.85	27.32	27.36	27.19
ab-----	35.89	37.99	40.55	40.13	39.92	31.28	32.86	34.51	34.37	34.07	34.94
an-----	1.75	1.12	1.54	1.90	--	3.21	4.49	3.80	1.78	2.35	1.76
C-----	--	--	--	--	--	0.39	0.30	0.48	0.18	0.28	--
ac-----	--	--	--	--	0.59	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--	--	--
wo } di-----	0.12	0.31	1.08	0.84	1.00	--	--	--	--	--	0.14
en } di-----	0.01	0.00	0.18	0.13	0.04	--	--	--	--	--	0.13
fs } di-----	0.12	0.35	0.99	0.79	1.08	--	--	--	--	--	0.00
en } hy-----	0.04	0.00	0.22	0.20	0.04	0.20	0.48	0.10	0.13	0.05	--
fs } hy-----	0.59	0.27	1.24	1.26	0.95	1.08	1.12	1.47	0.22	0.51	--
mt-----	0.38	0.47	1.02	1.08	0.65	0.44	0.58	0.61	0.68	0.56	0.61
il-----	0.11	0.10	0.40	0.36	0.21	0.21	0.34	0.06	0.23	0.13	0.17
ap-----	0.00	0.00	0.05	0.05	0.00	0.05	0.00	0.00	0.02	0.00	0.00

	71	72	73	74	75	76	77	78	79	80	81
Trace elements (ppm)											
Ba-----	--	12.8	515.	490.	400.	434.	1050.	801.	130.	<50.	23.
Be-----	--	7.9	5.8	5.8	7.1	3.1	2.4	3.1	5.5	7.3	5.3
Co-----	0.1	0.1	1.4	1.4	0.3	0.3	0.7	0.1	0.3	0.1	0.1
Cr-----	<1.2	<1.1	<8.0	<8.0	<2.0	<5.0	<5.0	10.7	1.9	1.9	<2.0
Cs-----	6.1	6.2	4.0	4.0	4.5	8.5	6.6	7.1	7.3	8.8	8.6
Hf-----	5.0	5.1	11.8	11.7	11.9	3.5	4.6	3.2	4.9	4.6	4.3
Li-----	--	92.	60.	61.	81.	56.	46.	38.	44.	170.	56.
Mo-----	--	--	3.2	3.1	3.3	3.0	3.5	2.3	8.1	4.6	5.7
Nb**-----	--	--	28.	29.	37.	14.	12.	12.	27.	36.	35.
Nb***-----	55.	52.	32.	33.	40.	16.	13.	15.	25.	45.	39.
Pb-----	32.	27.	13.	16.	18.	25.	25.	24.	17.	34.	26.
Rb-----	234.	232.	133.	130.	146.	176.	166.	172.	221.	325.	218.
Rb***-----	245.	255.	135.	145.	155.	202.	164.	182.	212.	322.	215.
Sb-----	0.8	0.9	0.6	0.6	0.6	0.4	0.4	0.6	1.2	2.2	<0.9
Sc-----	0.52	0.53	3.1	2.9	2.0	2.8	2.8	1.3	1.6	3.0	1.5
Sn-----	--	8.3	8.3	8.2	12.	2.8	1.9	2.7	3.4	2.9	2.8
Sr-----	--	4.8	25.	25.	7.	54.	127.	97.	18.	<1.	8.
Ta-----	5.83	5.76	2.48	2.38	3.25	1.29	1.13	1.19	2.95	3.83	3.29
Th-----	29.8	29.8	20.8	20.2	22.3	19.1	15.2	13.7	24.9	29.5	31.1
U-----	14.4	14.3	5.7	5.2	7.5	7.9	6.7	5.1	13.2	9.9	10.5
W-----	--	--	1.2	1.3	1.1	1.8	1.4	1.5	3.9	2.8	2.9
Y-----	--	60.	115.	130.	155.	34.	29.	8.	27.	52.	24.
Zn-----	45.	43.	68.	60.	73.	32.	30.	66.	38.	34.	20.
Zr-----	95.	90.	395.	395.	286.	94.	147.	72.	153.	100.	79.
La-----	17.	19.	54.	54.	68.	31.	37.	24.	40.	16.	36.
Ce-----	36.	38.	122.	115.	143.	59.	69.	46.	71.	38.	61.
Nd-----	20.	24.	66.	64.	79.	24.	26.	19.	29.	22.	20.
Sm-----	5.0	5.0	15.0	14.2	18.2	4.7	4.7	4.3	6.6	7.6	3.3
Eu-----	0.07	0.07	1.54	1.43	1.26	0.28	0.50	0.42	0.26	0.05	0.18
Gd-----	--	--	14.1	13.0	19.1	3.6	3.4	2.4	4.6	6.8	4.8
Tb-----	1.11	1.12	2.98	3.00	3.51	0.59	0.59	0.31	0.98	1.17	<0.40
Tm-----	0.86	0.86	1.96	1.81	2.25	0.29	0.35	0.36	0.53	0.62	0.39
Yb-----	5.2	5.3	13.6	12.3	17.2	2.6	2.2	0.2	4.6	4.6	2.8
Lu-----	0.73	0.75	1.87	1.80	2.26	0.37	0.32	<0.08	0.67	0.64	0.43
Nb/Ta-----	9.4	9.0	12.1	13.0	11.9	11.6	11.1	11.3	8.8	10.6	11.3
K/Rb-----	155.	142.	252.	238.	229.	199.	242.	213.	181.	119.	177.
Rb/Sr-----	--	53.1	5.4	5.8	22.1	3.7	1.3	1.9	11.8	--	26.9
Ca/Sr-----	--	551.	243.	232.	490.	89.	51.	56.	147.	--	402.
Th/U-----	2.1	2.1	3.7	3.9	3.0	2.4	2.3	2.7	1.9	3.0	3.0
Zr/Hf-----	19.	18.	34.	34.	24.	27.	32.	23.	31.	26.	18.
Ce/Yb-----	6.9	7.2	9.0	9.4	8.3	22.7	31.4	23.0	15.4	8.3	21.8
Eu/Eu*-----	0.04	0.04	0.32	0.32	0.20	0.21	0.38	0.41	0.15	0.02	0.14

See footnotes at end of table.

APPENDIX I.—*Chemical analyses of subalkalic silicic obsidians*—Continued

Country/State-----	NEVADA	IDAHO						WYOMING		
Volcanic field/region---	Timber Mountain	Snake River Plain			Blackfoot Volcanic Field			Yellowstone Volcanic Field		
Locality-----	Shoshone Mountain	Big Southern Butte	Ammon quadrangle	American Falls	Middle Cone	North Cone	China Hat	Mount Everts	Gibbon River	Summit Lake
Specimen-----	82	83	84	85	86	87	88	89	90	91
Collection No. (RLS)---	14	75	151	152	185	188	191	--	267	268
Chemical analyses (weight percent)										
SiO <sub>2</sub> -----	74.25	75.4	76.1	75.9	75.9	76.2	76.5	75.83	76.59	76.51
Al <sub>2</sub> O <sub>3</sub> -----	13.50	12.38	12.18	12.10	12.53	12.47	12.51	12.42	12.25	12.05
Fe <sub>2</sub> O <sub>3</sub> -----	0.44	0.58	0.45	0.47	0.40	0.44	0.39	0.94	0.50	0.47
FeO-----	0.86	1.04	1.30	0.79	0.50	0.47	0.51	0.63	0.72	1.11
MgO-----	0.18	<0.005	0.07	0.09	0.02	0.02	0.02	0.00	0.00	0.01
CaO-----	0.68	0.48	0.54	0.52	0.54	0.53	0.52	0.52	0.38	0.42
Na <sub>2</sub> O-----	4.00	4.29	3.54	3.46	4.20	4.16	4.12	3.70	4.01	3.65
K <sub>2</sub> O-----	5.33	4.61	5.03	5.12	4.51	4.34	4.53	5.08	4.78	5.10
H <sub>2</sub> O+-----	0.26	0.14	0.11	0.04	0.39	0.31	0.23	0.25	0.17	0.23
TiO <sub>2</sub> -----	0.22	0.09	0.23	0.23	0.06	0.06	0.06	0.10	0.07	0.13
P <sub>2</sub> O <sub>5</sub> -----	0.03	<0.005	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.01
MnO-----	0.04	0.04	0.05	0.05	0.07	0.06	0.07	0.04	0.03	0.04
Cl*-----	--	0.18	0.08	0.09	0.14	0.14	0.14	--	--	--
Cl**-----	0.05	0.22	0.07	0.09	0.14	0.14	0.15	0.06	0.11	0.08
F-----	--	0.30	0.12	0.13	0.32	0.32	0.34	--	--	--
F**-----	--	0.33	0.12	0.13	0.35	0.34	0.34	0.15	0.26	0.18
Subtotal-----	99.84	99.57	99.82	99.00	99.61	99.54	99.96	99.72	99.88	99.99
Less O=(F,Cl) <sub>2</sub> -----	0.01	0.18	0.07	0.07	0.19	0.17	0.18	0.08	0.13	0.09
Total-----	99.83	99.39	99.75	98.93	99.42	99.37	99.78	99.64	99.75	99.90
FeO <sup>1</sup> -----	1.26	1.56	1.71	1.21	0.86	0.87	0.86	1.48	1.17	1.53
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.66	0.64	0.74	0.63	0.56	0.52	0.57	0.40	0.59	0.70
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.75	0.93	0.70	0.68	0.93	0.96	0.91	0.73	0.84	0.72
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.91	0.97	0.92	0.93	0.94	0.93	0.93	0.93	0.96	0.96
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.01	1.04	1.01	1.01	1.02	1.00	1.01	1.01	1.02	1.02
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.07	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.04	0.05
Cl/F <sup>1†</sup> -----	--	0.63	0.61	0.72	0.42	0.42	0.42	0.40	0.42	0.44
CIPW norms										
Q-----	28.67	31.82	34.45	35.08	33.32	34.46	34.10	33.94	34.14	34.49
or-----	31.65	27.54	29.87	30.64	26.99	25.97	26.97	30.24	28.43	30.29
ab-----	34.01	36.70	30.10	29.65	35.99	35.64	35.13	31.54	34.16	31.04
an-----	3.16	0.92	2.50	2.39	2.04	2.57	2.28	2.30	1.32	1.44
C-----	--	--	--	--	--	--	--	--	--	--
ac-----	--	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--	--
wo }-----	0.02	0.62	0.03	0.06	0.25	0.01	0.11	0.13	0.22	0.25
en } di-----	0.01	0.00	0.00	0.02	0.02	0.01	0.01	0.00	0.00	0.00
fs }-----	0.01	0.71	0.03	0.05	0.26	0.01	0.11	0.14	0.24	0.27
en } hy-----	0.45	0.00	0.17	0.21	0.03	0.05	0.04	0.00	0.00	0.02
fs }-----	0.92	0.67	1.71	0.73	0.37	0.51	0.54	0.15	0.61	1.25
mt-----	0.64	0.85	0.66	0.69	0.59	0.65	0.57	1.37	0.73	0.69
il-----	0.42	0.17	0.44	0.44	0.12	0.12	0.12	0.19	0.13	0.25
ap-----	0.07	0.00	0.05	0.02	0.02	0.02	0.02	0.00	0.02	0.02

	82	83	84	85	86	87	88	89	90	91
Trace elements (ppm)										
Ba-----	651.	<50.	970.	975.	9.	3.	2.	--	21.	67.
Be-----	3.9	23.	3.9	3.6	15.	13.	14.	--	--	--
Co-----	0.9	<0.4	0.6	0.6	0.2	<0.4	<0.4	0.2	0.2	0.3
Cr-----	1.9	<7.0	<4.0	2.0	<2.0	<3.0	<3.0	<20.0	<5.0	<7.0
Cs-----	4.6	4.4	3.1	4.0	18.6	17.4	19.1	4.0	6.8	4.1
Hf-----	5.7	14.5	10.6	7.5	6.6	6.1	6.5	8.3	8.4	9.3
Li-----	54.	99.	34.	35.	100.	97.	98.	--	--	--
Mo-----	3.5	4.1	4.8	4.8	2.8	2.9	3.0	--	--	--
Nb**-----	26.	270.	51.	48.	90.	82.	77.	--	54.	58.
Nb***-----	32.	305.	63.	52.	94.	82.	81.	--	67.	71.
Pb-----	27.	101.	32.	26.	40.	42.	33.	--	41.	32.
Rb-----	186.	296.	175.	197.	473.	458.	491.	228.	295.	206.
Rb***-----	206.	299.	175.	195.	460.	455.	440.	--	300.	214.
Sb-----	0.4	0.5	0.2	0.4	0.5	0.3	<0.9	<3.	0.4	<2.0
Sc-----	2.4	0.12	3.0	1.9	2.2	2.1	2.3	1.6	0.91	1.3
Sn-----	3.5	18.	5.7	4.7	16.	16.	16.	--	--	--
Sr-----	90.	<5.	18.	20.	0.3	0.7	0.6	--	1.5	1.8
Ta-----	2.32	21.68	3.87	3.31	10.9	9.94	11.10	4.87	5.07	4.90
Th-----	28.2	20.7	25.2	25.9	49.1	50.1	52.7	32.2	36.2	28.8
U-----	5.8	11.0	6.7	6.9	35.1	33.6	35.0	8.6	10.0	7.9
W-----	2.6	4.7	2.5	3.4	4.8	4.3	5.0	--	--	--
Y-----	33.	245.	69.	59.	173.	177.	175.	--	110.	93.
Zn-----	29.	282.	65.	54.	51.	50.	48.	--	99.	101.
Zr-----	211.	338.	330.	224.	106.	110.	104.	--	165.	270.
La-----	61.	72.	84.	76.	17.	15.	21.	94.	43.	92.
Ce-----	99.	132.	159.	147.	45.	43.	59.	179.	96.	176.
Nd-----	35.	51.	60.	53.	30.	28.	35.	71.	44.	66.
Sm-----	6.0	15.6	13.1	9.6	10.1	9.6	10.3	15.9	13.3	15.8
Eu-----	0.53	0.27	0.98	0.97	0.04	0.04	0.03	0.61	0.07	0.46
Gd-----	4.6	16.6	10.1	10.3	13.9	16.1	14.9	13.2	11.4	12.0
Tb-----	0.62	4.26	2.17	1.85	2.56	2.40	2.61	2.44	2.76	2.39
Tm-----	0.34	3.22	0.83	0.91	2.40	2.41	2.55	1.16	1.36	1.34
Yb-----	2.6	23.6	6.1	6.0	17.4	16.9	17.8	8.0	9.1	8.0
Lu-----	0.40	3.04	0.85	0.80	2.41	2.29	2.48	1.07	1.20	1.05
Nb/Ta-----	12.5	13.3	14.7	15.1	8.4	8.3	7.1	--	11.9	13.2
K/Rb-----	215.	128.	239.	218.	81.	79.	85.	185.	135.	205.
Rb/Sr-----	22.9	--	9.7	9.8	1533.	650.	733.	--	200.	119.
Ca/Sr-----	54.	--	214.	186.	12863.	5411.	6193.	--	1811.	1668.
Th/U-----	4.9	1.9	3.8	3.8	1.4	1.5	1.5	3.7	3.6	3.7
Zr/Hf-----	37.	23.	31.	30.	16.	18.	16.	--	20.	29.
Ce/Yb-----	38.1	5.6	26.1	24.5	2.6	2.5	3.3	22.4	10.6	22.0
Eu/Eu*-----	0.31	0.05	0.26	0.30	0.01	0.01	0.01	0.13	0.02	0.10

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	WYOMING			UTAH							
Volcanic field/region---	Yellowstone Volcanic Field			Twin Peaks Volcanic Field					Mineral Mountains		
Locality-----	Elephant Back	Crystal Spring	Obsidian Cliff	Wildcat Hills	White Mountain	Rhyolite of Cudahy Mine			Bailey Ridge		North dome
Specimen-----	92	93	94	95	96	97	98	99	100	101	102
Collection No. (RLS-)---	269	270	271	106	116	103	104	105	136	137	138
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	76.14	76.39	76.71	76.9	73.2	76.3	76.0	75.9	77.0	77.0	76.5
Al <sub>2</sub> O <sub>3</sub> -----	12.18	12.30	12.29	12.26	13.36	13.09	13.09	12.96	12.56	12.62	12.70
Fe <sub>2</sub> O <sub>3</sub> -----	0.44	0.44	0.41	0.33	0.44	0.29	0.32	0.33	0.42	0.41	0.42
FeO-----	0.99	0.83	0.81	0.67	1.31	0.58	0.55	0.56	0.34	0.35	0.19
MgO-----	0.00	0.06	0.01	0.05	0.44	0.03	0.02	0.02	0.07	0.07	0.02
CaO-----	0.44	0.34	0.42	0.57	1.32	0.78	0.79	0.79	0.54	0.56	0.38
Na <sub>2</sub> O-----	3.46	3.79	3.87	3.19	4.07	3.83	3.84	3.86	3.60	3.59	4.32
K <sub>2</sub> O-----	5.27	4.88	4.91	5.27	4.35	4.75	4.76	4.71	5.00	5.01	4.48
H <sub>2</sub> O+-----	0.33	0.19	0.15	0.10	0.01	0.13	0.16	0.09	0.10	0.18	0.39
TiO <sub>2</sub> -----	0.16	0.09	0.08	0.11	0.15	0.06	0.06	0.06	0.14	0.14	0.07
P <sub>2</sub> O <sub>5</sub> -----	0.01	0.01	0.01	0.01	0.03	<0.005	<0.005	<0.005	0.01	0.01	0.01
MnO-----	0.04	0.03	0.03	0.03	0.08	0.06	0.06	0.06	0.05	0.05	0.10
Cl*-----	--	--	--	0.06	0.16	0.10	0.10	0.10	0.06	0.06	0.08
Cl**-----	0.08	0.10	0.09	--	--	--	--	--	0.07	0.08	0.08
F*-----	--	--	--	0.16	0.48	0.22	0.24	0.23	0.11	0.10	0.38
F**-----	0.15	0.18	0.19	--	--	--	--	--	0.11	0.12	0.42
Subtotal-----	99.69	99.63	99.98	99.71	99.40	100.22	99.98	99.67	100.01	100.17	100.06
Less O=(F,Cl) <sub>2</sub> -----	0.08	0.10	0.10	0.08	0.24	0.12	0.12	0.12	0.06	0.06	0.19
Total-----	99.61	99.53	99.88	99.63	99.16	100.10	99.86	99.55	99.95	100.11	99.87
FeO <sup>1</sup> -----	1.39	1.23	1.18	0.96	1.71	0.84	0.84	0.86	0.72	0.72	0.57
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.69	0.65	0.66	0.67	0.75	0.67	0.63	0.63	0.45	0.46	0.31
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.66	0.78	0.79	0.61	0.94	0.81	0.81	0.82	0.72	0.72	0.96
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.93	0.94	0.95	0.89	0.85	0.87	0.88	0.88	0.90	0.90	0.94
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.00	0.99	1.01	0.98	1.03	0.98	0.98	0.99	0.98	0.98	1.00
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.05	0.04	0.05	0.07	0.16	0.09	0.09	0.09	0.06	0.07	0.04
Cl/F <sup>1†</sup> -----	0.53	0.56	0.47	0.36	0.34	0.44	0.41	0.44	0.59	0.61	0.20
CIPW norms											
Q-----	34.66	34.69	34.27	36.76	29.08	33.88	33.58	33.60	35.73	35.66	33.65
or-----	31.42	29.08	29.15	31.33	26.01	28.15	28.28	28.04	29.63	29.66	26.69
ab-----	29.54	32.34	32.90	27.16	34.85	32.50	32.66	32.91	30.55	30.44	36.85
an-----	2.14	1.64	1.67	2.78	5.40	3.88	3.89	3.95	2.62	2.72	1.84
C-----	0.01	0.19	--	0.30	--	0.23	0.20	0.08	0.27	0.30	0.08
ac-----	--	--	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--	--	--
wo } di-----	--	--	0.15	--	0.58	--	--	--	--	--	--
en } di-----	--	--	0.00	--	0.21	--	--	--	--	--	--
fs } di-----	--	--	0.17	--	0.38	--	--	--	--	--	--
en } hy-----	0.00	0.15	0.02	0.13	0.90	0.08	0.05	0.05	0.18	0.18	0.05
fs } hy-----	1.28	1.08	0.91	0.84	1.59	0.75	0.76	0.77	0.14	0.17	0.07
mt-----	0.64	0.64	0.60	0.48	0.65	0.42	0.47	0.48	0.61	0.60	0.61
il-----	0.31	0.17	0.15	0.21	0.29	0.11	0.12	0.12	0.27	0.27	0.13
ap-----	0.02	0.02	0.02	0.02	0.07	0.00	0.00	0.00	0.02	0.02	0.02



	92	93	94	95	96	97	98	99	100	101	102
Trace elements (ppm)											
Ba-----	240.	38.	34.	105.	<50.	<50.	<50.	<50.	165.	180.	<50.
Be-----	--	--	--	5.3	7.0	4.9	4.6	4.6	4.2	4.0	9.6
Co-----	0.4	0.6	0.3	0.5	2.9	0.2	0.2	0.2	0.3	0.3	0.1
Cr-----	<8.0	<9.0	13.	<4.0	9.0	<4.0	<3.0	<3.0	<4.0	<4.0	<4.0
Cs-----	4.2	4.7	5.3	4.1	5.2	4.7	4.8	4.7	3.5	3.4	7.0
Hf-----	8.6	7.2	7.6	4.9	6.0	4.7	4.6	4.6	4.1	4.1	5.6
Li-----	--	--	--	52.	78.	66.	67.	67.	61.	57.	110.
Mo-----	--	--	--	4.6	2.1	2.8	2.5	2.8	4.3	4.5	5.9
Nb-----	51.	42.	44.	29.	36.	34.	37.	36.	26.	25.	54.
Nb***-----	60.	51.	54.	36.	35.	--	--	--	30.	30.	56.
Pb-----	34.	39.	39.	50.	48.	55.	52.	44.	25.	26.	29.
Rb-----	191.	199.	222	240.	291.	267.	263.	274.	195.	187.	346.
Rb***-----	203.	254.	259.	243.	284.	268.	278.	261.	200.	205.	360.
Sb-----	0.5	0.4	0.6	0.2	0.3	0.3	0.3	0.2	0.1	<0.3	0.3
Sc-----	2.3	1.3	1.1	1.7	2.6	1.8	1.8	1.8	2.3	2.2	3.6
Sn-----	--	--	--	5.8	8.7	4.7	4.9	4.7	1.7	1.7	3.6
Sr-----	11.	3.3	1.1	12.	20.	8.	<5.	7.	37.	40.	<5.
Ta-----	4.55	3.45	3.7	3.47	3.97	2.92	3.00	2.90	2.04	1.97	3.57
Th-----	30.1	29.6	26.4	45.6	33.6	27.9	27.9	27.7	22.1	21.7	39.3
U-----	7.9	6.4	7.3	8.9	10.9	7.1	7.2	7.1	6.2	6.2	11.6
W-----	--	--	--	3.2	4.4	3.9	3.5	3.6	2.4	1.9	3.6
Y-----	74.	89.	92.	55.	115.	48.	41.	48.	21.	18.	32.
Zn-----	63.	83.	83.	27.	70.	39.	40.	33.	24.	35.	50.
Zr-----	233.	175.	177.	128.	126.	100.	100.	102.	100.	97.	88.
La-----	95.	61.	56.8	69.	18.	12.	12.	12.	47.	47.	29.
Ce-----	185.	120.	118.0	125.	46.	34.	32.	33.	83.	82.	49.
Nd-----	70.	45.	56.9	44.	24.	20.	20.	18.	23.	23.	11.
Sm-----	14.9	12.1	12.3	9.4	8.3	6.2	6.2	6.2	4.1	4.0	1.5
Eu-----	0.70	0.16	0.18	0.28	0.31	0.20	0.20	0.20	0.33	0.33	0.02
Gd-----	11.2	9.7	9.3	7.9	8.1	6.2	5.2	5.6	3.4	2.6	<2.0
Tb-----	2.15	2.13	1.8	1.53	1.82	1.12	1.13	1.12	0.43	0.44	<0.20
Tm-----	1.27	1.24	0.9	1.13	2.05	0.99	1.08	1.05	0.36	0.35	0.42
Yb-----	6.6	6.7	7.1	7.9	12.8	7.6	7.5	7.6	2.5	2.5	3.8
Lu-----	0.91	0.94	0.91	1.10	2.07	1.05	1.07	1.07	0.42	0.42	0.70
Nb/Ta-----	12.4	13.5	13.2	9.4	8.9	11.6	12.3	12.4	13.7	14.0	15.4
K/Rb-----	229.	203.	177.	180.	127.	147.	142.	150.	208.	203.	103.
Rb/Sr-----	18.1	77.0	202.	20.3	14.2	33.5	--	37.3	5.4	5.1	--
Ca/Sr-----	281.	736.	2729.	340.	472.	697.	--	807.	104.	100.	--
Th/U-----	3.8	4.6	3.6	5.1	3.1	3.9	3.9	3.9	3.6	3.5	3.4
Zr/Hf-----	27.	24.	36.	26.	21.	21.	22.	22.	24.	24.	16.
Ce/Yb-----	28.0	17.9	16.6	15.8	3.6	4.5	4.3	4.3	33.2	32.8	12.9
Eu/Eu*-----	0.17	0.05	0.05	0.10	0.12	0.10	0.11	0.10	0.27	0.31	0.04

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	UTAH	COLORADO		ARIZONA				NEW MEXICO	
Volcanic field/region---	Mineral Mountains	Nathrop Field	San Juan Mountains	Superior	San Francisco Mountains			Taos Plateau	
Locality-----	Wildhorse Canyon	Bald Mountain	Beaver Creek	Queen Creek	Government Mountain	Sitgreaves southeast	R.S. Hill	Cerros	No Agua
Specimen-----	103	104	105	106	107	108	109	110	111
Collection No. (RLS)---	139	33	65L-161-A	35	48	53	47	27	66L-23-A

## Chemical analyses (weight percent)

SiO <sub>2</sub> -----	76.6	76.57	76.2	76.66	75.1	75.1	75.2	75.6	76.35
Al <sub>2</sub> O <sub>3</sub> -----	12.51	12.78	13.1	12.68	13.86	13.39	13.29	13.26	12.34
Fe <sub>2</sub> O <sub>3</sub> -----	0.39	0.35	0.32	0.35	0.36	0.51	0.51	0.36	0.47
FeO-----	0.36	0.33	0.44	0.36	0.55	0.48	0.51	0.28	0.60
MgO-----	0.07	0.05	0.15	0.09	0.03	<0.005	<0.005	0.05	0.03
CaO-----	0.54	0.45	0.69	0.48	0.77	0.39	0.36	0.67	0.38
Na <sub>2</sub> O-----	3.55	4.31	4.1	4.05	4.48	4.65	5.07	4.17	4.29
K <sub>2</sub> O-----	4.83	4.54	4.8	4.61	4.23	4.63	4.14	4.56	4.39
H <sub>2</sub> O+-----	0.11	0.22	0.16	0.11	0.17	0.08	0.02	0.15	0.91
TiO <sub>2</sub> -----	0.14	0.08	0.11	0.11	0.02	0.02	0.02	0.06	0.09
P <sub>2</sub> O <sub>5</sub> -----	0.01	0.00	0.02	0.01	0.01	0.005	0.005	<0.005	0.02
MnO-----	0.05	0.10	0.14	0.08	0.08	0.06	0.06	0.09	0.06
Cl*-----	0.07	--	--	--	0.06	0.04	0.04	0.08	--
Cl**-----	0.07	0.070	0.09	0.07	0.04	0.04	0.03	--	0.06
F*-----	0.11	--	--	--	0.08	0.42	0.41	0.09	--
F**-----	0.12	0.180	0.13	0.05	0.07	0.44	0.43	--	0.19
Subtotal-----	99.35	100.03	100.45	99.71	99.79	99.78	99.64	99.41	100.18
Less O=(F,Cl) <sub>2</sub> -----	0.06	0.09	0.08	0.04	0.04	0.19	0.08	0.06	0.09
Total-----	99.29	99.94	100.37	99.67	99.75	99.59	99.46	99.35	100.09
FeO <sub>t</sub> -----	0.71	0.65	0.73	0.68	0.87	0.94	0.97	0.60	1.02
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.48	0.48	0.58	0.51	0.60	0.48	0.50	0.44	0.56
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.74	0.95	0.85	0.88	1.06	1.00	1.23	0.91	0.98
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.89	0.94	0.91	0.92	0.86	0.95	0.96	0.89	0.96
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.96	1.00	1.01	0.99	0.96	1.00	1.01	0.98	1.01
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.06	0.05	0.08	0.06	0.09	0.04	0.04	0.08	0.04
Cl/F <sup>1†</sup> -----	0.61	0.39	0.69	1.4	0.68	0.09	0.09	0.87	0.32

## CIPW norms

Q-----	36.49	33.09	32.06	34.35	30.97	29.51	29.19	32.55	33.88
or-----	28.82	26.95	28.35	27.38	25.12	27.57	24.67	27.19	26.20
ab-----	30.33	36.63	34.67	34.45	38.10	39.65	43.26	35.61	36.66
an-----	2.64	2.13	3.16	2.33	3.77	1.88	1.29	3.35	1.46
C-----	0.49	--	--	0.18	0.54	0.00	--	0.25	--
ac-----	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--
wo }-----	--	0.05	0.05	--	--	--	0.19	--	0.13
en } di-----	--	0.01	0.02	--	--	--	0.00	--	0.01
fs }-----	--	0.04	0.03	--	--	--	0.21	--	0.13
en } hy-----	0.18	0.11	0.35	0.23	0.08	0.00	0.00	0.13	0.06
fs }-----	0.20	0.33	0.59	0.34	0.83	0.54	0.39	0.29	0.56
mt-----	0.57	0.51	0.46	0.51	0.53	0.75	0.75	0.53	0.69
il-----	0.27	0.15	0.21	0.21	0.04	0.04	0.04	0.12	0.17
ap-----	0.02	0.00	0.05	0.02	0.02	0.02	0.02	0.00	0.05

	103	104	105	106	107	108	109	110	111
Trace elements (ppm)									
Ba-----	190.	<50.	18.	193.	295.	4.	5.	130.	1.
Be-----	4.0	7.6	6.	2.8	4.6	20.	21.	--	9.
Co-----	0.3	0.1	0.2	0.1	0.2	<0.4	<0.4	0.2	0.09
Cr-----	<4.0	<6.0	12.	<4.0	<4.0	<5.0	<4.0	1.1	9.
Cs-----	3.5	7.2	7.8	2.0	2.4	8.6	9.3	2.1	6.8
Hf-----	4.2	4.0	4.8	3.2	3.4	8.6	9.5	3.3	5.9
Li-----	55.	90.	77.	36.	73.	550.	200.	--	133.
Mo-----	4.6	3.3	9.	2.3	2.4	1.4	1.4	--	3.
Nb**-----	26.	49.	50.	27.	44.	224.	240.	32.	110.
Nb***-----	23.	--	--	36.	45.	258.	252.	39.	--
Pb-----	23.	27.	19.	24.	34.	87.	82.	22.	50.
Rb**-----	181.	318.	225.	141.	118.	351.	389.	140.	280.
Rb***-----	200.	332.	--	129.	103.	392.	367.	135.	--
Sb-----	<0.4	0.5	1.1	0.2	0.7	1.4	1.9	0.4	1.1
Sc-----	2.2	3.9	1.5	2.8	1.4	0.26	0.30	3.0	7.69
Sn-----	1.8	3.6	--	1.5	3.5	15.0	11.0	--	--
Sr-----	40.	<5.0	8.7	15.	75.	1.0	1.0	35.	2.5
Ta-----	1.98	4.93	3.4	2.13	5.69	22.39	29.41	3.05	8.1
Th-----	23.3	37.7	22.8	13.7	10.3	41.4	47.2	10.2	24.3
U-----	6.2	18.0	10.8	3.6	5.2	12.9	17.1	3.5	8.3
W-----	1.5	2.2	--	1.6	2.3	2.1	1.5	--	--
Y-----	20.	36.	--	32.	14.	102.	105.	28.	--
Zn-----	22.	42.	--	35.	50.	147.	140.	30.	--
Zr-----	98.	61.	207.	80.	78.	163.	163.	58.	190.
La-----	46.	19.	33.5	29.	10.	9.	10.	13.	10.6
Ce-----	82.	45.	52.5	59.	18.	20.	24.	26.	27.6
Nd-----	22.	19.	19.3	22.	7.	13.	16.	12.	18.9
Sm-----	3.8	5.8	2.7	5.1	2.7	5.3	6.9	2.6	5.9
Eu-----	0.35	0.14	0.20	0.47	0.30	0.02	0.02	0.34	0.14
Gd-----	3.7	4.2	2.2	3.6	2.6	6.7	8.2	3.0	4.6
Tb-----	0.44	0.76	0.3	0.68	0.50	1.51	1.72	0.48	1.2
Tm-----	0.34	0.91	1.2	0.32	<0.20	<0.30	<0.40	0.30	0.7
Yb-----	2.6	2.7	1.1	2.4	1.7	8.3	9.2	2.5	6.0
Lu-----	0.43	0.48	0.15	0.34	0.24	1.16	1.28	0.39	0.67
Nb/Ta-----	12.4	9.9	14.7	14.8	7.8	10.8	8.4	11.6	13.6
K/Rb-----	200.	114.	171.	297.	341.	98.	94.	280.	126.
Rb/Sr-----	5.0	--	25.9	8.6	1.4	392.	367.	3.9	112.
Ca/Sr-----	97.	--	567.	229.	73.	2187.	2573.	137.	1086.
Th/U-----	3.8	2.1	2.1	3.8	2.0	3.2	2.8	2.9	2.9
Zr/Hf-----	23.	15.	43.	25.	23.	19.	17.	18.	32.
Ce/Yb-----	31.5	16.7	47.7	24.6	10.6	2.4	2.6	10.4	4.6
Eu/Eu*-----	0.29	0.09	0.25	0.34	0.35	0.01	0.01	0.37	0.08

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	NEW MEXICO										
Volcanic field/region---	Jemez Mountains Volcanic Field										Southwest New Mexico
Locality-----	Canovas Canyon Rhyolite		El Rechuelos Rhyolite			Cerro Toledo Rhyolite		Valles Rhyolite			Big Lue Mountains
Specimen-----	112	113	114	115	116	117	118	119	120	121	122
Collection No. (RLS-)---	200	15	25	73	194	17	72	76-61	Posos	76-79	102
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	76.4	76.36	76.74	77.0	76.9	76.37	76.6	75.68	76.49	73.16	76.6
Al <sub>2</sub> O <sub>3</sub> -----	12.74	12.67	12.73	12.77	12.82	12.14	12.12	12.78	12.59	13.42	12.69
Fe <sub>2</sub> O <sub>3</sub> -----	0.39	0.33	0.33	0.29	0.24	0.50	0.50	0.50	0.45	0.99	0.35
FeO-----	0.30	0.43	0.38	0.24	0.32	0.64	0.53	0.54	0.64	0.99	0.58
MgO-----	0.06	0.09	0.07	0.05	0.05	0.04	0.02	0.05	0.06	0.66	0.04
CaO-----	0.43	0.47	0.45	0.47	0.42	0.26	0.31	0.37	0.31	1.61	0.58
Na <sub>2</sub> O-----	4.31	3.56	3.85	3.91	4.23	4.39	4.30	4.38	4.34	3.92	3.80
K <sub>2</sub> O-----	4.55	5.40	4.94	4.71	4.49	4.41	4.34	4.73	4.59	4.20	4.73
H <sub>2</sub> O+-----	0.18	0.23	0.14	0.23	0.14	0.61	0.32	0.30	0.14	0.30	0.09
TiO <sub>2</sub> -----	0.11	0.10	0.08	0.08	0.07	0.07	0.08	0.13	0.10	0.30	0.07
P <sub>2</sub> O <sub>5</sub> -----	0.01	0.01	0.01	0.01	0.01	0.00	<0.005	<0.01	0.01	0.09	0.01
MnO-----	0.07	0.06	0.07	0.06	0.07	0.08	0.06	0.06	0.06	0.06	0.06
Cl*-----	0.06	--	--	0.06	0.04	--	0.15	--	--	--	0.06
Cl**-----	0.06	0.07	0.07	0.04	0.04	0.17	0.13	0.10	--	--	--
F*-----	0.03	--	--	0.03	0.05	--	0.13	--	--	--	0.05
F**-----	0.03	0.03	0.03	0.03	0.05	0.14	--	0.09	--	--	--
Subtotal-----	99.64	99.81	99.89	99.90	99.85	99.82	99.45	99.71	99.78	99.70	99.71
Less O=(F,Cl) <sub>2</sub> -----	0.03	0.03	0.03	0.03	0.03	0.10	0.09	0.06	--	--	0.04
Total-----	99.61	99.78	99.86	99.57	99.82	99.72	99.36	99.65	99.78	99.70	99.67
FeO <sub>T</sub> -----	0.65	0.73	0.68	0.50	0.54	1.09	0.98	0.99	1.05	1.88	0.89
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.43	0.57	0.54	0.45	0.57	0.56	0.51	0.52	0.59	0.50	0.62
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.95	0.66	0.78	0.83	0.94	1.00	0.99	0.93	0.95	0.93	0.80
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.94	0.92	0.92	0.90	0.92	0.99	0.97	0.97	0.96	0.82	0.90
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.99	0.99	0.98	0.97	0.98	1.03	1.02	1.02	1.01	1.04	0.98
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.05	0.05	0.05	0.05	0.05	0.03	0.04	0.04	0.03	0.20	0.07
Cl/F <sup>1†</sup> -----	2.3	2.3	2.3	1.5	0.85	1.2	1.1	1.1	--	--	1.1
CIPW norms											
Q-----	33.08	33.84	34.39	35.24	34.11	33.54	34.56	31.39	32.77	30.18	34.94
or-----	27.06	32.08	29.32	27.95	26.63	26.35	25.94	28.17	27.22	24.97	28.10
ab-----	36.70	30.28	32.72	33.22	35.93	37.56	36.81	37.35	36.86	33.37	32.33
an-----	1.99	2.28	2.24	2.28	2.03	0.40	0.96	1.25	1.32	6.66	2.83
C-----	--	0.14	0.23	0.41	0.26	--	--	--	--	--	0.29
ac-----	--	--	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--	--	--
wo }-----	0.04	--	--	--	--	0.38	0.25	0.25	0.07	0.33	--
en } di-----	0.02	--	--	--	--	0.05	0.02	0.06	0.01	0.22	--
fs }-----	0.02	--	--	--	--	0.37	0.25	0.21	0.06	0.08	--
en } hy-----	0.13	0.23	0.18	0.13	0.13	0.06	0.03	0.07	0.14	1.43	0.10
fs }-----	0.16	0.47	0.29	0.18	0.41	0.44	0.30	0.27	0.69	0.54	0.82
mt-----	0.57	0.48	0.48	0.42	0.35	0.73	0.73	0.73	0.66	1.44	0.44
il-----	0.21	0.19	0.15	0.15	0.13	0.13	0.15	0.25	0.19	0.57	0.13
ap-----	0.02	0.02	0.00	0.02	0.02	0.00	0.00	0.00	0.02	0.21	0.02

	112	113	114	115	116	117	118	119	120	121	122
Trace elements (ppm)											
Ba-----	337.	330.	8.0	<50.	11.0	<50.	<50.	34.	42.	586.	85.
Be-----	3.8	3.7	3.4	3.7	3.3	6.9	7.6	3.5	--	3.4	4.0
Co-----	0.2	0.2	0.1	<0.3	0.1	0.1	<0.3	0.2	0.3	3.7	0.3
Cr-----	<2.0	<4.0	<5.0	1.7	<3.0	<5.0	<5.0	1.0	4.0	13.2	<4.0
Cs-----	4.0	4.0	4.6	4.1	4.5	5.4	6.2	4.5	5.0	4.5	7.2
Hf-----	3.3	3.3	3.0	3.0	2.9	7.4	7.2	6.6	6.2	4.8	4.3
Li-----	45.	45.	66.	84.	63.	64.	61.	44.	--	57.	52.
Mo-----	5.7	5.2	3.9	3.3	4.4	9.9	8.9	5.9	--	4.1	3.2
Nb**-----	53.	51.	40.	40.	45.	96.	87.	58.	--	39.	32.
Nb***-----	54.	59.	54.	43.	47.	107.	96.	60.	59.	43.	32.
Pb-----	25.	22.	23.	41.	24.	29.	46.	29.	31.	21.	39.
Rb**-----	109.	117.	157.	153.	152.	189.	202.	140.	155.	151.	228.
Rb***-----	120.	118.	156.	152.	155.	206.	206.	150.	163.	151.	240.
Sb-----	<0.7	<2.0	0.3	<0.7	<0.8	0.4	<0.8	0.3	0.3	0.3	0.5
Sc-----	1.9	2.0	2.9	2.7	2.8	1.0	1.1	1.7	1.5	3.71	2.2
Sn-----	1.8	1.3	1.6	1.5	2.0	5.3	5.0	2.0	--	5.6	3.3
Sr-----	35.	34.	5.	<5.	4.	<5.	<5.	3.2	4.7	202.	10.
Ta-----	4.78	4.70	5.00	5.08	4.85	6.74	7.85	3.75	3.92	3.55	2.95
Th-----	23.2	24.5	18.3	17.0	17.5	22.9	23.7	17.3	17.7	21.1	31.3
U-----	8.3	8.0	9.9	10.8	8.5	7.5	10.3	5.5	6.8	6.9	6.6
W-----	2.3	1.6	1.9	2.3	2.5	6.6	6.0	2.9	--	3.0	2.6
Y-----	27.	31.	29.	17.	28.	82.	60.	48.	49.	31.	31.
Zn-----	23.	20.	23.	20.	18.	86.	94.	58.	61.	22.	36.
Zr-----	88.	85.	55.	67.	52.	152.	202.	187.	171.	135.	111.
La-----	31.	30.	18.	19.	18.	34.	36.	48.	53.	39.	30.
Ce-----	52.	54.	39.	37.	37.	71.	71.	93.	92.	69.	59.
Nd-----	17.	17.	15.	16.	16.	27.	30.	33.	41.	25.	28.
Sm-----	3.2	3.5	3.7	3.8	3.3	7.6	8.3	7.3	7.8	4.1	5.9
Eu-----	0.36	0.38	0.18	0.16	0.16	<0.30	0.05	0.26	0.23	0.47	0.20
Gd-----	<3.0	2.9	3.5	2.8	3.0	6.4	7.6	5.5	9.4	4.1	<4.0
Tb-----	<0.30	0.45	0.59	0.56	<0.40	1.54	1.58	1.07	1.18	0.67	0.98
Tm-----	<0.30	<0.20	0.91	0.29	<0.30	0.55	0.92	0.65	0.77	0.56	0.67
Yb-----	2.2	2.4	2.1	2.2	2.2	6.6	6.2	4.3	4.8	3.4	4.9
Lu-----	0.33	0.35	0.32	0.31	0.32	0.87	0.90	0.59	0.65	0.49	0.70
Nb/Ta-----	11.2	11.7	9.4	8.2	9.5	15.1	11.7	15.7	15.1	11.6	10.9
K/Rb-----	315.	380.	263.	257.	240.	178.	175.	262.	234.	231.	164.
Rb/Sr-----	3.4	3.5	31.2	--	38.8	--	--	46.9	34.7	0.75	24.0
Ca/Sr-----	88.	99.	643.	--	751.	--	--	826.	47.2	57.	415.
Th/U-----	2.8	3.1	1.9	1.6	2.1	3.1	2.3	3.2	2.6	3.1	4.7
Zr/Hf-----	27.	26.	18.	22.	18.	21.	28.	28.	28.	28.	26.
Ce/Yb-----	23.6	22.5	18.6	16.8	16.8	10.8	11.5	28.3	19.2	20.3	12.0
Eu/Eu*-----	--	0.37	0.15	0.15	0.16	--	0.02	0.14	0.08	0.36	0.11

See footnotes at end of table.

Country/State-----	MEXICO											
Volcanic field/region---	Western Neovolcanic Zone											
Locality-----	Magdalena-Tequila Mountains		Piedra Bola	Sierra la Primavera volcano complex								
Specimen----- Collection No. (RLS-)---	123 131	124 130	125 140	126 P-290	127 P-90	128 P-317	129 P-108	130 P-175	131 P-105	132 P-83	133 P-115	134 P-73
Chemical analyses (weight percent)												
SiO <sub>2</sub> -----	74.9	73.5	75.8	76.02	75.23	76.00	76.7	76.14	76.16	76.9	76.81	77.0
Al <sub>2</sub> O <sub>3</sub> -----	13.26	13.95	13.02	11.32	12.05	11.57	11.46	11.43	11.64	11.73	11.66	11.65
Fe <sub>2</sub> O <sub>3</sub> -----	0.62	0.64	0.41	0.73	0.71	0.74	0.79	0.84	0.65	0.74	0.69	0.71
FeO-----	0.78	0.89	0.64	1.02	1.29	1.08	0.98	0.95	0.83	0.74	0.80	0.76
MgO-----	0.06	0.11	0.09	0.04	0.06	0.05	--	0.05	0.03	--	0.03	--
CaO-----	0.41	0.53	0.51	0.22	0.34	0.27	0.22	0.24	0.24	0.23	0.23	0.23
Na <sub>2</sub> O-----	4.55	4.71	4.17	4.62	4.76	4.38	4.55	4.66	4.64	4.77	4.71	4.68
K <sub>2</sub> O-----	4.96	4.92	4.75	4.50	4.72	4.62	4.42	4.54	4.25	4.44	4.50	4.39
H <sub>2</sub> O+-----	0.09	0.08	0.11	0.45	0.41	0.12	0.31	0.47	0.56	0.45	0.37	0.55
TiO <sub>2</sub> -----	0.13	0.18	0.14	0.12	0.15	0.13	0.13	0.12	0.09	0.08	0.09	0.08
P <sub>2</sub> O <sub>5</sub> -----	0.01	0.02	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
MnO-----	0.06	0.06	0.05	0.04	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.04
Cl*-----	0.12	0.09	0.10	0.11	0.10	0.10	0.11	0.10	0.12	0.11	0.11	0.12
Cl**-----	0.10	0.09	0.10	--	--	--	--	--	--	--	--	--
F*-----	0.10	0.07	0.04	0.10	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10
F**-----	0.04	0.08	0.05	--	--	--	--	--	--	--	--	--
Subtotal-----	100.04	99.75	99.84	99.29	99.97	99.20	99.81	99.68	99.35	100.33	100.14	100.61
Less O=(F,Cl) <sub>2</sub> -----	0.07	0.05	0.04	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07
Total-----	99.97	99.70	99.80	99.22	99.91	99.14	99.75	99.62	99.28	100.26	100.07	100.54
FeO <sub>t</sub> -----	1.34	1.47	1.01	1.68	1.93	1.75	1.69	1.71	1.42	1.41	1.42	1.40
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.56	0.58	0.61	0.58	0.65	0.59	0.55	0.53	0.56	0.50	0.54	0.52
Na <sub>2</sub> O/(K <sub>2</sub> O) <sup>1</sup> -----	0.92	0.96	0.88	1.03	1.01	0.95	1.03	1.03	1.09	1.07	1.05	1.07
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.97	0.94	0.92	1.10	1.07	1.05	1.07	1.10	1.05	1.08	1.08	1.07
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.03	1.01	0.99	1.14	1.13	1.10	1.10	1.14	1.09	1.11	1.12	1.10
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.04	0.06	0.06	0.02	0.04	0.03	0.02	0.03	0.03	0.02	0.02	0.03
Cl/F <sup>1†</sup> -----	1.1	1.3	2.3	1.1	1.1	1.1	1.2	1.1	1.2	1.1	1.1	1.2
CIPW norms												
Q-----	28.4	25.76	31.98	33.87	30.02	33.04	34.05	33.35	33.44	33.32	33.46	33.84
Or-----	29.39	29.22	28.18	26.96	28.07	27.61	26.30	27.09	25.48	26.32	26.71	26.06
ab-----	38.60	40.05	35.43	33.63	35.93	34.17	34.58	33.85	36.74	35.73	35.08	35.65
an-----	1.11	2.40	2.48	--	--	--	--	--	--	--	--	--
C-----	--	--	0.12	--	--	--	--	--	--	--	--	--
ac-----	--	--	--	2.14	2.07	2.17	2.30	2.45	1.91	2.15	2.01	2.06
ns-----	--	--	--	0.83	0.53	0.20	0.37	0.74	0.22	0.54	0.62	0.42
wo } di-----	0.36	0.05	--	0.46	0.71	0.57	0.46	0.50	0.50	0.48	0.48	0.48
en } di-----	0.06	0.01	--	0.03	0.05	0.04	0.00	0.04	0.03	0.00	0.03	0.00
fs } di-----	0.33	0.04	--	0.49	0.74	0.59	0.52	0.52	0.54	0.54	0.51	0.54
en } hy-----	0.09	0.26	0.23	0.07	0.10	0.09	0.00	0.09	0.05	0.00	0.05	0.00
fs } hy-----	0.49	0.09	0.70	1.29	1.51	1.29	1.17	1.14	0.93	0.76	0.89	0.80
mt-----	0.90	0.93	0.60	--	--	--	--	--	--	--	--	--
il-----	0.25	0.34	0.27	0.23	0.29	0.25	0.25	0.23	0.17	0.15	0.17	0.15
ap-----	0.02	0.05	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	123	124	125	126	127	128	129	130	131	132	133	134
Trace elements (ppm)												
Ba-----	70.	430.	310.	<50.	<50.	<50.	<50.	<50.	<50.	<50.	<50.	<50.
Be-----	5.3	4.3	3.7	--	--	--	--	--	--	--	--	--
Co-----	0.2	0.4	0.5	--	--	--	--	0.2	--	0.3	0.5	<0.5
Cr-----	<4.0	<4.0	2.3	--	--	--	--	--	--	--	--	--
Cs-----	3.7	3.2	5.4	3.2	3.0	3.6	3.4	3.2	3.4	3.5	3.6	3.7
Hf-----	7.9	7.6	5.0	14.5	14.6	13.2	14.0	14.5	11.2	11.3	11.2	11.4
Li-----	36.	32.	36.	--	--	--	--	--	--	--	--	--
Mo-----	7.6	6.3	6.6	--	--	--	--	--	--	--	6.0	--
Nb-----	38.	30.	20.	--	--	--	--	--	--	--	--	--
Nb***-----	51.	41.	16.	65.	64.	70.	60.	62.	85.	74.	51.	69.
Pb-----	25.	22.	17.	21.	18.	24.	25.	28.	25.	18.	16.	31.
Pb***-----	153.	127.	156.	--	--	--	--	--	--	--	--	--
Rb-----	160.	135.	154.	160.	162.	170.	157.	162.	170.	177.	165.	165.
Sb-----	0.7	0.8	0.6	0.4	<0.9	0.4	0.3	0.4	0.7	0.6	0.4	<0.8
Sc-----	2.3	3.2	2.2	0.63	1.79	0.98	0.67	0.74	0.70	0.70	0.71	0.69
Sn-----	4.5	3.7	2.6	--	--	--	--	--	--	--	--	--
Sr-----	7.	26.	33.	--	--	--	--	--	--	--	--	--
Ta-----	3.16	2.48	1.93	4.31	3.69	3.84	3.74	3.87	--	3.76	3.56	3.57
Th-----	14.6	12.1	17.2	18.3	16.8	18.9	17.5	17.9	16.6	17.1	17.2	16.6
U-----	5.3	4.2	7.1	7.6	5.4	6.9	6.3	5.8	5.6	6.1	5.4	5.6
W-----	2.7	1.4	1.8	--	--	--	--	--	--	--	--	--
Y-----	49.	39.	22.	51.	52.	75.	50.	54.	49.	49.	50.	49.
Zn-----	70.	44.	32.	116.	104.	105.	112.	103.	108.	102.	96.	95.
Zr-----	242.	279.	146.	500.	616.	521.	548.	568.	373.	381.	375.	382.
La-----	52.	43.	32.	55.	76.	66.	56.	60.	38.	39.	40.	40.
Ce-----	103.	84.	60.	122.	162.	134.	122.	130.	88.	92.	91.	90.
Nd-----	43.	33.	25.	50.	64.	54.	48.	51.	35.	37.	40.	39.
Sm-----	8.4	6.4	4.6	10.6	11.6	10.8	10.3	10.6	8.4	8.7	8.4	8.5
Eu-----	0.17	0.38	0.22	0.09	0.10	0.06	0.09	0.09	0.06	0.06	0.07	0.06
Gd-----	6.7	4.9	3.6	9.7	9.5	9.3	8.9	9.4	8.0	8.2	--	8.3
Tb-----	1.36	1.08	0.67	1.57	1.54	1.62	1.53	1.53	1.35	1.37	1.37	1.34
Tm-----	0.74	0.74	0.40	0.95	0.87	0.83	0.82	0.83	--	0.80	--	0.80
Yb-----	4.8	3.8	2.7	5.9	6.0	5.9	5.9	6.0	5.5	5.8	5.8	5.7
Lu-----	0.67	0.55	0.41	0.88	0.94	0.85	0.84	0.88	0.80	0.84	0.79	0.83
Nb/Ta-----	14.1	14.3	9.3	15.1	17.3	18.2	16.0	16.0	--	19.7	14.3	19.3
K/Rb-----	257.	303.	256.	233.	242.	226.	234.	233.	208.	208.	226.	221.
Rb/Sr-----	22.9	5.2	4.7	--	--	--	--	--	--	--	--	--
Ca/Sr-----	419.	146.	111.	--	--	--	--	--	--	--	--	--
Th/U-----	2.8	2.9	2.4	2.4	3.1	2.7	2.8	3.1	3.0	2.8	3.2	3.0
Zr/Hf-----	31.	37.	29.	34.	42.	39.	39.	39.	33.	34.	33.	34.
Ce/Yb-----	21.5	22.1	22.2	20.7	27.0	22.7	20.7	21.7	16.0	15.9	15.7	15.8
Eu/Eu*-----	0.07	0.21	0.17	0.03	0.03	0.02	0.03	0.03	0.02	0.02	0.03	0.02

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	MEXICO											
Volcanic field/region---	Western Neovolcanic Zone			Central Neovolcanic Zone				Eastern Neovolcanic Zone				
Locality-----	Sierra la Primavera volcano complex			Los Azufres Region				Los Humeros			Las Derrumbadas Region	
Specimen-----	135	136	137	138	139	140	141	142	143	144	145	146
Collection No. (RLS)---	P-40	P-67	P-15	274	275	276	273	280	277	278	279	125
Chemical analyses (weight percent)												
SiO <sub>2</sub> -----	76.3	76.82	76.67	77.3	76.7	76.8	76.9	75.7	76.7	70.6	73.8	74.2
Al <sub>2</sub> O <sub>3</sub> -----	11.67	11.65	11.82	12.58	12.50	12.43	12.62	12.34	12.48	14.63	13.99	14.04
Fe <sub>2</sub> O <sub>3</sub> -----	0.66	0.65	0.56	0.43	0.41	0.44	0.52	0.57	0.47	0.84	0.32	0.09
FeO-----	0.81	0.81	0.67	0.55	0.59	0.61	0.48	0.58	0.45	1.06	0.73	0.52
MgO-----	--	0.03	0.02	0.02	0.02	0.03	0.02	0.03	0.04	0.20	0.02	0.03
CaO-----	0.23	0.23	0.30	0.39	0.36	0.43	0.39	0.35	0.31	0.69	0.60	0.48
Na <sub>2</sub> O-----	4.62	4.65	4.47	3.95	3.83	3.87	4.06	4.20	4.02	4.98	4.37	4.42
K <sub>2</sub> O-----	4.39	4.39	4.43	4.67	4.57	4.62	4.49	4.66	4.53	4.91	4.17	4.15
H <sub>2</sub> O+-----	0.47	0.51	0.88	0.14	0.24	0.18	0.16	0.33	0.18	0.30	0.82	0.98
TiO <sub>2</sub> -----	0.08	0.08	0.06	0.07	0.07	0.08	0.07	0.10	0.11	0.30	0.03	0.02
P <sub>2</sub> O <sub>5</sub> -----	<0.01	<0.01	<0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.05	0.04
MnO-----	0.04	0.04	0.04	0.04	0.03	0.05	0.04	0.03	0.05	0.06	0.05	0.12
Cl*-----	0.12	0.12	0.13	0.05	0.05	0.03	0.08	0.11	0.07	0.10	0.05	0.05
Cl**-----	--	--	--	0.07	0.06	0.04	0.11	0.14	0.09	0.12	0.06	0.01
F*-----	0.10	0.10	0.10	0.08	0.06	0.06	0.07	0.07	0.06	0.07	0.06	0.08
F**-----	--	--	--	0.07	0.06	0.05	0.06	0.06	0.05	0.05	0.05	0.08
Subtotal-----	99.49	100.08	100.15	100.29	99.45	99.64	99.92	99.09	99.48	98.78	99.06	99.22
Less O=(F,Cl) <sub>2</sub> -----	0.07	0.07	0.07	0.05	0.04	0.03	0.05	0.06	0.04	0.05	0.03	0.05
Total-----	99.42	100.01	100.08	100.24	99.41	99.61	99.87	99.03	99.44	98.73	99.03	99.17
FeO <sub>t</sub> -----	1.40	1.40	1.17	0.94	0.96	1.01	0.95	1.09	0.87	1.82	1.02	0.60
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.55	0.55	0.54	0.56	0.59	0.58	0.48	0.50	0.49	0.56	0.70	0.84
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.05	1.06	1.01	0.85	0.84	0.84	0.90	0.90	0.89	1.01	1.05	1.07
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.06	1.06	1.03	0.92	0.90	0.91	0.91	0.97	0.92	0.92	0.84	0.84
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.09	1.10	1.07	0.97	0.95	0.98	0.97	1.02	0.97	1.01	0.92	0.91
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.03	0.03	0.03	0.05	0.04	0.05	0.05	0.04	0.04	0.07	0.07	0.06
Cl/F <sup>1</sup> -----	1.2	1.2	1.3	0.83	0.85	0.70	1.4	2.0	1.4	1.9	1.0	0.56
CIPW norms												
Q-----	33.39	33.73	33.54	35.33	36.18	35.57	35.22	33.06	35.42	21.16	31.32	31.75
or-----	26.26	26.11	26.43	27.59	27.25	27.47	26.64	27.94	26.99	29.51	25.11	24.99
ab-----	36.02	35.72	36.49	33.42	32.71	32.95	34.49	36.06	34.30	42.86	37.68	38.12
an-----	--	--	--	1.87	1.74	2.08	1.88	1.07	1.49	3.12	2.70	2.16
C-----	--	--	--	0.34	0.63	0.61	0.40	--	0.43	--	1.34	1.53
ac-----	1.93	1.89	1.50	--	--	--	--	--	--	--	--	--
ns-----	0.32	0.41	--	--	--	--	--	--	--	--	--	--
wo } di-----	0.48	0.48	0.63	--	--	--	--	0.26	--	0.04	--	--
en } di-----	0.00	0.03	0.03	--	--	--	--	0.04	--	0.02	--	--
fs } di-----	0.55	0.51	0.68	--	--	--	--	0.25	--	0.03	--	--
en } hy-----	0.00	0.05	0.02	0.05	0.05	0.08	0.05	0.04	0.10	0.49	0.05	0.08
fs } hy-----	0.90	0.93	0.50	0.61	0.69	0.72	0.41	0.25	0.35	0.86	1.14	1.11
mt-----	--	--	0.07	0.62	--	0.64	0.76	0.84	0.69	1.24	0.47	0.13
il-----	0.15	0.15	0.12	0.13	0.13	0.15	0.13	0.19	0.21	0.58	0.06	0.04
ap-----	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.09	0.12	0.09



	135	136	137	138	139	140	141	142	143	144	145	146
Trace elements (ppm)												
Ba-----	<50.	<50.	<50.	75.	95.	210.	6.	126.	430.	673.	1040.	10.
Be-----	--	--	--	2.1	2.2	2.0	2.6	3.7	2.6	2.3	1.8	5.4
Co-----	<0.2	0.5	0.2	0.3	0.3	0.4	0.2	0.3	0.3	1.5	<0.03	0.1
Cr-----	--	--	--	--	--	--	--	--	--	--	--	<4.0
Cs-----	3.6	3.5	4.4	13.1	7.7	6.6	8.9	4.6	3.3	5.2	5.2	10.6
Hf-----	11.4	11.2	8.8	5.2	3.6	4.0	4.1	5.1	4.1	9.0	2.3	2.1
Li-----	--	--	--	61.	51.	47.	61.	44.	36.0	35.	42.	88.
Mo-----	--	--	--	2.1	2.0	2.8	3.0	5.0	5.4	8.6	1.6	0.68
Nb**-----	--	--	--	16.	13.	13.	20.	19.	15.	20.	13.	19.
Nb***-----	65.	64.	67.	19.	15.	14.	23.	20.	19.	20.	16.	20.
Pb-----	25.	24.	15.	20.	21.	20.	22.	20.	19.	16.	20.	20.
Rb**-----	--	--	--	262.	162.	145.	173.	151.	119.	145.	122.	190.
Rb***-----	165.	166.	193.	193.	171.	152.	173.	160.	129.	152.	128.	210.
Sb-----	<0.6	0.9	0.6	--	--	--	--	--	--	--	--	0.8
Sc-----	0.68	0.69	1.09	3.76	2.57	2.55	2.69	2.76	2.49	3.03	1.03	3.7
Sn-----	--	--	--	4.2	4.8	4.0	6.0	7.0	2.6	3.5	2.8	2.4
Sr-----	--	--	--	5.	7.	15.	<1.	5.	17.	55.	111.	7.
Ta-----	3.70	3.44	3.37	2.94	1.58	1.37	2.00	2.14	1.70	1.71	1.33	2.57
Th-----	16.5	15.9	19.4	24.1	15.4	14.6	15.9	23.3	18.2	19.7	4.2	5.8
U-----	5.9	5.9	6.4	8.9	4.7	4.2	5.5	6.7	5.1	6.4	3.6	6.4
W-----	--	--	--	1.7	1.4	1.2	1.4	1.9	1.3	1.6	1.0	1.6
Y-----	52.	50.	47.	35.	31.	28.	37.	38.	29.	31.	8.	25.
Zn-----	104.	98.	83.	32.	27.	29.	40.	31.	21.	32.	56.	50.
Zr-----	367.	377.	226.	100.	100.	120.	113.	150.	124.	367.	54.	22.
La-----	39.	38.	35.	31.	27.	39.	24.	43.	37.	38.	13.	5.
Ce-----	93.	87.	78.	62.	55.	72.	47.	79.	67.	70.	24.	14.
Nd-----	39.	38.	35.	26.	25.	27.	21.	28.	25.	25.	10.	7.
Sm-----	8.3	8.4	7.9	7.7	5.2	5.4	5.2	6.4	5.0	5.6	3.0	2.4
Eu-----	0.05	0.06	0.03	0.13	0.13	0.20	0.09	0.19	0.31	0.57	0.51	0.06
Gd-----	7.8	7.5	6.8	8.8	6.1	6.6	6.3	7.1	5.3	5.7	2.6	2.6
Tb-----	1.33	1.35	1.24	1.22	0.71	0.66	0.86	0.86	0.62	0.75	0.27	0.47
Tm-----	0.81	0.77	0.72	0.49	0.33	0.33	0.58	0.57	0.44	0.49	<0.08	0.65
Yb-----	5.6	5.5	5.4	3.9	2.6	2.3	3.2	3.9	2.8	3.1	0.2	2.7
Lu-----	0.82	0.79	0.78	0.56	0.36	0.33	0.44	0.53	0.41	0.47	0.02	0.36
Nb/Ta-----	17.6	18.6	19.9	6.0	8.9	9.9	10.8	9.1	10.0	11.7	10.9	7.6
K/Rb-----	221.	220.	191.	201.	222.	252.	215.	242.	292.	268.	270.	164.
Rb/Sr-----	--	--	--	39.	24.	10.1	87.	32.0	7.6	2.8	1.2	30.
Ca/Sr-----	--	--	--	557.	368.	205.	1394.	500.	130.	90.	39.	490.
Th/U-----	2.8	2.7	3.0	2.7	2.3	3.5	2.9	3.5	3.6	3.1	1.2	0.91
Zr/Hf-----	32.	34.	26.	19.	28.	30.	28.	29.	30.	41.	23.	11.
Ce/Yb-----	16.6	15.8	14.4	15.9	21.2	31.3	14.7	20.3	23.9	22.6	120.	5.2
Eu/Eu*-----	0.02	0.02	0.01	0.05	0.07	0.10	0.05	0.09	0.19	0.31	0.56	0.07

See footnotes at end of table.

APPENDIX I.—*Chemical analyses of subalkalic silicic obsidians*—Continued

Country/State-----	MEXICO					GUATEMALA		COLOMBIA
Volcanic Field/Region---	Eastern Neovolcanic Zone							
Locality-----	Las Derrumbadas	Tulancingo		Zacualtipan		El Fiscal	Cerro Iztepequa	Popayan
Specimen-----	147	148	149	150	151	152	153	154
Collection No. (RLS)---	126	127	128	132	129	134	135	133
Chemical analyses (weight percent)								
SiO <sub>2</sub> -----	74.6	74.3	75.0	75.7	74.8	75.5	74.5	76.1
Al <sub>2</sub> O <sub>3</sub> -----	14.08	12.44	11.25	11.44	12.85	13.63	13.80	13.82
Fe <sub>2</sub> O <sub>3</sub> -----	0.11	0.75	1.83	1.86	0.39	0.51	0.41	0.10
FeO-----	0.52	1.74	0.45	0.45	1.09	0.32	0.81	0.49
MgO-----	0.03	<0.005	0.05	0.05	0.13	0.14	0.24	0.12
CaO-----	0.48	0.51	0.10	0.12	0.67	0.97	1.18	0.71
Na <sub>2</sub> O-----	4.39	4.80	5.15	5.25	3.44	4.11	3.95	4.25
K <sub>2</sub> O-----	4.16	4.38	4.44	4.53	5.34	4.05	4.24	3.68
H <sub>2</sub> O+-----	0.76	0.08	0.08	0.07	0.09	0.10	0.10	0.09
TiO <sub>2</sub> -----	0.02	0.20	0.20	0.21	0.23	0.14	0.22	0.09
P <sub>2</sub> O <sub>5</sub> -----	0.05	0.01	0.01	0.01	0.03	0.02	0.04	0.08
MnO-----	0.13	0.05	0.15	0.15	0.02	0.09	0.06	0.10
Cl*-----	0.05	0.15	0.19	0.18	0.07	0.06	0.07	0.03
Cl**-----	0.01	0.13	0.19	0.19	0.06	0.06	0.07	0.04
F-----	0.08	0.13	0.22	0.23	0.11	0.02	0.02	0.03
F**-----	0.08	0.14	0.24	0.19	0.12	0.02	0.01	0.01
Subtotal-----	99.48	99.53	99.13	100.23	99.26	99.66	99.63	99.70
Less O=(F,Cl) <sub>2</sub> -----	0.05	0.09	0.14	0.13	0.06	0.02	0.02	0.02
Total-----	99.43	99.44	98.99	100.10	99.20	99.64	99.61	99.68
FeO <sup>1</sup> -----	0.53	2.42	2.10	2.13	1.44	0.78	1.18	0.58
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.83	0.70	0.20	0.19	0.74	0.39	0.66	0.83
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.06	1.10	1.16	1.16	0.64	1.01	0.93	1.15
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.83	1.02	1.18	1.18	0.89	0.82	0.80	0.79
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.90	1.09	1.20	1.20	0.98	0.95	0.96	0.89
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.06	0.06	0.01	0.01	0.08	0.12	0.14	0.09
Cl/F <sup>1+</sup> -----	0.68	1.0	0.82	0.88	0.60	2.9	3.9	1.0
CIPW norms								
Q-----	32.18	28.37	31.88	31.45	32.53	33.99	32.29	35.60
or-----	24.94	26.10	26.60	26.83	31.88	24.06	25.19	21.85
ab-----	37.69	39.93	33.61	33.70	29.41	34.96	33.61	36.13
an-----	2.08	--	--	--	3.16	4.71	5.62	3.01
C-----	1.63	--	--	--	0.27	0.77	0.67	1.75
ac-----	--	0.90	5.37	5.39	--	--	--	--
ns-----	--	--	1.04	1.10	--	--	--	--
wo }-----	--	1.04	0.18	0.22	--	--	--	--
en } di-----	--	0.00	0.03	0.03	--	--	--	--
fs }-----	--	1.18	0.17	0.21	--	--	--	--
en } hy-----	0.08	0.00	0.10	0.09	0.33	0.35	0.60	0.30
fs }-----	1.09	1.44	0.62	0.55	1.35	0.10	0.90	0.86
mt-----	0.16	0.65	--	--	0.57	0.74	0.60	0.15
il-----	0.04	0.38	0.39	0.40	0.44	0.27	0.42	0.17
ap-----	0.12	0.02	0.02	0.02	0.07	0.05	0.09	0.19

	147	148	149	150	151	152	153	154
Trace elements (ppm)								
Ba-----	9.	885.	11.	8.	305.	950.	1090.	1440.
Be-----	5.6	5.8	10.0	10.0	6.2	2.1	1.8	2.2
Co-----	0.1	<0.2	<0.2	<0.2	1.2	0.2	0.9	0.2
Cr-----	1.3	3.4	<5.0	<5.0	<5.0	<4.0	<3.0	1.2
Cs-----	11.0	5.9	4.1	4.1	15.7	7.3	2.7	3.8
Hf-----	2.2	17.0	25.2	24.4	6.9	3.0	3.9	1.9
Li-----	92.	63.	68.	71.	82.	71.	39.	43.
Mo-----	.64	5.8	5.9	6.6	3.6	2.2	2.9	2.3
Nb**-----	20.	45.	86.	83.	19.	10.	10.	15.
Nb***-----	20.	49.	84.	88.	24.	12.	11.	21.
Pb-----	27.	20.	23.	26.	24.	22.	20.	22.
Rb**-----	193.	119.	195.	190.	283.	144.	96.	117.
Rb***-----	217.	141.	209.	205.	296.	157.	103.	120.
Sb-----	0.6	1.7	0.3	0.3	1.0	0.7	<0.3	0.3
Sc-----	3.8	0.77	3.2	3.1	3.1	1.6	1.8	1.4
Sn-----	3.1	6.1	7.1	6.2	9.4	1.8	1.3	1.2
Sr-----	8.	16.	3.	2.	40.	157.	157.	135.
Ta-----	2.62	2.79	5.66	5.59	2.23	1.12	0.89	1.33
Th-----	5.1	12.6	19.3	18.0	36.6	10.1	6.5	6.8
U-----	6.3	3.4	5.9	6.4	9.0	4.7	2.8	4.8
W-----	1.4	1.5	2.1	1.6	2.4	2.0	1.1	2.3
Y-----	25.	95.	124.	115.	47.	17.	14.	14.
Zn-----	50.	204.	218.	233.	27.	34.	22.	40.
Zr-----	22.	683.	943.	928.	212.	89.	148.	40.
La-----	5.	77.	40.	39.	56.	25.	24.	11.
Ce-----	12.	160.	92.	91.	110.	46.	42.	22.
Nd-----	4.	77.	36.	32.	38.	19.	13.	9.
Sm-----	2.4	15.5	9.3	11.0	8.8	3.3	2.9	2.0
Eu-----	0.07	1.64	1.52	1.44	0.46	0.54	0.50	0.37
Gd-----	2.4	13.4	10.3	9.9	7.4	2.7	2.2	1.6
Tb-----	0.45	2.64	2.43	2.30	1.26	0.43	0.40	0.32
Tm-----	0.25	1.36	1.76	1.71	0.82	0.18	0.30	<0.10
Yb-----	2.5	9.4	12.6	12.5	4.8	1.9	1.8	0.9
Lu-----	0.34	1.24	1.77	1.81	0.68	0.29	0.28	0.15
Nb/Ta-----	7.6	16.9	15.2	14.9	9.6	9.8	11.8	13.5
K/Rb-----	159.	258.	176.	183.	150.	214.	342.	255
Rb/Sr-----	27.1	8.8	69.7	103.	7.4	1.0	0.66	0.89
Ca/Sr-----	429.	228.	238.	429.	120.	44.2	53.7	37.6
Th/U-----	0.81	3.7	3.3	2.8	4.1	2.2	2.3	1.4
Zr/Hf-----	10.	40.	37.	38.	31.	30.	38.	21.
Ce/Yb-----	4.8	17.0	7.3	7.3	22.9	24.2	23.3	24.4
Eu/Eu*-----	0.09	0.35	0.48	0.38	0.18	0.56	0.60	0.64

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	ECUADOR				PERU		BOLIVIA	CHILE	
Volcanic field/region---	Galapagos Islands						S. Bolivia	Central	
Locality-----	Caldera Chacana	Alcedo			unknown	Macusani	unknown	Volcan Laguna del Maule	
Specimen-----	155	156	157	158	159	160	161	162	163
Collection No. (RLS)---	146	186	192	193	206	215	225	203	204

Chemical analyses (weight percent)									
SiO <sub>2</sub> -----	77.2	70.6	70.6	71.0	76.2	72.6	74.5	75.9	73.7
Al <sub>2</sub> O <sub>3</sub> -----	12.84	13.33	13.17	13.36	13.25	15.65	13.86	12.77	14.20
Fe <sub>2</sub> O <sub>3</sub> -----	0.20	1.34	1.01	1.10	0.30	0.11	0.65	0.43	0.55
FeO-----	0.35	3.00	3.88	2.83	0.34	0.45	0.87	0.48	0.62
MgO-----	0.07	0.28	0.18	0.24	0.08	0.01	0.19	0.12	0.23
CaO-----	0.58	1.52	1.73	1.23	0.60	0.18	1.10	0.67	0.87
Na <sub>2</sub> O-----	3.65	5.73	5.73	5.93	4.29	4.20	3.57	4.17	5.15
K <sub>2</sub> O-----	4.59	2.85	2.66	3.01	4.30	3.60	4.79	4.56	3.93
H <sub>2</sub> O+-----	0.06	0.20	0.18	0.14	0.12	0.29	0.20	0.15	0.20
TiO <sub>2</sub> -----	0.10	0.41	0.41	0.37	0.10	0.04	0.21	0.17	0.25
P <sub>2</sub> O <sub>5</sub> -----	0.01	0.04	0.03	0.03	0.01	0.42	0.03	0.01	0.03
MnO-----	0.05	0.16	0.18	0.14	0.08	0.09	0.08	0.07	0.09
Cl*-----	0.03	0.10	0.10	0.10	0.05	0.05	0.12	0.11	0.10
Cl**-----	0.03	0.09	0.10	0.12	0.05	0.04	0.09	0.10	0.12
F*-----	0.03	0.09	0.10	0.10	0.03	1.37	0.11	0.03	0.04
F**-----	0.02	0.10	0.09	0.09	0.02	1.35	0.10	0.03	0.04
Subtotal-----	99.76	99.65	99.95	99.58	99.75	99.78 <sup>5</sup>	100.28	99.64	99.97
Less O=(F, Cl <sub>2</sub> )-----	0.02	0.06	0.06	0.06	0.02	0.58	0.07	0.04	0.04
Total-----	99.74	99.59	99.89	99.52	99.73	99.20 <sup>5</sup>	100.21	99.60	99.93

FeO <sub>t</sub> -----	0.53	4.21	4.79	3.82	0.61	0.55	1.46	0.87	1.12
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.64	0.69	0.79	0.72	0.53	0.80	0.57	0.53	0.53
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.80	2.01	2.15	1.97	1.00	1.17	0.75	0.91	1.31
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.85	0.94	0.93	0.98	0.88	0.69	0.80	0.92	0.90
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.94	1.15	1.17	1.14	0.97	0.71	0.94	1.02	1.01
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.07	0.18	0.21	0.14	0.07	0.02	0.13	0.08	0.10
Cl/F <sup>1†</sup> -----	1.2	1.0	1.0	1.2	2.0	0.03	1.2	3.7	2.3

CIPW norms									
Q-----	37.03	22.22	21.89	21.52	33.40	34.92	32.50	32.78	26.50
or-----	27.22	16.97	15.79	17.92	25.53	21.85	28.35	27.12	23.31
ab-----	31.0	48.85	48.69	50.56	36.47	36.51	34.25	35.52	43.74
an-----	2.82	2.25	2.37	0.95	2.92	0.00	5.27	2.68	4.04
C-----	0.84	--	--	--	0.47	4.98	0.88	--	--
ac-----	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--
wo } di-----	--	2.12	2.53	2.09	--	--	--	0.25	0.04
en } di-----	--	0.34	0.20	0.30	--	--	--	0.11	0.02
fs } di-----	--	1.96	2.61	1.98	--	--	--	0.14	0.02
en } hy-----	0.18	0.36	0.25	0.30	0.20	0.03	0.47	0.19	0.55
fs } hy-----	0.41	2.09	3.36	1.99	0.36	0.86	0.86	0.24	0.42
mt-----	0.29	1.96	1.47	1.61	0.44	0.16	0.94	0.63	0.80
il-----	0.19	0.78	0.78	0.71	0.19	0.08	0.40	0.33	0.48
ap-----	0.02	0.09	0.07	0.07	0.02	0.33	0.07	0.02	0.07

	155	156	157	158	159	160	161	162	163
Trace elements (ppm)									
Ba-----	900.	400.	410.	435.	625.	<50.	675.	700.	750.
Be-----	1.8	5.0	5.0	5.2	2.7	32.	3.4	2.4	2.5
Co-----	0.1	1.2	0.8	1.5	0.2	3.1	0.2	0.5	0.2
Cr-----	<4.0	<2.0	<2.0	0.6	<2.0	<4.0	--	<2.0	<2.0
Cs-----	10.4	0.8	0.9	1.0	6.8	503.	10.6	8.3	4.4
Hf-----	2.3	20.0	21.8	21.3	3.0	1.3	6.1	4.0	5.3
Li-----	57.	24.	25.	28.	44.	3400.	160.	43.	32.
Mo-----	3.5	5.7	5.2	6.0	2.4	0.26	3.8	3.4	3.7
Nb**-----	13.	74.	74.	79.	16.	52.	23.	11.	11.
Nb***-----	13.	74.	76.	83.	16.	60.	28.	11.	15.
Pb-----	15.	16.	10.	10.	20.	31.	29.	22.	22.
Rb**-----	165.	65.	62.	50.	165.	1100.	221.	201.	162.
Rb***-----	170.	71.	62.	71.	183.	1174.	216.	195.	170.
Sb-----	1.5	<1.0	<2.0	<1.0	0.5	3.9	1.3	0.5	<0.8
Sc-----	1.3	6.1	7.2	4.7	2.0	2.3	4.2	2.2	2.3
Sn-----	0.7	5.3	6.8	8.4	1.4	250.	1.7	1.8	2.1
Sr-----	88.	120.	128.	90.	85.	1.	152.	62.	120.
Ta-----	1.40	4.96	5.35	5.64	1.78	22.10	2.34	1.32	1.28
Th-----	19.0	9.2	9.4	10.4	18.0	1.3	21.9	26.6	21.0
U-----	8.3	2.6	2.3	2.8	7.9	16.9	8.1	7.3	5.9
W-----	2.6	1.8	1.9	2.1	1.7	76.	4.1	1.7	1.9
Y-----	8.	101.	114.	108.	19.	31.	43.	22.	20.
Zn-----	21.	170.	156.	142.	33.	106.	64.	16.	36.
Zr-----	52.	850.	860.	840.	67.	28.	211.	108.	174.
La-----	17.	61.	64.	66.	22.	1.	47.	36.	36.
Ce-----	32.	133.	135.	136.	39.	3.	91.	66.	67.
Nd-----	12.	69.	68.	73.	14.	<20.	41.	23.	25.
Sm-----	2.6	16.2	17.9	17.5	2.7	1.5	9.9	3.7	4.4
Eu-----	0.25	2.94	3.29	2.81	0.36	<0.04	1.16	0.43	0.69
Gd-----	2.6	16.8	16.7	16.7	<3.0	<3.0	8.4	<3.0	3.9
Tb-----	0.24	2.33	2.57	2.76	<0.40	0.17	1.16	<0.40	<0.40
Tm-----	<0.10	1.60	1.68	1.50	0.28	<0.30	0.43	0.34	0.38
Yb-----	0.9	9.0	9.9	10.0	1.3	0.3	3.2	2.0	2.1
Lu-----	0.12	1.25	1.38	1.35	0.21	0.04	0.44	0.31	0.33
Nb/Ta-----	9.3	14.9	14.0	14.4	9.0	2.5	10.9	8.3	10.2
K/Rb-----	224.	333.	356.	352.	195.	25.	184.	194.	192.
Rb/Sr-----	1.9	0.59	0.48	0.79	22.	1174.	1.4	3.2	1.4.
Ca/Sr-----	47.1	90.5	96.6.	97.7	50.	1286.	52.	77.	52.
Th/U-----	2.3	3.5	4.1	3.7	2.3	0.1	2.7	3.6	3.6
Zr/Hf-----	23.	43.	39.	39.	22.	22.	35.	27.	33.
Ce/Yb-----	35.6	14.8	13.6	13.6	30.0	10.0	28.4	33.0	31.9
Eu/Eu*-----	0.32	0.55	0.59	0.47	--	--	0.40	--	0.51

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	CHILE			SCOTIA SEA		ICELAND				
Volcanic field/region---	Central Chile			South Shetland Islands		Torfajökull Volcanic Complex				
Locality-----	Volcan Laguna del Maule			Deception Island		Ljósu-fjöll	Prestahnukur	Kerling-arfjöll	Hrafninn-uhraun	Laugahraun
Specimen-----	164	165	166	167		168	169	170	171	172
Collection No. (RLS)---	205	220	221	213		180	1	11	42	177
										178

## Chemical analyses (weight percent)

SiO <sub>2</sub> -----	75.0	74.6	74.5	67.8	74.3	76.73	76.94	73.2	70.0	69.5
Al <sub>2</sub> O <sub>3</sub> -----	13.28	14.12	14.17	14.98	12.01	12.26	12.26	13.17	14.58	14.36
Fe <sub>2</sub> O <sub>3</sub> -----	0.52	0.53	0.54	0.97	0.88	0.45	0.33	0.74	0.74	1.01
FeO-----	0.43	0.54	0.58	3.36	1.46	1.15	1.10	1.61	2.01	2.03
MgO-----	0.14	0.20	0.21	0.70	0.00	0.10	0.00	0.13	0.26	0.26
CaO-----	0.70	0.73	0.75	1.92	0.32	1.08	0.93	0.96	1.16	1.18
Na <sub>2</sub> O-----	4.53	4.88	4.87	6.87	5.36	4.29	4.28	4.88	5.47	5.51
K <sub>2</sub> O-----	4.17	3.90	3.90	1.82	4.58	3.32	3.45	3.78	4.43	4.21
H <sub>2</sub> O+-----	0.12	0.21	0.21	0.12	0.23	0.22	0.24	0.16	0.12	0.59
TiO <sub>2</sub> -----	0.18	0.23	0.25	0.74	0.15	0.11	0.10	0.20	0.33	0.34
P <sub>2</sub> O <sub>5</sub> -----	0.01	0.03	0.04	0.09	0.00	0.01	0.01	0.02	0.04	0.04
MnO-----	0.09	0.10	0.10	0.20	0.08	0.05	0.04	0.08	0.08	0.10
Cl*-----	0.11	0.13	0.11	0.16	0.17	--	--	0.12	0.16	0.12
Cl**-----	0.11	0.18	0.13	0.16	0.17	0.05	0.04	0.12	--	--
F*-----	0.03	0.04	0.04	0.06	0.34	--	--	0.20	0.20	0.19
F**-----	0.03	0.04	0.04	0.03	0.32	0.13	0.13	0.17	--	--
Subtotal-----	99.31	100.27	100.28	99.77	99.87	99.95	99.85	99.23	99.58	99.44
Less O=(F,Cl) <sub>2</sub> -----	0.04	0.05	0.05	0.05	0.18	0.07	0.06	0.11	0.12	0.11
Total-----	99.27	100.22	100.23	99.72	99.69	99.88	99.79	99.12	99.46	99.33
FeO <sup>1</sup> -----	0.90	1.02	1.07	4.23	2.25	1.56	1.40	2.28	2.68	2.94
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.45	0.50	0.52	0.78	0.62	0.72	0.77	0.69	0.73	0.67
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.09	1.25	1.25	3.77	1.17	1.29	1.24	1.29	1.23	1.31
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.90	0.87	0.86	0.89	1.15	0.87	0.88	0.92	0.95	0.95
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.00	0.96	0.96	1.12	1.20	1.03	1.02	1.05	1.09	1.10
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.08	0.08	0.09	0.22	0.03	0.14	0.12	0.11	0.12	0.12
Cl/F <sup>1†</sup> -----	3.8	3.7	2.9	3.7	0.51	0.38	0.31	0.65	0.78	0.63

## CIPW norms

Q-----	31.20	29.39	29.29	14.92	28.53	36.24	36.43	27.89	18.13	18.43
or-----	24.88	23.08	23.07	10.82	27.30	19.71	20.50	22.62	26.42	25.25
ab-----	38.70	41.35	41.25	58.45	36.59	36.47	36.42	41.81	46.71	47.32
an-----	3.44	3.43	3.46	4.69	--	4.41	4.07	2.90	2.17	2.05
C-----	0.07	0.62	0.67	--	--	--	--	--	--	--
ac-----	--	--	--	--	2.57	--	--	--	--	--
ns-----	--	--	--	--	1.45	--	--	--	--	--
wo }-----	--	--	--	1.80	0.67	0.38	0.21	0.75	1.41	1.52
en } di-----	--	--	--	0.52	0.00	0.05	0.00	0.11	0.29	0.33
fs }-----	--	--	--	1.35	0.76	0.36	0.24	0.71	1.22	1.29
en } hy-----	0.35	0.50	0.52	1.23	0.00	0.20	0.00	0.22	0.36	0.33
fs }-----	0.23	0.36	0.39	3.19	1.85	1.30	1.43	1.48	1.49	1.27
mt-----	0.76	0.77	0.78	1.41	0.00	0.66	0.48	1.09	1.08	1.49
il-----	0.35	0.44	0.48	1.43	0.29	0.21	0.19	0.39	0.63	0.66
ap-----	0.02	0.07	0.09	0.21	0.00	0.02	0.02	0.05	0.09	0.09

	164	165	166	167	168	169	170	171	172	173
Trace elements (ppm)										
Ba-----	680.	724.	739.	287.	<50.	685.	--	880.	545.	545.
Be-----	2.6	2.9	2.8	3.0	7.1	4.2	--	4.9	--	--
Co-----	0.3	0.3	0.3	2.5	<0.2	0.5	<0.4	1.1	1.7	13.6
Cr-----	<3.0	1.2	1.9	<4.0	3.9	0.9	<7.0	<7.0	0.4	4.0
Cs-----	5.8	4.5	4.5	2.0	2.0	1.0	1.0	0.9	1.2	1.0
Hf-----	4.2	4.9	5.0	11.9	22.1	8.1	7.9	10.5	16.0	16.8
Li-----	38.	34.	28.	28.	36.	38.	--	28.	--	--
Mo-----	4.2	4.0	3.8	2.6	6.2	3.2	--	5.1	--	--
Nb**-----	12.	11.	11.	16.	--	60.	--	130.	--	--
Nb***-----	12.	13.	13.	14.	235.	69.	--	132.	126.	129.
Pb-----	23.	19.	16.	14.	13.	19.	--	14.	14.	15.
Rb*-----	182.	165.	165.	24.	172.	82.	82.	76.	117.	111.
Rb***-----	188.	163.	161.	36.	166.	86.	--	110.	113.	108.
Sb-----	<0.8	0.8	1.5	<2.0	0.5	<0.9	0.6	<0.7	0.3	0.4
Sc-----	2.5	2.3	2.3	10.7	0.43	2.1	1.7	1.3	2.5	2.8
Sn-----	1.6	1.2	1.1	3.5	5.6	7.0	--	7.6	--	--
Sr-----	80.	99.	110.	140.	<5.	73.	--	57.	80.	100.
Ta-----	1.18	1.18	1.17	1.26	17.30	4.46	4.54	8.52	8.15	8.11
Th-----	24.0	20.0	20.6	5.0	20.1	12.8	12.3	10.9	17.0	15.9
U-----	6.7	5.8	6.0	1.2	7.0	3.5	3.3	3.7	5.1	4.9
W-----	2.0	1.8	1.8	0.94	3.3	1.8	--	2.0	--	--
Y-----	25.	24.	23.	73.	115.	115.	--	128.	64.	65.
Zn-----	29.	36.	36.	100.	179.	109.	--	140.	110.	110.
Zr-----	122.	174.	190.	500.	903.	185.	--	480.	681.	731.
La-----	35.	35.	34.	29.	100.	61.	56.	70.	95.	91.
Ce-----	58.	64.	63.	65.	199.	124.	107.	157.	169.	167.
Nd-----	21.	26.	24.	39.	83.	62.	56.	66.	63.	67.
Sm-----	3.8	5.0	4.8	10.1	19.8	14.1	13.9	15.8	14.3	14.2
Eu-----	0.51	0.69	0.68	2.05	0.70	2.27	2.05	2.31	1.61	1.83
Gd-----	3.3	3.8	4.2	10.0	14.7	13.0	11.6	12.7	9.9	9.1
Tb-----	<0.4	0.42	0.41	1.59	3.12	2.53	2.59	2.43	1.38	1.98
Tm-----	0.37	0.30	0.31	0.98	1.38	1.36	1.33	1.38	0.84	1.06
Yb-----	1.9	2.2	2.2	7.5	11.2	9.7	9.5	8.3	6.4	6.4
Lu-----	0.28	0.30	0.31	1.11	1.57	1.29	1.26	1.16	0.88	0.88
Nb/Ta-----	10.2	10.2	10.3	11.9	13.6	14.5	--	15.4	15.5	15.9
K/Rb-----	184.	199.	201.	420.	229.	320.	--	285.	325.	324.
Rb/Sr-----	2.4	1.7	1.5	0.26	--	1.2	--	1.9	1.4	1.1
Ca/Sr-----	63.	53.	49.	98.	--	106.	--	120.	104.	84.
Th/U-----	3.6	3.5	3.4	4.2	2.9	3.7	3.7	3.0	3.3	3.2
Zr/Hf-----	29.	36.	38.	42.	41.	23.	--	46.	43.	44.
Ce/Yb-----	30.5	29.1	29.	8.7	17.8	12.8	11.3	18.9	26.4	26.1
Eu/Eu*-----	0.44	0.49	0.47	0.63	0.14	0.50	0.50	0.50	0.41	0.50

See footnotes at end of table.

APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	ICELAND					ITALY			
Volcanic field/region---	Torfajökull Volcanic Complex					Sardinia	Lipari Island		Vulcano
Locality-----	Domadals- hraun	Hrafninn- uhryggur	Askja 1875	Oraefajökull		Mount Arci	Roche Rosse	Mount Pelato	1739? flow
Specimen-----	174	175	176	177	178	179	180	181	182
Collection No. (RLS)---	176	37	61	68	57	209	65	210	197
Chemical analyses (weight percent)									
SiO <sub>2</sub> -----	70.1	74.9	72.1	73.2	73.2	74.3	74.7	74.6	73.2
Al <sub>2</sub> O <sub>3</sub> -----	14.59	12.17	12.77	13.34	13.00	13.86	13.13	13.24	13.49
Fe <sub>2</sub> O <sub>3</sub> -----	0.78	0.74	1.11	0.80	0.67	0.30	0.47	0.43	0.60
FeO-----	2.16	2.49	2.84	1.54	1.49	1.33	1.16	1.21	1.33
MgO-----	0.25	0.08	0.73	0.09	0.01	0.21	0.04	0.04	0.12
CaO-----	1.14	1.67	2.69	0.80	0.76	0.70	0.87	0.61	0.87
Na <sub>2</sub> O-----	5.45	4.42	4.08	5.10	5.13	3.50	4.23	4.16	4.21
K <sub>2</sub> O-----	4.38	2.70	2.30	4.11	3.84	5.05	5.05	4.92	5.08
H <sub>2</sub> O+-----	0.08	0.15	0.05	0.06	0.05	0.13	0.14	0.12	0.14
TiO <sub>2</sub> -----	0.32	0.25	0.92	0.18	0.17	0.26	0.08	0.09	0.11
P <sub>2</sub> O <sub>5</sub> -----	0.04	0.02	0.19	0.02	0.01	0.07	0.01	0.01	0.01
MnO-----	0.08	0.11	0.11	0.07	0.07	0.07	0.12	0.08	0.09
Cl*-----	0.15	0.06	0.03	0.17	0.19	0.12	0.34	0.30	0.31
Cl**-----	--	0.05	0.02	0.17	0.17	--	0.35	--	--
F*-----	0.19	0.10	0.05	0.14	0.15	0.15	0.15	0.15	0.15
F**-----	--	0.09	0.05	0.13	0.15	--	0.13	--	--
Subtotal-----	99.71	99.85	99.97	99.62	98.73	100.05	100.48	99.96	99.71
Less O=(F,Cl) <sub>2</sub> -----	0.11	0.05	0.03	0.10	0.10	0.09	0.14	0.13	0.13
Total-----	99.60.	99.80	99.94	99.52	99.63	99.96	100.34	99.83	99.58
FeO <sup>1</sup> -----	2.86	3.16	3.85	2.26	2.14	1.60	1.58	1.60	1.87
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.73	0.77	0.72	0.66	0.69	0.82	0.71	0.74	0.69
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.24	1.64	1.77	1.24	1.34	0.69	0.84	0.85	0.83
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.94	0.84	0.72	0.96	0.97	0.81	0.95	0.92	0.92
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.08	1.09	1.10	1.07	1.08	0.90	1.10	1.00	1.04
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.12	0.23	0.42	0.09	0.08	0.08	0.09	0.07	0.09
Cl/F <sup>1†</sup> -----	0.78	0.59	0.55	1.2	1.2	0.78	2.5	2.1	2.1
CIPW norms									
Q-----	18.37	34.26	32.45	25.83	27.13	32.25	28.38	29.57	26.91
or-----	26.07	16.03	13.61	24.47	23.07	29.95	30.02	29.25	30.29
ab-----	46.45	37.57	34.58	43.48	44.14	29.72	35.64	35.42	35.94
an-----	2.43	5.42	9.75	1.38	1.12	3.03	1.95	2.94	2.93
C-----	--	--	--	--	--	1.54	--	--	--
ac-----	--	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--	--
wo }-----	1.26	1.16	0.99	1.04	1.10	--	1.04	0.02	0.57
en } di-----	0.24	0.07	0.38	0.12	0.02	--	0.06	0.00	0.08
fs }-----	1.12	1.23	0.62	1.03	1.23	--	1.11	0.02	0.53
en } hy-----	0.39	0.14	1.44	0.11	0.01	0.53	0.04	0.10	0.22
fs }-----	1.85	2.54	2.36	0.99	0.83	1.90	0.74	1.86	1.42
mt-----	1.14	1.08	1.61	1.17	0.99	0.44	0.70	0.63	0.88
il-----	0.61	0.48	1.75	0.34	0.33	0.50	0.15	0.17	0.21
ap-----	0.09	0.05	0.44	0.05	0.02	0.16	0.02	0.02	0.02



	174	175	176	177	178	179	180	181	182
Trace elements (ppm)									
Ba-----	585.	615.	400.	795.	820.	337.	<50.	65.	105.
Be-----	--	3.1	1.9	5.0	5.2	--	8.1	--	--
Co-----	1.7	0.7	4.0	0.7	<0.4	1.3	0.4	0.6	1.2
Cr-----	3.8	<9.0	<9.0	<6.0	<6.0	1.3	1.1	<0.9	1.6
Cs-----	1.1	0.7	<2.0	1.0	1.0	4.0	16.5	17.0	18.0
Hf-----	16.4	12.8	9.2	12.4	12.6	4.2	6.6	6.6	7.1
Li-----	--	31.	23.	33.	35.	--	88.	--	--
Mo-----	--	3.3	2.3	5.0	5.0	--	5.9	--	--
Nb**-----	--	54.	37.	69.	74.	--	32.	--	--
Nb***-----	118.	58.	31.	75.	78.	48.	30.	50.	44.
Pb-----	16.	10.	11.	17.	16.	30.	46.	22.	26.
Rb**-----	107.	59.	60.	102.	91.	241.	313.	317.	328.
Rb***-----	114.	69.	64.	103.	101.	260.	319.	297.	300.
Sb-----	0.4	<0.9	<0.8	0.4	0.4	0.5	1.2	1.5	1.9
Sc-----	2.6	4.6	11.1	2.4	1.5	4.1	1.1	1.2	1.6
Sn-----	--	6.1	3.9	7.7	5.4	--	5.5	--	--
Sr-----	85.	97.	116.	40.	55.	67.	20.	12.	43.
Ta-----	7.76	3.67	2.58	6.19	5.85	3.59	3.00	2.97	2.94
Th-----	16.2	7.5	7.3	13.8	12.8	20.1	55.7	55.3	59.9
U-----	5.2	2.1	2.3	4.1	3.1	5.6	18.5	16.6	17.3
W-----	--	1.0	0.94	2.0	2.1	--	4.3	--	--
Y-----	62.	108.	57.	93.	116.	42.	32.	64.	56.
Zn-----	110.	132.	75.	107.	135.	86.	61.	50.	54.
Zr-----	699.	565.	406.	472.	493.	120.	192.	171.	198.
La-----	91.	56.	41.	85.	87.	33.	66.	71.	81.
Ce-----	165.	101.	82.	159.	176.	71.	126.	118.	137.
Nd-----	61.	63.	39.	76.	78.	33.	47.	48.	49.
Sm-----	13.3	14.4	9.7	16.5	17.7	8.0	9.2	9.2	9.6
Eu-----	1.57	2.26	2.01	1.97	2.59	0.53	0.14	0.15	0.22
Gd-----	9.1	11.0	8.6	13.1	15.6	6.3	8.2	10.2	9.6
Tb-----	1.90	2.60	1.50	2.74	1.78	1.08	1.21	<0.4	<0.4
Tm-----	0.84	1.16	1.48	1.29	1.41	0.39	0.66	0.70	0.89
Yb-----	6.3	9.7	6.1	8.5	9.2	2.5	4.7	4.7	4.9
Lu-----	0.84	1.41	0.93	1.23	1.28	0.34	0.70	0.71	0.71
Nb/Ta-----	15.2	15.3	13.2	11.6	13.0	13.4	10.3	16.8	15.0
K/Rb-----	320.	324.	298.	331.	316.	161.	130.	138.	141.
Rb/Sr-----	1.3	0.71	0.55	2.6	1.8	3.9	16.0	24.8	7.0
Ca/Sr-----	96.	123.	166.	143.	99.	75.	311.	363.	145.
Th/U-----	3.1	3.5	3.2	3.4	4.1	3.6	3.0	3.3	3.5
Zr/Hf-----	43.	44.	44.	38.	39.	29.	29.	26.	28.
Ce/Yb-----	26.2	10.4	13.4	18.7	19.1	28.4	26.8	25.1	28.0
Eu/Eu*-----	0.45	0.56	0.68	0.41	0.48	0.23	0.05	0.05	0.07

See footnotes at end of table.

APPENDIX I.—*Chemical analyses of subalkalic silicic obsidians—Continued*

Country/State-----	TURKEY		U.S.S.R	JAPAN						
Volcanic field/region---	Cappa- docia	Armenia	Armenia	Hokkaido		Nagano Prefecture	Shizuoka Prefecture	Izu Islands	Saga Prefecture	Kumamoto Prefecture
Locality-----	Kocadag	Sulphan Dag	Erevan	Okushiri	Island	Wada-Toge Rhyolite	Amagi	Kozu-Shima	Arita	Aso
Specimen-----	183	184	185	186	187	188	189	190	191	192
Collection No. (RLS)---	67	66	211	168	198	145	165	38	166	167

## Chemical analyses (weight percent)

SiO <sub>2</sub> -----	74.1	75.3	74.5	76.4	76.0	76.0	72.8	77.0	74.5	71.8
Al <sub>2</sub> O <sub>3</sub> -----	14.00	13.15	14.26	12.79	13.01	12.40	13.90	12.68	12.96	15.26
Fe <sub>2</sub> O <sub>3</sub> -----	0.46	0.36	0.50	0.23	0.20	0.29	0.85	0.32	0.26	0.63
FeO-----	1.14	0.94	0.65	0.41	0.37	0.48	1.55	0.40	0.79	1.08
MgO-----	0.15	<0.01	0.22	0.10	0.07	0.07	0.77	0.12	0.03	0.42
CaO-----	1.06	0.52	0.97	0.84	0.72	0.59	2.64	0.76	0.60	1.81
Na <sub>2</sub> O-----	4.54	4.06	4.53	3.59	3.64	3.97	3.85	4.33	3.88	4.51
K <sub>2</sub> O-----	4.17	4.68	4.01	4.44	4.45	4.50	2.40	3.49	4.51	3.59
H <sub>2</sub> O+-----	0.10	0.20	0.14	0.36	0.31	0.56	0.20	0.20	0.39	0.16
TiO <sub>2</sub> -----	0.14	0.09	0.19	0.09	0.08	0.10	0.34	0.11	0.05	0.34
P <sub>2</sub> O <sub>5</sub> -----	0.03	0.03	0.04	0.02	0.01	0.01	0.09	0.02	0.02	0.08
MnO-----	0.06	0.03	0.10	0.10	0.12	0.10	0.09	0.08	0.05	0.10
Cl <sup>*</sup> -----	0.12	0.02	0.04	0.08	0.08	0.09	0.08	0.07	0.06	0.08
Cl <sup>**</sup> -----	--	--	--	0.09	--	0.10	0.07	0.05	0.07	0.08
F <sup>*</sup> -----	0.05	0.06	0.07	0.02	0.02	0.12	0.04	0.02	0.05	0.03
F <sup>**</sup> -----	--	--	--	0.01	--	0.11	0.03	0.03	0.05	0.03
Subtotal-----	100.12	99.44	100.22	99.47	99.08	99.32	99.59	99.60	98.16	99.89
Less O=(F,Cl) <sub>2</sub> -----	0.05	0.03	0.04	0.03	0.03	0.09	0.03	0.02	0.04	0.03
Total-----	100.07	99.41	100.18	99.44	99.05	99.23	9.56	99.58	98.12	99.86
FeO <sub>t</sub> -----	1.55	1.26	1.10	0.62	0.55	0.74	2.32	0.68	1.02	1.65
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.71	0.72	0.57	0.64	0.65	0.62	0.65	0.56	0.75	0.63
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.09	0.87	1.13	0.81	0.82	0.88	1.60	1.24	0.86	1.26
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.86	0.89	0.83	0.84	0.83	0.90	0.64	0.86	0.87	0.74
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.99	0.97	0.95	0.96	0.93	0.99	0.99	0.97	0.95	0.96
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.12	0.06	0.11	0.10	0.09	0.07	0.42	0.10	0.07	0.22
Cl/F <sup>1†</sup> -----	2.4	0.33	0.53	5.2	3.6	.83	2.3	2.7	1.2	2.6

## CIPW norms

Q-----	28.64	32.41	30.22	36.72	36.39	34.59	34.12	36.76	33.62	27.16
or-----	24.68	27.89	23.70	26.50	26.65	26.99	14.29	20.77	27.29	21.30
ab-----	38.47	34.65	38.34	30.68	31.22	34.10	32.81	36.89	33.62	38.31
an-----	5.07	2.40	4.55	4.08	3.55	2.77	12.60	3.67	2.91	8.49
ac-----	0.16	0.54	0.80	0.61	0.93	--	0.39	0.45	0.67	0.86
ns-----	--	--	--	--	--	--	--	--	--	--
wo-----	--	--	--	--	--	0.06	--	--	--	--
en } di-----	--	--	--	--	--	0.01	--	--	--	--
fs }-----	--	--	--	--	--	0.05	--	--	--	--
en } hy-----	0.37	0.00	0.55	0.25	0.18	0.16	1.93	0.30	0.08	1.05
fs }-----	1.60	1.35	0.65	0.61	0.61	0.62	1.76	0.44	1.28	1.09
mt-----	0.67	0.53	0.73	0.34	0.29	0.43	1.24	0.47	0.39	0.92
il-----	0.27	0.17	0.36	0.17	0.15	0.19	0.65	0.21	0.10	0.65
ap-----	0.07	0.07	0.09	0.05	0.02	0.02	0.21	0.05	0.19	0.30

	183	184	185	186	187	188	189	190	191	192
Trace elements (ppm)										
Ba-----	498.	475.	525.	915.	950.	55.	510.	665.	225.	710.
Be-----	4.1	3.0	--	1.8	--	3.3	0.98	1.5	3.7	2.0
Co-----	0.6	0.4	0.8	0.2	0.3	0.3	3.8	0.3	0.2	0.7
Cr-----	<5.0	<6.0	<2.0	<2.0	<2.0	<5.0	2.2	<6.0	2.8.	<2.0
Cs-----	6.8	5.3	5.3	11.6	12.7	21.1	2.5	2.8	11.3	6.1
Hf-----	4.8	3.8	4.8	2.0	2.0	4.7	3.2	2.6	2.7	5.6
Li-----	49.	58.	--	36.	--	60.	23.	27.	79.	43.
Mo-----	3.2	2.7	--	1.2	--	2.7	2.2	1.2	1.2	2.6
Nb**-----	--	--	--	8.8	--	17.	5.8	8.	19.	14.
Nb***-----	43.	21.	43.	10.	10.	20.	6.	10.	21.	12.
Pb-----	30.	25.	15.	13.	15.	23.	19.	11.	25.	21.
Rb**-----	167.	165.	145.	196.	201.	259.	55.	77.	176.	118.
Rb***-----	161.	164.	135.	200.	200.	270.	51.	80.	193.	135.
Sb-----	0.7	0.8	0.7	0.2	0.4	1.3	0.3	<0.9	0.6	0.4
Sc-----	1.3	3.2	3.2	2.0	2.0	5.2	6.2	3.6	1.8	1.9
Sn-----	2.2	3.2	--	0.5	--	3.3	0.8	1.6	6.8	1.2
Sr-----	110.	16.	135.	133.	110.	20.	262.	65.	40.	290.
Ta-----	2.28	1.17	3.62	0.82	0.96	1.88	0.41	0.90	2.47	1.03
Th-----	26.4	17.9	19.3	17.7	19.8	26.4	4.1	5.9	15.2	11.6
U-----	8.1	5.7	9.6	4.6	5.6	7.6	1.4	2.1	4.2	2.8
W-----	3.5	2.1	--	1.5	--	2.7	0.76	1.3	3.5	1.9
Y-----	19.	27.	32.	15.	27.	44.	20.	25.	26.	18.
Zn-----	54.	39.	38.	8.	10.	30.	25.	16.	38.	44.
Zr-----	197.	133.	157.	39.	40.	81.	112.	78.	52.	218.
La-----	35.	34.	38.	24.	23.	19.	15.	22.	23.	29.
Ce-----	61.	64.	59.	43.	40.	47.	28.	40.	41.	54.
Nd-----	21.	30.	23.	14.	16.	24.	14.	20.	15.	21.
Sm-----	3.9	6.2	3.7	3.4	2.9	6.3	2.9	4.0	3.3	3.7
Eu-----	0.54	0.49	0.52	0.45	0.42	0.22	0.65	0.54	0.17	0.83
Gd-----	3.8	5.2	3.7	3.0	<4.0	6.1	2.5	3.4	3.1	3.0
Tb-----	0.63	0.92	0.61	0.38	<0.3	1.10	0.32	0.70	0.62	0.49
Tm-----	0.37	0.61	0.45	0.26	0.44	0.76	0.30	0.47	0.38	0.36
Yb-----	2.9	3.2	2.5	2.1	2.2	4.7	1.9	3.1	2.3	2.2
Lu-----	0.43	0.47	0.40	0.34	0.35	0.65	0.30	0.50	0.32	0.35
Nb/Ta-----	18.9	18.0	11.9	11.5	10.4	9.8	14.4	10.0	8.1	12.6
K/Rb-----	215.	237.	247.	184.	185.	138.	391.	363.	194.	221.
Rb/Sr-----	1.5	10.3	1.0	1.5	1.8	13.5	0.19	1.2	4.8	0.47
Ca/Sr-----	69.	232.	51.	45.	47.	211.	72.	84.	107.	45.
Th/U-----	3.3	3.1	2.0	3.9	3.5	3.5	2.9	2.9	3.6	4.1
Zr/Hf-----	41.	35.	33.	20.	20.	17.2	35.	30.	19.	39.
Ce/Yb-----	21.0	20.0	23.6	20.5	18.2	10.0	14.7	12.9	17.8	24.5
Eu/Eu*-----	0.44	0.26	0.43	0.44	--	0.14	0.75	0.45	0.10	0.78

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	JAPAN			INDONESIA						
Volcanic field/region---	Kagoshima Prefecture	Miyagi Prefecture	Shizuoka Prefecture	South Sumatra	Krakatau	Java				
Locality-----	Io Jima	Narugo	Atami	South Kenak Besar	Gunung Krakatau	Gunung Kiaraberes	Nagrek	Samarang	Nagrek	Daradjat- Pasir Kiamis
Specimen-----	193	194	195	196	197	198	199	200	201	202
Collection No. (RLS)---	169	207	208	111	110	108	107	114	113	109

## Chemical analyses (weight percent)

SiO <sub>2</sub> -----	72.2	72.1	77.2	76.5	69.1	77.1	76.7	76.4	77.1	76.4
Al <sub>2</sub> O <sub>3</sub> -----	13.50	14.35	12.33	13.62	14.86	12.38	12.32	12.88	12.37	12.92
Fe <sub>2</sub> O <sub>3</sub> -----	0.82	0.04	0.46	0.17	1.05	0.30	0.29	0.33	0.31	0.33
FeO-----	2.46	2.09	1.21	0.62	2.29	0.72	0.86	0.96	0.73	0.95
MgO-----	0.63	0.87	0.20	0.10	0.82	0.11	0.09	0.13	0.11	0.13
CaO-----	2.63	3.17	1.55	0.66	3.05	1.00	0.77	1.12	1.00	1.18
Na <sub>2</sub> O-----	4.05	4.43	4.41	4.36	4.86	3.48	3.39	3.73	3.70	3.79
K <sub>2</sub> O-----	2.61	1.17	1.81	3.41	2.18	3.94	4.78	3.89	3.95	3.90
H <sub>2</sub> O+-----	0.16	0.14	0.12	0.11	0.12	0.36	0.08	0.10	0.05	0.10
TiO <sub>2</sub> -----	0.66	0.44	0.21	0.07	0.72	0.12	0.11	0.15	0.12	0.15
P <sub>2</sub> O <sub>5</sub> -----	0.13	0.05	0.03	0.05	0.16	0.01	0.01	0.02	0.01	0.01
MnO-----	0.10	0.12	0.08	0.13	0.14	0.04	0.04	0.05	0.05	0.05
Cl*-----	0.08	0.07	0.14	0.07	0.17	0.11	0.15	0.11	0.10	0.11
Cl**-----	0.08	--	--	--	--	--	--	--	--	--
F-----	0.05	0.04	0.05	0.03	0.07	0.04	0.07	0.06	0.03	0.06
F**-----	0.05	--	--	--	--	--	--	--	--	--
Subtotal-----	100.08	99.08	99.80	99.90	99.59	99.70	99.66	99.93	99.63	100.08
Less O=(F,Cl) <sub>2</sub> -----	0.04	0.03	0.05	0.03	0.07	0.04	0.06	0.05	0.04	0.05
Total-----	100.04	99.05	99.75	99.87	99.52	99.66	99.60	99.88	99.59	100.03
FeO <sup>1</sup> -----	3.20	2.13	1.62	0.77	3.23	0.99	1.13	1.26	1.01	1.25
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.75	0.98	0.72	0.78	0.69	0.71	0.75	0.74	0.70	0.74
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.55	3.79	2.44	1.28	2.23	0.88	0.71	0.96	0.94	0.97
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.70	0.60	0.75	0.80	0.70	0.81	0.87	0.80	0.84	0.81
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.06	1.00	0.98	0.89	1.07	0.95	0.99	0.96	0.99	0.97
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.39	0.57	0.25	0.08	0.43	0.13	0.09	0.15	0.13	0.15
Cl/F <sup>1†</sup> -----	1.5	2.0	3.0	2.2	2.3	3.1	2.3	1.8	2.9	1.9

## CIPW norms

Q-----	31.45	32.79	40.55	36.27	24.66	39.38	36.61	36.80	37.95	36.21
or-----	15.46	7.00	10.75	20.21	12.98	23.47	28.43	23.07	23.47	23.09
ab-----	34.34	37.93	37.51	37.01	41.44	29.68	28.87	31.67	31.48	32.13
an-----	10.97	15.58	7.53	2.96	12.39	4.94	3.78	5.44	4.92	5.80
C-----	--	0.15	0.37	1.68	--	0.60	0.20	0.55	0.22	0.34
ac-----	--	--	--	--	--	--	--	--	--	(6)
ns-----	--	--	--	--	--	--	--	--	--	--
wo } di-----	0.52	--	--	--	0.75	--	--	--	--	--
en } di-----	0.19	--	--	--	0.34	--	--	--	--	--
fs } di-----	0.35	--	--	--	0.41	--	--	--	--	--
en } hy-----	1.39	2.19	0.50	0.25	1.72	0.28	0.23	0.33	0.28	0.32
fs } hy-----	2.59	3.34	1.65	1.13	2.02	0.96	1.24	1.34	0.99	1.32
mt-----	1.19	0.06	0.67	0.25	1.53	0.44	0.42	0.48	0.45	0.48
il-----	1.26	0.85	0.40	0.13	1.38	0.23	0.21	0.29	0.23	0.29
ap-----	0.30	0.12	0.07	0.12	0.37	0.02	0.02	0.05	0.02	0.02

	193	194	195	196	197	198	199	200	201	202
Trace elements (ppm)										
Ba-----	460.	495.	620.	655.	405.	570.	392.	565.	590.	560.
Be-----	1.3	--	--	2.3	1.7	1.5	1.5	1.7	1.5	1.5
Co-----	3.0	4.6	1.2	0.2	2.7	0.6	0.7	0.8	0.6	0.7
Cr-----	2.0	<4.0	<3.0	<4.0	<6.0	<4.0	<5.0	<5.0	<4.0	<5.0
Cs-----	3.0	1.4	2.5	3.5	2.3	9.1	11.8	11.9	9.5	10.0
Hf-----	5.1	3.7	5.0	2.1	6.2	3.4	4.8	5.0	3.2	4.8
Li-----	23.	--	--	33.	21.	34.	38.	37.	35.	37.
Mo-----	2.9	--	--	1.3	3.5	2.4	3.3	2.1	2.1	2.3
Nb**-----	6.2	--	--	9.6	8.	10.	8.	9.6	11.	7.2
Nb***-----	6.	--	--	10.	--	9.	8.	--	--	9.
Pb**-----	21.	11.	11.	20.	12.	15.	18.	34.	33.	25.
Rb**-----	74.	28.	27.	95.	59.	161.	203.	177.	157.	183
Rb***-----	75.	23.	30.	97.	58.	156.	197.	193.	153.	175.
Sb-----	0.5	<2.0	0.8	0.3	0.3	0.9	0.8	0.7	0.8	0.7
Sc-----	11.7	12.1	7.5	2.1	13.6	1.7	3.4	4.6	1.7	4.4
Sn-----	1.7	--	--	1.0	1.8	2.1	3.5	2.3	1.4	2.5
Sr-----	178.	205.	150.	80.	220.	85.	37.	90.	85.	95.
Ta-----	0.50	0.52	0.30	0.70	0.41	0.79	0.75	0.64	0.83	0.56
Th-----	6.6	2.9	2.1	7.2	7.6	18.7	24.8	19.5	19.8	16.4
U-----	1.6	<3.0	1.5	2.7	1.4	3.7	5.6	4.9	4.2	4.3
W-----	1.1	--	--	1.2	0.85	3.2	3.0	2.6	2.6	2.9
Y-----	35.	34.	41.	17.	50.	10.	55.	25.	12.	30.
Zn-----	60.	37.	32.	28.	58.	20.	19.	29.	15.	24.
Zr-----	180.	108.	156.	70.	294.	106.	123.	168.	104.	173.
La-----	19.	12.	11.	15.	25.	26.	32.	26.	26.	27.
Ce-----	39.	26.	25.	28.	53.	44.	65.	52.	46.	52.
Nd-----	21.	16.	19.	11.	32.	19.	28.	22.	17.	19.
Sm-----	5.3	3.7	4.2	2.8	8.3	3.2	7.2	5.7	3.4	5.7
Eu-----	1.01	0.90	0.79	0.37	1.66	0.41	0.44	0.67	0.41	0.66
Gd-----	3.6	4.2	4.2	3.2	6.5	<3.0	6.5	2.7	2.7	4.9
Tb-----	0.90	0.67	0.72	0.46	1.24	0.41	1.12	0.83	0.43	0.72
Tm-----	0.49	0.49	0.59	0.37	0.87	0.34	0.73	0.50	0.37	0.42
Yb-----	3.9	3.7	3.9	2.3	5.1	2.4	5.0	3.6	2.4	3.7
Lu-----	0.55	0.56	0.60	0.31	0.77	0.37	0.71	0.50	0.36	0.52
Nb/Ta-----	12.2	--	--	14.0	19.5	12.0	10.7	15.0	13.3	14.5
K/Rb-----	289.	422.	501.	292.	312.	210.	201.	167.	214.	185.
Rb/Sr-----	0.42	0.11	0.20	1.2	0.26	1.8	5.3	2.1	1.8	1.8
Ca/Sr-----	106.	111.	74.	59.	99.	84.	149.	89.	84.	89.
Th/U-----	4.1	5.6	1.4	2.7	5.3	5.1	4.5	4.0	4.7	3.8
Zr/Hf-----	35.	29.	31.	33.	47.	31.	26.	34.	33.	36.
Ce/Yb-----	10.0	7.0	6.4	12.2	10.4	18.3	13.0	14.4	19.2	14.1
Eu/Eu*-----	0.70	0.71	0.58	0.38	0.70	0.45	0.20	0.53	0.42	0.38

See footnotes at end of table.

## APPENDIX I.—Chemical analyses of subalkalic silicic obsidians—Continued

Country/State-----	INDONESIA							
Volcanic field/region---	Celebes		Halmahera					
Locality-----	Kp. Tataaran	Pasokan (Belang)	Mount Todoku	Mount Rano (west)	Mount Popolodio	Mount Alon	Mount Rano (southwest)	
Specimen-----	203	204	205	206	207	208	209	210
Collection No. (RLS)---	101	112	170	171	172	173	174	195
Chemical analyses (weight percent)								
SiO <sub>2</sub> -----	75.9	76.3	72.5	73.5	69.1	74.1	72.9	74.2
Al <sub>2</sub> O <sub>3</sub> -----	12.89	12.96	13.60	13.73	15.56	13.34	13.55	13.60
Fe <sub>2</sub> O <sub>3</sub> -----	0.47	0.44	0.77	0.59	1.08	0.46	0.49	0.56
FeO-----	1.30	1.35	1.86	1.55	2.04	1.36	1.56	1.30
MgO-----	0.15	0.16	0.57	0.25	0.83	0.17	0.25	0.21
CaO-----	1.19	1.23	1.89	1.38	2.91	1.37	1.42	1.10
Na <sub>2</sub> O-----	4.43	4.43	4.47	4.60	4.65	4.53	4.63	4.78
K <sub>2</sub> O-----	3.15	3.09	3.26	3.34	2.60	3.52	3.32	3.48
H <sub>2</sub> O+-----	0.05	0.11	0.19	0.20	0.18	0.20	0.20	0.17
TiO <sub>2</sub> -----	0.22	0.22	0.31	0.31	0.47	0.24	0.32	0.26
P <sub>2</sub> O <sub>5</sub> -----	0.02	0.02	0.04	0.04	0.13	0.03	0.04	0.02
MnO-----	0.07	0.08	0.10	0.10	0.12	0.09	0.10	0.10
Cl*-----	0.14	0.12	0.12	0.15	0.14	0.13	0.12	0.13
Cl**-----	--	--	0.12	0.12	0.10	.14	0.13	--
F*-----	0.06	0.06	0.06	0.08	0.08	0.07	0.07	0.08
F**-----	--	--	0.06	0.06	0.06	0.07	0.07	--
Subtotal-----	100.04	100.57	99.74	99.80	99.86	99.61	98.97	99.99
Less O=(F,Cl) <sub>2</sub> -----	0.06	0.05	0.05	0.06	0.06	0.06	0.06	0.06
Total-----	99.98	100.52	99.69	99.74	99.80	99.55	98.91	99.93
FeO <sub>T</sub> -----	1.72	1.75	2.56	2.08	3.01	1.77	2.00	1.80
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.73	0.75	0.71	0.72	0.65	0.75	0.76	0.70
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.41	1.43	1.37	1.38	1.79	1.29	1.39	1.37
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.83	0.82	0.80	0.81	0.67	0.83	0.80	0.86
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.00	0.99	1.05	1.00	1.01	1.02	0.98	1.00
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.16	0.16	0.24	0.17	0.40	0.17	0.18	0.13
Cl/F <sup>1†</sup> -----	2.4	2.2	2.0	1.9	1.8	2.0	1.9	1.6
CIPW norms								
Q-----	34.63	34.93	28.67	30.00	24.07	30.76	29.50	29.82
or-----	18.65	18.21	19.39	19.86	15.44	20.97	19.90	20.65
ab-----	37.56	37.38	38.06	39.16	39.55	38.64	39.74	40.61
an-----	5.79	5.96	7.46	6.63	13.66	5.72	6.48	5.35
C-----	0.08	0.14	--	0.14	0.12	--	--	0.02
aC-----	--	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--	--
wo }-----	--	--	0.71	--	--	0.39	0.17	--
en } di-----	--	--	0.27	--	--	0.08	0.04	--
fs }-----	--	--	0.46	--	--	0.34	0.14	--
en } hy-----	0.37	0.40	1.16	0.63	2.08	0.35	0.59	0.53
fs }-----	1.77	1.90	2.01	2.05	2.13	1.56	2.01	1.69
mt-----	0.68	0.64	1.12	0.86	1.57	0.67	0.72	0.82
il-----	0.42	0.42	0.59	0.59	0.90	0.46	0.62	0.50
ap-----	0.05	0.05	0.09	0.09	0.30	0.07	0.09	0.05

	203	204	205	206	207	208	209	210
Trace elements (ppm)								
Ba-----	475.	430.	520.	550.	465.	540.	530.	525.
Be-----	1.3	1.2	1.5	1.4	1.3	1.4	1.4	--
Co-----	0.9	1.0	3.3	1.2	3.6	0.7	1.2	1.0
Cr-----	<6.0	<5.0	2.2	<4.0	<4.0	1.1	1.1	<3.0
Cs-----	4.0	4.0	4.4	4.5	3.6	4.7	4.7	5.1
Hf-----	6.1	6.2	6.3	6.6	5.0	6.6	6.8	6.9
Li-----	25.	25.	34.	35.	30.	36.	35.	--
Mo-----	2.5	2.3	2.0	2.1	1.4	2.0	2.0	--
Nb**-----	7.	9.2	7.2	4.5	4.8	5.2	6.	--
Nb***-----	5.	--	7.	6.	5.	7.	5.	--
Pb-----	6.	16.	19.	28.	17.	17.	20.	18.
Rb**-----	88.	77.	68.	76.	58.	71.	76.	74.
Rb***-----	78.	76.	72.	70.	65.	85.	85.	82.
Sb-----	0.4	<0.5	0.7	0.6	0.5	0.5	0.7	1.0
Sc-----	8.2	8.1	12.4	10.8	12.0	10.3	10.9	10.5
Sn-----	1.9	1.6	1.7	1.8	1.7	2.2	2.1	--
Sr-----	90.	85.	122.	133.	240.	110.	140.	105.
Ta-----	0.44	0.48	0.33	0.28	0.26	0.30	0.34	0.41
Th-----	6.5	6.5	5.4	5.5	4.3	5.9	5.5	6.2
U-----	0.7	1.5	1.5	1.6	1.3	1.7	1.7	1.4
W-----	1.1	0.90	1.3	1.4	1.3	1.4	1.5	--
Y-----	50.	49.	47.	49.	45.	57.	52.	58.
Zn-----	40.	37.	52.	53.	54.	57.	51.	62.
Zr-----	262.	262.	227.	242.	175.	216.	235.	243.
La-----	17.	17.	19.	20.	17.	20.	20.	21.
Ce-----	39.	38.	43.	45.	38.	45.	45.	47.
Nd-----	24.	22.	26.	27.	20.	29.	24.	29.
Sm-----	6.0	6.1	6.5	6.6	5.8	6.9	6.9	6.8
Eu-----	0.91	0.87	1.06	1.14	1.20	1.06	1.20	1.07
Gd-----	5.9	5.6	5.9	6.1	5.8	6.1	5.7	7.7
Tb-----	1.08	1.09	1.16	1.24	0.89	1.00	1.09	1.27
Tm-----	0.69	0.78	0.75	0.75	0.57	0.78	0.77	0.74
Yb-----	5.0	4.9	5.3	5.3	4.4	5.5	5.6	5.8
Lu-----	0.76	0.75	0.76	0.79	0.64	0.78	0.79	0.84
Nb/Ta-----	13.6	19.2	21.5	18.9	18.9	20.3	16.2	--
K/Rb-----	335.	338.	376.	396.	332.	344.	324.	352.
Rb/Sr-----	0.87	0.89	0.59	0.53	0.27	0.77	0.61	0.78
Ca/Sr-----	95.	103.	111.	74.	87.	89.	73.	75.
Th/U-----	9.1	4.3	3.6	3.4	3.3	3.5	3.2	4.4
Zr/Hf-----	43.	42.	36.	37.	35.	33.	35.	35.
Ce/Yb-----	7.8	7.8	8.1	8.5	8.6	8.2	8.0	8.1
Eu/Eu*-----	0.47	0.46	0.53	0.55	0.60	0.51	0.59	0.46

See footnotes at end of table.

APPENDIX I.—*Chemical analyses of subalkalic silicic obsidians*—Continued

Country/State-----	PAPUA NEW GUINEA				NEW BRITAIN	NEW ZEALAND	
Volcanic field/region---	Admiralty Islands						
Locality-----	Tuluman Island	Lou Island		Pam Lin Island	Talasea	Ongaroto	Tauhara
Specimen-----	211	212	213	214	215	216	217
Collection No. (RLS-)---	70	62	58	64	60	3	71
Chemical analyses (weight percent)							
SiO <sub>2</sub> -----	69.47	71.80	73.55	73.63	76.0	76.97	76.8
Al <sub>2</sub> O <sub>3</sub> -----	13.90	13.90	13.58	13.32	12.73	12.25	12.58
Fe <sub>2</sub> O <sub>3</sub> -----	0.90	0.27	0.48	0.52	0.53	0.39	0.49
FeO-----	2.62	1.81	1.44	1.39	0.64	0.81	0.82
MgO-----	0.49	0.45	0.38	0.29	0.21	0.15	0.15
CaO-----	1.89	1.26	1.01	0.85	1.20	0.90	1.09
Na <sub>2</sub> O-----	5.38	4.95	4.84	4.74	3.93	3.89	4.04
K <sub>2</sub> O-----	3.21	4.45	4.11	4.22	3.78	3.89	3.47
H <sub>2</sub> O+-----	0.06	0.04	0.21	0.28	0.08	0.22	0.07
TiO <sub>2</sub> -----	0.45	0.29	0.26	0.22	0.24	0.14	0.19
P <sub>2</sub> O <sub>5</sub> -----	0.13	0.04	0.03	0.02	0.03	0.03	0.02
MnO-----	0.10	0.06	0.07	0.06	0.06	0.05	0.04
Cl*-----	0.37	0.38	0.32	0.31	0.15	--	0.12
Cl**-----	0.35	0.34	0.28	0.30	0.14	0.14	0.09
F*-----	0.14	0.12	0.11	0.13	0.05	--	0.03
F**-----	0.13	0.11	0.11	0.12	0.05	0.04	0.03
Subtotal-----	99.10 <sup>7</sup>	99.80	100.37	99.97	99.62	99.87	99.90
Less O=(F,Cl) <sub>2</sub> -----	0.14	0.13	0.12	0.12	0.05	0.05	0.04
Total-----	99.06 <sup>7</sup>	99.67	100.25	99.85	99.57	99.82	99.86
FeO <sup>1</sup> -----	3.43	2.05	1.87	1.86	1.12	1.16	1.26
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.74	0.87	0.75	0.73	0.55	0.68	0.63
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.68	1.11	1.18	1.12	1.04	1.00	1.16
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.89	0.93	0.91	0.93	0.83	0.87	0.83
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.13	1.10	1.05	1.05	1.00	1.00	--
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.22	0.13	0.11	0.09	0.16	0.12	0.15
Cl/F <sup>1†</sup> -----	2.7	3.0	2.6	2.5	3.0	3.5	3.4
CIPW norms							
Q-----	21.10	22.38	26.55	27.38	35.90	37.12	37.24
or-----	19.25	26.49	24.35	25.12	22.48	23.11	20.57
ab-----	46.20	42.19	41.06	40.41	33.47	33.09	34.29
an-----	4.36	2.58	3.20	2.63	5.80	4.29	5.29
C-----	--	--	--	--	0.06	0.08	0.25
ac-----	--	--	--	--	--	--	--
ns-----	--	--	--	--	--	--	--
wo }-----	1.79	1.44	0.68	0.62	--	--	--
en } di-----	0.49	0.44	0.23	0.18	--	--	--
fs }-----	1.40	1.06	0.47	0.47	--	--	--
en } hy-----	0.75	0.69	0.72	0.55	0.53	0.38	0.38
fs }-----	2.17	1.69	1.48	1.42	0.46	1.03	0.86
mt-----	1.32	0.39	0.70	0.76	0.77	0.57	0.71
il-----	0.87	0.56	0.50	0.42	0.46	0.27	0.36
ap-----	0.31	0.09	0.07	0.05	0.07	0.07	0.05



	211	212	213	214	215	216	217
Trace elements (ppm)							
Ba-----	721.	800.	755.	771.	540.	844.	730.
Be-----	2.8	2.4	2.3	2.5	0.86	1.6	1.9
Co-----	3.3	1.8	1.2	0.9	0.6	0.5	0.7
Cr-----	2.7	<7.0	<7.0	<6.0	<6.0	<5.0	<6.0
Cs-----	1.7	2.1	1.9	2.0	1.3	5.3	5.6
Hf-----	10.9	9.5	7.9	7.6	3.4	3.3	4.3
Li-----	16.	18.	19.	20.	18.	49.	41.
Mo-----	3.7	3.6	4.3	3.2	4.7	1.6	1.5
Nb**-----	53.	46.	42.	42.	3.2	6.3	8.4
Nb***-----	52.	48.	42.	36.	3.	9.	8.
Pb-----	7.	9.	9.	16.	19.	22.	22.
Rb**-----	121.	151.	149.	158.	51.	134.	125.
Rb***-----	115.	146.	155.	158.	55.	145.	129.
Sb-----	<0.6	<0.6	<0.8	<0.7	<0.7	<0.7	<0.7
Sc-----	7.1	4.1	4.0	3.8	4.0	2.7	4.0
Sn-----	2.9	4.0	2.2	3.0	1.2	2.8	2.1
Sr-----	95.	68.	70.	46.	216.	78.	100.
Ta-----	4.13	3.77	3.37	3.56	0.21	0.80	0.82
Th-----	10.2	11.9	11.5	12.0	2.7	14.2	13.1
U-----	3.3	3.2	3.0	3.8	1.8	3.1	3.6
W-----	1.4	1.6	1.5	1.3	0.43	1.3	1.7
Y-----	51.	36.	31.	38.	27.	29.	19.
Zn-----	63.	44.	42.	46.	31.	29.	33.
Zr-----	539.	435.	342.	322.	162.	100.	178.
La-----	47.	44.	43.	43.	13.	26.	23.
Ce-----	86.	80.	82.	78.	24.	47.	48.
Nd-----	42.	33.	31.	35.	14.	18.	19.
Sm-----	9.0	6.5	6.4	6.6	3.2	3.6	4.0
Eu-----	1.67	1.17	0.99	0.94	0.66	0.48	0.61
Gd-----	6.9	6.2	5.6	5.3	2.9	3.0	3.4
Tb-----	1.56	0.93	0.98	1.05	0.47	0.50	0.74
Tm-----	0.82	0.64	0.61	0.60	0.33	0.41	0.47
Yb-----	5.4	4.2	4.3	4.4	2.4	2.4	2.6
Lu-----	0.83	0.64	0.62	0.63	0.38	0.34	0.39
Nb/Ta-----	12.7	12.5	12.5	11.0	14.8	9.6	10.0
K/Rb-----	232.	253.	220.	222.	571.	223.	223.
Rb/Sr-----	1.2	2.2	2.2	3.4	0.26	1.9	1.3
Ca/Sr-----	142.	132.	103.	132.	40.	83.	78.
Th/U-----	3.1	3.8	3.9	3.2	1.5	4.6	3.7
Zr/Hf-----	49.	46.	43.	42.	48.	30.	41.
Ce/Yb-----	15.9	19.0	19.1	17.7	10.0	19.6	18.5
Eu/Eu*-----	0.65	0.53	0.51	0.48	0.67	0.45	0.46

\*Analyses performed by the University of Reading.  
 \*\*Analyses performed by the U.S. Geological Survey.  
 \*\*\*Analyses performed by the University of Lancaster.  
 †Cl/F ratios calculated from raw (ppm) data.

--, not determined.

<sup>1</sup> By weight.  
<sup>2</sup> Molecular.  
<sup>3</sup> Probably reflects contamination.  
<sup>4</sup> Normative wollastonite, 0.07 percent.  
<sup>5</sup> Total includes Li<sub>2</sub>O, 0.73 percent by weight.  
<sup>6</sup> Normative wollastonite (0.05 percent) and hematite (0.09 percent).  
<sup>7</sup> Total includes H<sub>2</sub>O-, 0.10 percent by weight.

## NORTH AMERICA

## UNITED STATES OF AMERICA

## ALASKA

## UMNAK ISLAND VOLCANIC FIELD

- 1 (190) Microvesicular obsidian, cracked, slightly hydrated, lava dome, southwest Umnak Island, Aleutian Islands, Alaska. Lat 53°10.14' N., long 168°24.85' W. Collected by R.L. Smith and T.P. Miller. Same locality as that studied by Byers (1959, table 2, No. 32 (major element analysis), and table 3, No. 32 (modal analysis)).
- 2 (56) Obsidian agglutinate lava, northwest slope of Somma I of Okmok caldera, northwest Umnak Island, Aleutian Islands, Alaska. Lat 53°29.02' N., long 168°9.18' W. Collected by R.L. Smith and T.P. Miller. Same locality as that studied by Byers (1959, table 2, No. 19 (major element analyses) and table 3, No. 19 (modal analysis)). See also table 15, sample No. 242 this study.

## KATMAI VOLCANIC FIELD

- 3 (214) Microvesicular obsidian, lava dome, Novarupta, Valley of Ten Thousand Smokes, Alaska. Lat 58°16.57' N., long 155°9.41' W. Supplied by Wes Hildreth.

## WRANGELL MOUNTAINS VOLCANIC FIELD

- 4 (39) Porphyritic obsidian, strongly annealed, lava flow, southeast slope of Capital Mountains, northwestern Wrangell Mountains, Alaska. Lat 62°24.01' N., long 144°2.26' W. Collected by R.L. Smith.
- 5 (196) Glass separate of sample 4 (39).
- 6 (45) Obsidian, Apache tear, lava flow, west side of Ptarmigan Lake, eastern Wrangell Mountains, Alaska. Lat 141°11.67' W., long 61°51.96' N. Collected by R.L. Smith and D.H. Richter.

## INDIAN RIVER

- 7 (46) Obsidian, Apache tear. Residual litter from rhyolite lava flow, drainage divide between Indian and Little Indian rivers, Koyukuk River

valley, 29 km southeast of Hughes, Alaska. Lat 65°49' N., long 154°00' W. Supplied by W.W. Patton, Jr. and T.P. Miller. This obsidian is in all probability the same as that studied by Ross and Smith (1955) from "Norwikakat River," Alaska, U.S. National Museum No. 6384. We have never been able to find this locality on a map.

## OREGON

## SOUTH SISTER

- 8 (187) Porphyritic microvesicular obsidian, lava from southernmost vent of Holocene chain of vents, south flank of South Sister, Cascade Range, Deschutes County, Oregon. Lat 44°2.03' N., long 121°45.33' W. Collected by R.L. Smith and H.R. Shaw.
- 9 (189) Porphyritic microvesicular obsidian, early lobe of lava from northernmost vent of Holocene chain of vents, southeast flank of South Sister, Cascade Range, Deschutes County, Oregon. Lat 44°4.32' N., long 121°44.77' W. Collected by R.L. Smith and H.R. Shaw.
- 10 (199) Glass separate of sample 9 (189).

## CRATER LAKE VOLCANIC FIELD

- 11 (8-3Av) Porphyritic dacite glass, The Watchman, Crater Lake, Klamath County, Oregon. Lat 42°56.62' N., long 122°10.61' W. Supplied by Donald C. Noble.
- 12 (8-3Av-G) Rhyolitic glass separate from sample 11 (8-3Av). Supplied by Donald C. Noble.
- 13 (9-2v) Porphyritic obsidian, Grouse Hill, Crater Lake, Klamath County, Oregon. Lat 42°59.46' N., long 122°7.32' W. Supplied by Donald C. Noble.
- 14 (9-2v-G) Glass separate from sample 13 (9-2v). Supplied by Donald C. Noble.
- 15 (9-16v) Porphyritic obsidian, Llao Rock, Crater Lake, Klamath County, Oregon. Lat 42°58.78' N., long 122°7.32' W. Supplied by Donald C. Noble.
- 16 (9-16v-G) Glass separate from sample 15 (9-16v). Supplied by Donald C. Noble.
- 17 (9-19v) Porphyritic obsidian, lava, Redcloud Cliff, Klamath County, Crater Lake, Oregon. Lat 42°56.76' N., long 122°2.74' W. Supplied by Donald C. Noble.

- 18 (9-19v-G) Glass separate from sample 17 (9-19v). Supplied by Donald C. Noble.
- 19 (222) Porphyritic obsidian, Cleetwood lava flow, Crater Lake, Oregon. Lat 42°58.76' N., long 122°4.39' W. Supplied by Charles R. Bacon, No. 79C160.
- 20 (223) Porphyritic obsidian, lava, Cloudcap, Crater Lake, Oregon. Lat 42°56.01' N., long 122°2.47' W. Supplied by Charles R. Bacon, No. 79C161.
- 21 (224) Porphyritic obsidian, lava, Llao Rock flow, Crater Lake, Oregon. Lat 42°58.35' N., long 122°8.6' W. Supplied by Charles R. Bacon, No. 79C153.

## NEWBERRY VOLCANIC FIELD

- 22 (144) Obsidian, Lost Lake, Big Obsidian flow, Newberry Caldera, Deschutes County, Oregon. Lat 43°42.3' N., long 121°14.56' W. Collected by R.L. Smith.
- 23 (156) Obsidian, East Lake, southwest obsidian flow, Newberry Caldera, Deschutes County, Oregon. Lat 43°42.84' N., long 121°13.81' W. Collected by R.L. Smith.

## SOUTHEAST OREGON VOLCANIC AREA

- 24 (159) Obsidian, lava dome, East Butte, Deschutes County, Oregon. Lat 43°40.14' N., long 120°58.33' W. Collected by R.L. Smith and G.W. Walker.
- 25 (157) Obsidian, lava dome, Quartz Mountain, Deschutes County, Oregon. Lat 43°38.11' N., long 120°53.7' W. Collected by R.L. Smith and G.W. Walker.
- 26 (162) Obsidian, lava dome, Cougar Mountain, Lake County, Oregon. Lat 43°24.46' N., long 120°53.33' W. Collected by R.L. Smith and G.W. Walker.
- 27 (158) Obsidian, lava dome, northwest cluster of Glass Buttes, Lake County, Oregon. Lat 43°33.38' N., long 120°1.85' W. Collected by R.L. Smith and G.W. Walker.
- 28 (154) Obsidian, lava flow, roadcut on U.S. Highway 395, 4.6 miles south of U.S. Highway 20, near Riley, Lake County, Oregon. Lat 43°29.05' N., long 119°32.22' W. Collected by R.L. Smith and G.W. Walker.
- 29 (54) Obsidian, residual block from lava flow, Horse Mountain, Lake County, Oregon. Lat 43°8.24' N., long 120°10.37' W. Collected by R.L. Smith and G.W. Walker.

- 30 (163) Obsidian, lava, southwest base of Razorback Ridge, Drewes Ranch, Lake County, Oregon. Lat 42°16.62' N., long 120°42.29' W. Collected by R.L. Smith and G.W. Walker.
- 31 (161) Obsidian, Apache tear, lava dome, east side of Tucker Hill, Lake County, Oregon. Lat 42°35.27' N., long 120°25.27' W. Collected by R.L. Smith and G.W. Walker.
- 32 (155) Obsidian, Apache tears, lava dome, McComb Butte, Lake County, Oregon. Lat 42°35.14' N., long 120°37.13' W. Collected by R.L. Smith and G.W. Walker.
- 33 (164) Obsidian, welded tuff, lithophysal cooling unit, mouth of Orijana Canyon, Poker Jim Ridge, northern Hart Mountain, Harney County, Oregon. Lat 42°48.51' N., long 119°29.63' W. Collected by R.L. Smith and G.W. Walker.
- 34 (160) Obsidian, cobble in alluvial fan, eroded from nearby lavas, northwest base of Beatys Butte, Harney County, Oregon. Lat 42°25' N., long 119°22.13' W. Collected by R.L. Smith and G.W. Walker.

#### CALIFORNIA

##### WARNER MOUNTAINS VOLCANIC AREA

- 35 (51) Obsidian, lava dome, west side of Sugar Hill near lookout tower, Warner Mountains. Modoc County, California. Lat 41°48.11' N., long 120°19.70' W. Collected by R.L. Smith and W.A. Duffield.
- 36 (52) Porphyritic obsidian, lava flow, residual block on erosion surface, southeast flank of Sugar Hill, Warner Mountains, Modoc County, California. Lat 41°47.03' N., long 120°18.80' W. Collected by R.L. Smith and W.A. Duffield.
- 37 (40) Obsidian, lava, northwest flank of Buck Mountain, Warner Mountains, Modoc County, California. Lat 41°45' N., long 120°18.25' W. Collected by R.L. Smith and W.A. Duffield.
- 38 (41) Obsidian, lava, north flank of Buck Mountain, Warner Mountains, Modoc County, California. Lat 41°43.78' N., long 120°16.81' W. Collected by R.L. Smith and W.A. Duffield.
- 39 (44) Obsidian, lava, block from residual litter on eroded top of flow, east flank of Buck Mountain near head of Boyd Creek. Warner Mountain escarpment, Modoc County, California. Lat 41°42.57' N., long 120°15.36' W. Collected by R.L. Smith and W.A. Duffield.

##### MEDICINE LAKE HIGHLANDS VOLCANIC FIELD

- 40 (142) Obsidian, lava, residual block on eroded flow, Grasshopper Flat, Medicine Lake Highlands, Modoc County, California. Lat 41°31.35' N., long 121°42.40' W. Collected by R.L. Smith.
- 41 (143) Obsidian, lava flow, Little Glass Mountain, Medicine Lake Highlands, Modoc County, California. Lat 41°34.59' N., long 121°40.6' W. Collected by R.L. Smith and I. Friedman.
- 42 (141) Obsidian, lava flow, rhyolitic part, middle of flow, Big Glass Mountain, Medicine Lake Highlands, Modoc County, California. Lat 41°37.43' N., long 121°27.66' W. Collected by R.L. Smith and I. Friedman.
- 43 (RGM-1) Obsidian, lava flow, Big Glass Mountain, Medicine Lake Highlands, Modoc County, California. U.S. Geological Survey Chemical Rock Standard RGM-1. Tatlock and others (1976, p. 11). Supplied by F.J. Flanagan.

##### SONOMA VOLCANIC FIELD

- 44 (43) Obsidian, block from roadcut in lava dome, Napa Glass Mountain, Napa County, California. Lat 38°31.76' N., long 122°29.14' W. Collected by R.L. Smith.

##### CLEAR LAKE VOLCANIC FIELD

- 45 (153) Obsidian, clast in tuff, rhyolite of Bonanza Springs, Loch Lomond, Lake County, California. Lat 38°51.55' N., long 122°43.27' W. Supplied by B.C. Hearn.
- 46 (149) Obsidian, lava flow, Camel Back Ridge, rhyolite of Thurston Creek, Lake County, California. Lat 38°54.19' N., long 122°47.34' W. Collected by R.L. Smith and B.C. Hearn.
- 47 (7) Obsidian, lava flow, rhyolite of Thurston Creek, Manning Flat, Lake County, California. Lat 38°55.41' N., long 122°41.82' W. Collected by R.L. Smith and I. Friedman. Major element analyst: Ellen S. Daniels, Denver RAL, USGS. Analysis previously unpublished.
- 48 (150) Obsidian, lava dome, rhyolite of Borax Lake, Clear Lake Park, Lake County, California. Lat 38°58.13' N., long 122°38.7' W. Supplied by B.C. Hearn.

##### MONO-INYO VOLCANIC FIELD

- 49 (148) Obsidian, lava flow, Northwest Coulee, Mono Craters, Mono County, California. Lat 37°54.46'

N., long 119°2.13' W. Collected by R.L. Smith and I. Friedman.

- 50 (147) Obsidian, lava dome, Panum Dome, Mono Craters, Mono County, California. Lat 37°55.88' N., long 119°2.47' W. Collected by R.L. Smith and I. Friedman.
- 51 (MC73-1A) Obsidian, lava dome, Obsidian Dome, Inyo Craters chain, Mono County, California. Lat 37°46' N., long 119°01' W. Supplied by R.A. Bailey.
- 52 (M72-8) Obsidian, lava dome, "early rhyolite" sequence, Long Valley Caldera, Mono County, California. Lat 37°40' N., long 118°00' W. Supplied by R.A. Bailey.
- 53 (M72-21) Obsidian, lava dome, "early rhyolite" sequence, Long Valley Caldera, Mono County, California. Lat 37°41' N., long 118°53' W. Supplied by R.A. Bailey.
- 54 (M72-62) Sparsely porphyritic obsidian, Hot Creek lava flow, moat rhyolite sequence, Long Valley Caldera, Mono County, California. Lat 37°38' N., long 118°50' W. Supplied by R.A. Bailey.

##### BIG PINE VOLCANIC FIELD

- 55 (9) Obsidian, lava flow, 7 miles south of Big Pine, Inyo County, California. Lat 37°3.38' N., long 118°17.87' W. Collected by R.L. Smith and I. Friedman. Major element analyst: Ellen S. Daniels, Denver RAL, USGS. Analysis previously unpublished.

##### NORTHERN COSO MOUNTAINS

- 56 (5) Obsidian, Apache tears, intrusive margin of dome, northern end of the Coso Mountains, about 10 miles northeast of Olancho, Inyo County, California. Lat 36°20.54' N., long 117°50.61' W. Collected by R.L. Smith and I. Friedman. Major element analyst: Ellen S. Daniels, Denver RAL, USGS. Analysis previously unpublished.

##### COSO VOLCANIC FIELD

- 57 (CD-3) Spherulitic obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°4.97' N., long 117°51.71' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 13).
- 58 (CD-4A) Lithophysal obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat

36°4.86' N., long 117°51.08' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 10).

- 59 (CD-5) Spherulitic obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°4.73' N., long 117°51.44' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 14).
- 60 (CD-17) Obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°3.07' N., long 117°49.13' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 15).
- 61 (CD-22) Obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°1.89' N., long 117°50.46' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 19).
- 62 (CD-7) Obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°6.15' N., long 117°48.21' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 5).
- 63 (CD-20) Obsidian, Apache tears, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°2.48' N., long 117°48.58' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 16).
- 64 (CD-23) Obsidian, lava flow, Coso Volcanic Field, Inyo County, California. Lat 36°1.32' N., long 117°49.46' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 20).
- 65 (CD-30) Scoriaceous obsidian, lava flow, Coso Volcanic Field, Inyo County, California. Lat 35°59.76' N., long 117°48.5' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 24).
- 66 (CD-33) Spherulitic obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat 35°59.39' N., long 117°48.94' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 25).
- 67 (CD-8) Obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°5.54' N., long 117°47.29' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 4).
- 68 (CD-12) Lithophysal obsidian, lava dome, Cactus Peak, Coso Volcanic Field, Inyo County, California. Lat 36°4.73' N., long 117°49.21' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 6).
- 69 (CD-14) Obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°3.92' N., long 117°49.75' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 27).

- 70 (CD-18) Obsidian, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°3.01' N., long 117°48.95' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 17).
- 71 (CD-19) Obsidian, Apache tears, lava dome, Coso Volcanic Field, Inyo County, California. Lat 36°2.77' N., long 117°48.36' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 18).
- 72 (CD-21A) Obsidian, lava flow, Sugarloaf Mountain, Coso Volcanic Field, Inyo County, California. Lat 36°1.49' N., long 117°49.05' W. Collected by R.L. Smith and W.A. Duffield. Bacon and others (1981, sample No. 26).

#### SALTON SEA VOLCANIC FIELD

- 73 (49) Obsidian, lava dome, Obsidian Butte, Salton Sea, Imperial County, California. Lat 33°10.14' N., long 115°38.23' W. Collected by R.L. Smith and L.J.P. Muffler.
- 74 (50) Obsidian, lava dome, Red Island, Salton Sea, Imperial County, California. Lat 33°11.89' N., long 115°36.61' W. Collected by R.L. Smith and L.J.P. Muffler.
- 75 (212) Obsidian, lava dome, Mullet Island, Salton Sea, Imperial County, California. Lat 33°13.51' N., long 115°36.45' W. Supplied by K.J. Murata.

#### NEVADA

##### PERSHING COUNTY

- 76 (21) Obsidian, Apache tear, residual in perlite, near head of Cow Creek, north end of Seven Troughs Range, Pershing County, Nevada. Lat 40°35.68' N., long 118°46.43' W. Collected by R.L. Smith and D.B. Tatlock. Major element analyst: Elaine L. Munson, Denver RAL, USGS. Analysis previously unpublished.
- 77 (29) Obsidian, Apache tear, residual in perlite, 9 miles southeast of Rabbit Hole, Pershing County, Nevada. Lat 40°38.24' N., long 118°39.82' W. Collected by R.L. Smith and D.B. Tatlock. Major element analyst: Elaine L. Munson, Denver RAL, USGS. Analysis previously unpublished.
- 78 (31) Obsidian, Apache tear, residual in perlite, U.S. Gypsum perlite mine, Trinity Range, 8 miles northwest of Lovelock, Pershing County, Nevada. Lat 40°17.3' N., long 118°33.53' W. Collected by R.L. Smith and D.B. Tatlock. Major

element analyst: Elaine L. Munson, Denver RAL, USGS. Analysis previously unpublished.

- 79 (74) Obsidian, residual litter on distal part of eroded lava flow from McGee Mountain. Nevada Highway 120, Humboldt County, Nevada. Lat 41°54.32' N., long 118°58.83' W. Collected by R.L. Smith and H.R. Shaw.

#### ESMERALDA COUNTY

- 80 (226) Obsidian, cobble in alluvial fan, from unknown source in Clayton Ridge, Esmeralda County, Nevada. Lat 37°39' N., long 117°33' W. Supplied by J.R. Davis.
- 81 (202) Obsidian, Apache tear, residual in perlite, basal glass of lava flow, northeast end of Monte Cristo Range, Esmeralda County, Nevada. Lat 38°13.78' N., long 117°36.51' W. Supplied by M.L. Silberman.

#### TIMBER MOUNTAIN VOLCANIC FIELD

- 82 (14) Obsidian, Apache tears, residual in perlite, basal glass of lava flow, rhyolite of Shoshone Mountain, Nevada Test Site, Nye County, Nevada. Lat 37°1.08' N., long 116°18.14' W. Collected by R.L. Smith and P.P. Orkild. Major element analyst: Ellen S. Daniels, Denver RAL, USGS. Analysis previously unpublished.

#### IDAHO

##### SNAKE RIVER PLAIN

- 83 (75) Obsidian, erosional litter from lava dome, south side of Big Southern Butte, Butte County, Idaho. Lat 43°23.11' N., long 113°0.56' W. Collected by R.L. Smith and R.G. Luedke.
- 84 (151) Obsidian, welded tuff, archetype deposit, near Ammon, Bonneville County, Idaho. Lat 43°23.51' N., long 111°51.48' W. Collected by C.S. Ross and R.L. Smith.
- 85 (152) Obsidian, welded tuff, Walcott Tuff, Snake River Canyon below American Falls, Power County, Idaho. Lat 42°46.62' N., long 112°52.41' W. Collected by R.L. Smith.

#### BLACKFOOT VOLCANIC FIELD

- 86 (185) Porphyritic obsidian, incipiently spherulitic, lava dome, southwest side of Middle Cone, Blackfoot Lava Field, Caribou County, Idaho.

Lat 42°49.32' N., long 111°36.04' W. Collected by R.L. Smith and R.G. Luedke.

- 87 (188) Porphyritic obsidian, incipiently spherulitic, lava dome, southwest side of North Cone, Blackfoot Lava Field, Caribou County, Idaho. Lat 42°50' N., long 111°34.94' W. Collected by R.L. Smith and R.G. Luedke.
- 88 (191) Porphyritic obsidian, incipiently spherulitic, lava dome, north side of China Hat, Blackfoot Lava Field, Caribou County, Idaho. Lat 42°48.92' N., long 111°36.31' W. Collected by R.L. Smith and R.G. Luedke.

## WYOMING

### YELLOWSTONE VOLCANIC FIELD

- 89 (7YC-288A) Apache tears from densely fused air-fall tuff, just below base of ash-flow tuff of Member A, Huckleberry Ridge Tuff, Island Park Caldera, Yellowstone National Park, Wyoming. Sample from bluff on south rim of Mt. Everts about 1.4 km northwest of Undine. Lat 44°57.5' N., long 110°39.36' W. Supplied by R.L. Christiansen. Sparse phenocrysts.
- 90 (267) Obsidian, rhyolite of Gibbon River flow, from low plateau about 2 km southeast of Norris Geyser Basin. Yellowstone National Park, Wyoming. Lat 44°42.77' N., long 110°42.15' W. Supplied by R.L. Christiansen. No. 65YR-7. Sparse phenocrysts.
- 91 (268) Obsidian, phenocrystic, rhyolite of Summit Lake flow, from top of bluffs on west side of Black Sand Basin (Upper Geyser Basin), Yellowstone National Park, Wyoming. Lat 44°27.57' N., long 110°52.03' W. Supplied by R.L. Christiansen. No. 6YC-73.
- 92 (269) Obsidian, phenocrystic, rhyolite of Elephant Back flow, from Elephant Back about 2 km northwest of Fishing Bridge, Yellowstone National Park, Wyoming. Lat 44°34.73' N., long 110°24.49' W. Supplied by R.L. Christiansen. No. 8YC-374C.
- 93 (270) Obsidian, rhyolite of Crystal Spring flow, from 350 m northeast of Obsidian Lake, Yellowstone National Park, Wyoming. Lat 44°50.74' N., long 110°42.53' W. Supplied by R.L. Christiansen. No. 8YC-396A.
- 94 (271) Obsidian, rhyolite of Obsidian Cliff flow, from near mouth of dry gully, about 0.6 km east of Lake of the Woods, Yellowstone National Park, Wyoming. Lat 44°28.24' N., long 110°42.44' W.

Lipman and others (1969, table 1, No. 15), Zielinski and others (1977, table 1). Our sample supplied by R.L. Christiansen. No. 6YC-64.

## UTAH

- 95 (106) Obsidian, Apache tears, residual litter from lava flow on south side of Wildcat Hills, Box Elder County, Utah. Lat 41°49.46' N., long 113°1.81' W. Collected by R.L. Smith and R.G. Luedke.
- 96 (116) Snowflake obsidian, strongly annealed, lava dome, White Mountain, Millard County, Utah. Lat 38°54.86' N., long 112°29.83' W. Collected by R.L. Smith and R.G. Luedke.

### TWIN PEAKS VOLCANIC FIELD

- 97 (103) Obsidian, lava, east of South Twin Peak, residual in perlite, rhyolite of Cudahy Mine, Twin Peak Volcanic Field, Millard County, Utah. Lat 38°44.86' N., long 112°44.48' W. Collected by R.L. Smith and H.R. Shaw.
- 98 (104) Obsidian, northwest lava flow, blocks from breccia, rhyolite of Cudahy Mine, Twin Peaks Volcanic Field, Millard County, Utah. Lat 38°46.35' N., long 112°49.83' W. Collected by R.L. Smith and H.R. Shaw.
- 99 (105) Obsidian, alluvial blocks from southwest lava flow, rhyolite of Cudahy Mine, Twin Peaks Volcanic Field, Millard County, Utah. Lat 38°43.51' N., long 112°49.48' W. Collected by R.L. Smith and H.R. Shaw.

### MINERAL MOUNTAINS VOLCANIC FIELD

- 100 (136) Obsidian, lava flow, nose of Bailey Ridge flow, Mineral Mountains, Beaver County, Utah. Lat 38°29.05' N., long 112°49.74' W. Collected by R.L. Smith and W.P. Nash.
- 101 (137) Obsidian, lava flow, northeast side of Bailey Ridge flow, Mineral Mountains, Beaver County, Utah. Lat 38°29.19' N., long 112°49.05' W. Collected by R.L. Smith and W.P. Nash.
- 102 (138) Porphyritic obsidian, clast from air-fall deposit, residual litter on granite ridge crest near northernmost rhyolite dome, northern Mineral Mountains, Beaver County, Utah. Lat 38°31.08' N., long 112°47.93' W. Collected by R.L. Smith and W.P. Nash.
- 103 (139) Obsidian, lava flow, nose of Wildhorse Canyon flow, Mineral Mountains, Beaver

County, Utah. Lat 38°26.49' N., long 112°50.86' W. Collected by R.L. Smith and W.P. Nash.

## COLORADO

### NATHROP AREA

- 104 (33) Obsidian, Apache tears, lava dome (rhyolite of Nathrop), Bald Mountain, near Nathrop, Chaffee County, Colorado. Lat 38°47.03' N., long 106°1.72' W. Collected by R.L. Smith and R.E. Van Alstine. Major element analyst: Elaine L. Munson, Denver RAL, USGS. Partial analysis and mode published in Lipman and others (1968, table 1, No. 11); remainder of analysis previously unpublished.
- 105 (65L-161-A) Obsidian, Apache tears, basal glass of lava dome, Beaver Creek, San Juan Mountains, Rio Grande County, Colorado. Lat 37°34.46' N., long 106°39.61' W. Supplied by P.W. Lipman. Major element analysis and mode from Lipman (1975, table 11, No. 11) except H<sub>2</sub>O<sup>+</sup>, H<sub>2</sub>O, Cl, and F, taken from Lipman and others (1968 table 1, No. 1). Minor elements from Zielinski and others (1977, table 1).

## ARIZONA

### SUPERIOR

- 106 (35) Obsidian, Apache tears (archetype deposit), lava, Queen Creek near the Old Pinal Townsite, Pinal County, Arizona. Lat 33°17' N., long 11°8.5' W. Collected by R.L. Smith and D.W. Peterson. Major element analyst: Paula M. Bushman, Denver RAL, USGS. Analysis previously unpublished.

### SAN FRANCISCO MOUNTAINS VOLCANIC FIELD

- 107 (48) Obsidian, block from lava dome, Government Mountain, San Francisco Volcanic Field, Coconino County, Arizona. Lat 35°20.68' N., long 111°54.4' W. Collected by R.L. Smith and H.R. Shaw.
- 108 (53) Obsidian, annealed relict mass in spherulitic domain, lava dome, southeast unit of Sitgreaves cluster, San Francisco Volcanic Field, Coconino County, Arizona. Lat 35°20' N., long 111°58.35' W. Collected by R.L. Smith and H.R. Shaw.
- 109 (47) Obsidian, lava dome. R. S. Hill, outlier of Sitgreaves cluster, San Francisco Volcanic

Field, Coconino County, Arizona. Lat 35°21.62' N., long 111°57.53' W. Collected by R.L. Smith and H.R. Shaw.

## NEW MEXICO

### TAOS PLATEAU VOLCANIC FIELD

- 110 (27) Obsidian, Apache tears, lava dome. Cerros No Agua, Taos County, New Mexico. Lat 36°45.68' N., long 105°56.97' W. Collected by C.S. Ross and R.L. Smith. An analysis of perlite associated with this obsidian is shown as sample 218 (28).
- 111 (66L-23-A) Obsidian, Apache tears, lava dome. Cerros No Agua, Taos County, New Mexico. Lat 36°45.68' N., long 105°56.97' W. Supplied by P.W. Lipman. This sample, studied by Lipman and others (1969, table 1, No. 5) and by Zielinski and others (1977), is clearly different chemically from our sample 110 (27) collected by Ross and Smith and studied by them (1955, p. 1081, table 1, No. 5a) and by Friedman and Smith (1958, p. 224, table 1, No. 36-3). The latitude and longitude given here are the same as for our sample 110 and are probably slightly incorrect.

### JEMEZ MOUNTAINS VOLCANIC FIELD

- 112 (200) Obsidian, Apache tears, lava flow, Canovas Canyon Rhyolite, southern Jemez Mountains, Sandoval County, New Mexico. Lat 35°40.14' N., long 106°34.08' W. Collected by R.L. Smith and R.A. Bailey.
- 113 (15) Obsidian, Apache tears, lava flow, Canovas Canyon Rhyolite, southern Jemez Mountains, Sandoval County, New Mexico. Lat 35°41.76° N., long 106°34.5' W. Collected by C.S. Ross and R.L. Smith. Major element analyst: Elaine L. Munson, Denver RAL, USGS. Analysis previously unpublished.
- 114 (25) Obsidian, Apache tears, lava dome, El Rechuelos Rhyolite, northern Jemez Mountains, Rio Arriba County, New Mexico. Lat 36°3.92' N., long 106°25.5' W. Collected by R.L. Smith. Major element analyst: Elaine L. Munson, Denver RAL, USGS. Analysis previously unpublished.
- 115 (73) Obsidian, annealed mini-columns, lava dome carapace, El Rechuelos Rhyolite, northern Jemez Mountains, Rio Arriba County, New

Mexico. Lat 36°2.97' N., longitude 106°25.33' W. Collected by R.L. Smith and R.A. Bailey.

- 116 (194) Obsidian, cobble from alluvial deposit, from lava dome, El Rechuelos Rhyolite, northern Jemez Mountains, Rio Arriba County, New Mexico. Lat 36°7.97' N., long 106°25.33' W. Collected by R.L. Smith.
- 117 (17) Obsidian, block from hot avalanche deposit from lava dome, Cerro Toledo Rhyolite, Obsidian Ridge, east-central Jemez Mountains, Sandoval County, New Mexico. Lat 35°48.6' N., long 106°24.5' W. Collected by C.S. Ross and R.L. Smith. Major element analyst: Elaine L. Munson, Denver RAL, USGS. Analysis previously unpublished.
- 118 (72) Obsidian, block (clast) eroded from vent tuffs, Cerro Toledo Rhyolite, Santa Clara Canyon, north-central Jemez Mountains, Rio Arriba County, New Mexico. Lat 36°0.27' N., long 106°25.67' W. Collected by R.L. Smith.
- 119 (76-61) Obsidian, block, lava dome, Valles Rhyolite, top of Cerro del Medio, Valles Caldera, Sandoval County, New Mexico. Lat 35°54.32' N., long 106°26.92' W. Collected by R.L. Smith. Major element analyst: Vertie C. Smith, Denver RAL, USGS. Analysis previously unpublished.
- 120 (Posos) Obsidian, lithophysal block, alluvial from lava flow, Valles Rhyolite northwest flank Cerro del Medio, Valles Caldera, Sandoval County, New Mexico. Lat 35°56.22' N., long 106°26.83' W. Collected by C.S. Ross and R.L. Smith. This obsidian has long been used as a reference standard and may well have been used for a greater variety of measurements than any other obsidian. The locality has been referred to by many names by many authors: Los Posos, Posos, San Antonio, Puerto de Abrigo, Valles Caldera, and simply Jemez Mountains or New Mexico. The locality once supplied spectacular lithophysae containing cristobalite, alkali feldspar, fayalite, and magnetite, but over-collecting has made choice samples scarce. Major element analyst: Vertie C. Smith, Denver RAL, USGS. Analysis previously unpublished.
- 121 (76-79) Porphyritic obsidian, incipient hydration on cracks, lava flow, Valles Rhyolite, Banco Bonito, Valles Caldera, Sandoval County, New Mexico. Lat 35°50.14' N., long 106°34.5' W. Collected by R.L. Smith and R.A. Bailey. Major element analyst: Vertie C. Smith, Denver RAL, USGS. Analysis previously unpublished.

### MOGOLLON VOLCANIC AREA

- 122 (102) Obsidian, Apache tears, lava flow, Big Lue Mountains area, Grant County, New Mexico. Lat 33°8.11' N., long 109°1.77' W. Supplied by James C. Ratte.

## MEXICO

- 123 (131) Obsidian, lithophysae, lava flow, km 747, Mexico Federal Highway 15 near Magdalena, Jalisco, Mexico. Lat 20°54.5' N., long 103° 54' W. Collected by R.L. Smith.
- 124 (130) Obsidian, phenocrystic, lava flow, km 744, Mexico Federal Highway 15 near Magdalena, Jalisco, Mexico. Lat 20°54.5' N., long 103° 53.5' W. Collected by R.L. Smith.
- 125 (140) Obsidian, Apache tear, lava flow, top of plateau south of Rio Santiago, Federal Highway 70, north of Guadalajara, Jalisco, Mexico. Lat 20°43' N., long 103°17.5' W. Collected by R.L. Smith.
- 126-137 (See table for collection numbers.) Obsidians (some microvesicular) from lava flows and domes, Sierra la Primavera volcano complex, Jalisco, Mexico. Approx lat 20°35' N., approx long 103°32' W. Samples supplied by Gail Mahood. Sample localities, descriptions, and coordinates are given in Mahood (1981a, appendix 1, p. 147).
- 138 (274) Obsidian, residual blocks from lava flow, Jeraguero, Michoacan, Mexico. Approx lat 19°54.5' N., approx long 100°30.5' W. Collected by R.L. Smith.
- 139 (275) Obsidian, blocks in lava flow, roadside quarry, Zinapécuaro, Michoacan, Mexico. Lat 19°50.5' N., long 100°50' W. Collected by R.L. Smith.
- 140 (276) Obsidian, clast in coarse pyroclastic deposit, quarry east of Acámbaro, Guanajuato, Mexico. Lat 20°01' N., long 100°39' W. Collected by R.L. Smith.
- 141 (273) Obsidian, porphyritic block in lava flow, roadcut Los Azufres, Cerro San Andres, Michoacan, Mexico. Approx lat 19°49' N., approx long 100°41' W. Collected by R.L. Smith.
- 142 (280) Obsidian, clast in ash flow, Punte Carretara, Los Humeros volcanic complex, Vera Cruz, Mexico. Lat 19°42' N., long 97°15.5' W. Collected by R.L. Smith and C. Yáñez.
- 143 (277) Obsidian, lava flow, Oyameles Rhyolite, west wall of Los Potreros Caldera, Los Humeros

volcanic complex, Puebla, Mexico. Lat 19°43' N., long 97°30.5' W. Collected by R.L. Smith and C. Yáñez.

- 144 (278) Obsidian porphyritic, rhyolite lava of Cueva Ahumada, Los Potreros Caldera, Los Humeros volcanic complex, Puebla, Mexico. Lat 19°40' N., long 97°27' W. Collected by R.L. Smith and C. Yáñez.

- 145 (279) Obsidian, microvesicular clast, rhyolitic maar deposit, El Xalapazquillo, southeast of Las Derrumbadas, Puebla, Mexico. Lat 19°14' N., long 97°26' W. Collected by R.L. Smith and C. Yáñez.

- 146 (125) Obsidian, phenocrystic, exact provenance uncertain. This obsidian was collected in 1950 by the late Carl Fries, Jr., and labeled by him, Xalapazquillo, Puebla, Mexico. The obsidian, together with many textural variants (pumice, scoria, and so forth), was sent along with obsidian from other localities to C.S. Ross, and studied by Ross and Smith (1955), and was considered unusual by them because of its high H<sub>2</sub>O content and peculiar physical properties. After the death of Fries, several unsuccessful attempts were made to relocate this source. Part of the problem may involve the term Xalapazquillo as a proper place name. Maps of the region show many "Xalapazco's" and "Xalapazquillo's" applied to maars, most of which are associated with basalts. However in 1980, Smith was guided to a rhyolitic Xalapazquillo by C. Yáñez who was mapping in the Las Derrumbadas area. A sample collected at that time is included in our present study and is listed as No. 145 (279) above. This sample is also a high-water obsidian and, although it shows strong chemical similarities to 146 (125) and 147 (126), it is clearly a different glass. The true source for the Fries samples remains uncertain, although the chemical signatures indicate a strong provincial relation between the two sources.

- 147 (126) Obsidian. A second sample similar to 146 (125) from the same locality.

- 148 (127) Obsidian, highway cut between km 145 and 146 about 5 km N.-NE. of Tulancingo, Hidalgo, Mexico (Tuxpan Highway). Lat 20°6.5' N., long 98°20.5' W. Supplied by C. Fries, Jr., 1959.

- 149 (128) Obsidian, from Las Minitas about 4 km east of Rancho Guajolote, Hidalgo, Mexico. Approx lat 20°08' N., long 98°38' W. Supplied by C. Fries, Jr., 1959.

- 150 (132) Obsidian, from Tulancingo, Hidalgo, Mexico. Specific locality uncertain, but probably

related to 149 (128) by their chemical similarity. Supplied by C. Fries, Jr., 1959.

- 151 (129) Obsidian, from road metal pit near Zacualtipán, near junction with road to Huayacocotla, Hidalgo, Mexico. Lat 20°37' N., long 98°37.5' W. Supplied by C. Fries, Jr., 1959.

## CENTRAL AMERICA

### GUATEMALA

- 152 (134) Obsidian, El Fiscal, Guatemala. Approx lat 14°44' N., approx long 90°21.3' W. Supplied by Alexander R. McBirney, No. G-637.

- 153 (135) Obsidian, Cerro Ixtepequa, Guatemala. Approx lat 14°24.5' N., approximate long 89°59.5' W. Supplied by Alexander R. McBirney, No. G-664.

## SOUTH AMERICA

### COLOMBIA

- 154 (133) Obsidian, phenocrystic, microvesicular, welded breccia, lava near Popayan, Colombia. Approx lat 2°25' N., approx long 76°32' W. Supplied by I. Friedman.

### ECUADOR

- 155 (146) Obsidian, lava flow, Caldera Chacana, Pintag, Provincia de Pichincha, near Volcan Antisana, Ecuador. Approx lat 0°30' S., approx long 78°12' W. Supplied by M.L. (Pete) Hall. No. 38-18.

### ECUADOR (GALAPAGOS ISLANDS)

- 156 (186) Obsidian, phenocrystic, agglutinate lava flow on southwest floor of Alcedo caldera, Isla Isabela, Galapagos Islands, Ecuador. Lat 0°26.4' S., long 91°7.3' W. Supplied by Keith A. Howard.

- 157 (192) Obsidian, phenocrystic, probably agglutinated precaldra lava on southeast rim of Alcedo caldera, Isla Isabela, Galapagos Islands, Ecuador. Lat 0°26.1' S., long 91°5.2' W. Supplied by Keith A. Howard.

- 158 (193) Obsidian, phenocrystic, agglutinate, post(?) caldera lava flow on southwest flank of Alcedo volcano, Isla Isabela, Galapagos Islands, Ecuador. Lat 0°30.8' S., long 91°7.8' W. Supplied by Keith A. Howard.

## PERU

- 159 (206) Obsidian, specific locality unknown. Supplied by G.E. Ericksen.

- 160 (215) Obsidian, float cobble, collected near Macusani. Lat 14°4' S., long 70°27' W. Supplied by P.A. Jezek.

## CHILE (BOLIVIA?)

- 161 (225) Obsidian, block of densely welded breccia found in a mining camp near Chiguana, Bolivia, by Keith A. Howard and sent to R.L. Smith as a probable Andean obsidian. Further research by Smith on samples not considered in this compendium suggests that this obsidian is almost certainly from Chile. It is chemically indistinguishable from obsidians from the region of the Jarellon caldera near the three corners of Bolivia, Chile, and Argentina. Lat 22°55' S. and long 67°26' W.

- 162 (203) Obsidian, dome lava, Laguna del Maule area, central Chile. Lat 36°02' S., long 70°26' W. Supplied by Francisco Munizaga (sample FM68) by courtesy of G.E. Ericksen.

- 163 (204) Obsidian, dome lava, Laguna del Maule area, central Chile. Lat 36°02' S., long 70°26' W. Supplied by Francisco Munizaga (sample FM67A) by courtesy of G.E. Ericksen.

- 164 (205) Obsidian, lava flow, Laguna del Maule, central Chile. Lat 36°0.5' S., long 70°34.5' W. Supplied by Francisco Munizaga (sample FM13) by courtesy of G.E. Ericksen.

- 165 (220) Obsidian, lava flow, Laguna del Maule, central Chile. Lat 36°05.5' S., long 70°31' W. Supplied by Francisco Munizaga (sample FM 78) by courtesy of G.E. Ericksen.

- 166 (221) Obsidian, lava flow, Laguna del Maule, central Chile. Lat 36°08' S., long 70°27' W. Supplied by Francisco Munizaga (sample FM 81) by courtesy of G.E. Ericksen.

## ANTARCTICA

### SOUTH SHETLAND ISLANDS

- 167 (213) Obsidian, lava block, Ross Hill, Deception Island. Lat 62°56' S., long 60°34' W. Supplied by P.E. Baker.

## EUROPE

## ICELAND

- 168 (180) Obsidian, upper Quaternary dome lava, Botna-skyrtunna, Ljósufjöll central volcano, western Iceland. Lat 64°56' N., long 22°34' W. Supplied by H. Sigurdsson. Major element analysis in Bailey and Macdonald (1970, table 1, No. 7, No. 491).
- 169 (1) Obsidian, phenocrystic, Apache tears, dome lava, Prestahnukur, southwest base of Geitlandsjökull, Iceland. Lat 63°45.31' N., long 20°42' W. Collected by R.L. Smith and Tomas Trygvasson. D/H data by Friedman and Smith (1958), <sup>18</sup>O/<sup>16</sup>O data by Muelenbachs (1973). Major element analyst: Ellen S. Daniels, Denver RAL, USGS. Analysis previously unpublished.
- 170 (11) Obsidian, another sample from Prestahnukur, Iceland. Same locality as 169 (1) but smaller Apache tears and darker glass. Major element analyst: Ellen S. Daniels, Denver RAL, USGS. Analysis previously unpublished.
- 171 (42) Obsidian, residual boulder litter from rhyolitic volcano, hot spring area near headwaters of major north-flowing stream, Kerlingarfjöll, southwest of the Hofsjökull, central Iceland. Lat 63°51.84' N., long 19°15.16' W. Collected by R.L. Smith and Tomas Trygvasson.
- 172 (177) Obsidian, Holocene lava flow, Hrafninnuhraun, Torfajökull central volcano, south Iceland. Lat 63°58' N., long 19°16' W. Supplied by H. Sigurdsson, No. 426.
- 173 (178) Obsidian, Holocene lava flow, Laugahraun, Torfajökull central volcano, south Iceland. Lat 63°59' N., long 19°06' W. Supplied by H. Sigurdsson, No. 462.
- 174 (176) Obsidian, Holocene lava flow, Domadalshraun, Torfajökull central volcano, south Iceland. Lat 64°02' N., long 19°07' W. Supplied by H. Sigurdsson, No. 424.
- 175 (37) Obsidian, dome lava, dikelike ridge, Hrafninnuhryggur, Krafla, northeast Iceland. Lat 65°6.04' N., long 16°43.37' W. Collected by R.L. Smith and I. Friedman.
- 176 (61) Obsidian, agglutinate mantle, vulcanian phase of 1875 eruption of Askja volcano, Iceland. Lat 65°2' N., long 16°42' W. Supplied by R.S.J. Sparks, No. As 238.

- 177 (68) Obsidian, Hof rhyolite dome, Oraefi central volcano, southeastern Iceland. Lat 63°56' N., long 16°44' W. Supplied by R.S.J. Sparks, No. Or 1.
- 178 (57) Obsidian, summit caldera domes, Oraefi central volcano, southeastern Iceland. Lat 63°57' N., long 16°44' W. Supplied by R.S.J. Sparks, No. Or 2.

## ITALY

- 179 (209) Obsidian, southeast of Capanna, MTE, Arci, Sardinia, Italy. Approx lat 39°45' N., approx long 8°35' E. Supplied by Smithsonian Institution, USNM No. 99252. Courtesy of W.G. Melson, curator.
- 180 (65) Obsidian, Roche Rosse lava flow, Lipari Island, Italy. Lat 38°30' N., long 14°56' E. Supplied by W.F. Price.
- 181 (210) Obsidian, Mount Pelato lava, Lipari Island, Italy. Lat 38°30' N., long 14°56' E. Supplied by Smithsonian Institution, USNM No. 113108-1. Courtesy of W.G. Melson, curator.
- 182 (197) Obsidian, lava flow of 1739(?), Vulcano, Italy. Highly contaminated with more mafic inclusions. This sample was handpicked to separate the glassy part from the xenoliths. Lat 38°24.5' S., long 14°58' E. Supplied by D. Swanson.

## TURKEY

- 183 (67) Obsidian, flow or dome, Kocadag massif, Ismir-Karaburun area, west Turkey. Lat 38°22' N., long 26°36' E. Supplied by L. Villari and D.K. Bailey, No. U57.
- 184 (66) Obsidian, lava flow, northern slope of Sulphan Dag volcano, Lake Van, Armenia, Turkey. Lat 38°56' N., long 42°48' E. Supplied by L. Villari and D.K. Bailey, No. Ag 31.

## FORMER SOVIET ARMENIA

- 185 (211) Obsidian, probably residual in perlitic lava flow. Location reported as between Erevan and Deliganes (perhaps Dilizhan-RLS), Russian Armenia. Obsidian localities are known along this road southwest of Lake Sevan from volcanoes Gutansar and Atis. Lat (approx) 40°25.91' N., long (approx) 44°42' E. Supplied by Smithsonian Institution, USNM No. 52092. Courtesy of W.G. Melson, curator.

## ASIA

## JAPAN

- 186 (168) Obsidian, porphyritic, Okushiri Island, west of Hokkaido, Japan. Lat 42°10' N., long 139°30' E. Supplied by K. Mimura and M. Hata, No. MH-OKI.
- 187 (198) Glass separate from 186 (168).
- 188 (145) Obsidian, Wada-Toge Rhyolite, Wada Pass, Nagano Prefecture, Honshu, Japan. Lat 36°09' N., long 138°8.67' E. Supplied by K. Mimura, No. WD-2.
- 189 (165) Obsidian, Kawago-daira lava, Amagi volcano, Izu Peninsula, Honshu, Japan. Lat 34°50' N., long 139°01' E. Supplied by K. Ono and K. Mimura, JGS Cat. No. R10641.
- 190 (38) Obsidian, phenocrystic biotite rhyolite, dome lava, Kozu-Shima, Izu Islands, Japan. Lat 34°13' N., long 139°09' E. Supplied by the Geological Survey of Japan, Courtesy of N. Isshiki, No. NI600728071.
- 191 (166) Obsidian, Apache tears, Arita, Saga Prefecture, Kyushu, Japan. Lat 33°13' N., long 129°55' E. Supplied by K. Ono and K. Mimura, JGS Cat. No. R11461.
- 192 (167) Obsidian, Sakanashi rhyolite, Aso caldera, Kumamoto Prefecture, Kyushu, Japan. Lat 32°55' N., long 131°9' E. Supplied by K. Ono, No. 64AS85.
- 193 (169) Obsidian, Nagahama rhyolite, Io Jima Island, Kikai caldera, Kagoshima Prefecture, Ryukyu Islands, Japan. Lat 30°47' N., long 130°18' E. Supplied by K. Ono, No. 78IO186-3.
- 194 (207) Obsidian, Ogatake, Narugo volcano, Miyagi Prefecture, Honshu, Japan. Lat 38°44' N., long 140°43' E. Supplied by the Smithsonian Institution, USNM No. 108980 (LIST 53071301). Courtesy of W.G. Melson, curator.
- 195 (208) Obsidian, Kamitaga, Atami, east coast of Izu Peninsula, Shizuoka Prefecture, Honshu, Japan. Lat 35°05' N., long 139°05' E. Supplied by the Smithsonian Institution, USNM No. 108954. Courtesy of W.G. Melson, curator.

## INDONESIA

## SUMATRA

- 196 (111) Obsidian, occurrence uncertain, South Kenak Besar (Djambi), South Sumatra. Possibly Bukit Besar, lat 2°38' S., long 101°45' E. Supplied by M.T. Zen, No. S 9412.



## KRAKATAU

- 197 (110) Obsidian, clast from 1883 eruption of Krakatau, northwest slope of Gunung Krakatau, Indonesia. Lat 6°09' S., long 105°25.5' E. Supplied by M.T. Zen, No. S 976.

## JAVA

- 198 (108) Obsidian, occurrence uncertain, Gunung Kiaraberes, Bogor, western Java. Lat 6°43' S., long 106°41' E. Supplied by M.T. Zen, No. I 929.
- 199 (107) Obsidian, occurrence uncertain, Nagrek, western Java. Latitude and longitude uncertain. Supplied by M.T. Zen.
- 200 (114) Obsidian, occurrence uncertain, Samarang (Garut), western Java. Lat 7°13.09' S., long 107°50.45' E. Supplied by M.T. Zen, No. T.A.43.
- 201 (113) Obsidian, occurrence uncertain, Nagrek, western Java. Latitude and longitude uncertain. Supplied by M.T. Zen. This sample is geochemically virtually identical to sample 198 (108) and very different from 199 (107), also listed as from Nagrek. We think the stable element geochemical signatures are diagnostic within the limits of analytical error. Sample 198 (108) appears to be well located. However, sample labels can be transposed, especially with multiple handling and especially in museum collections. The samples are probably from the same locality.
- 202 (109) Obsidian, occurrence uncertain, cone between Daradjat-Pasir Kiamis, Tjitjalengka, western Java. Lat 7°13.64' S., long 107°45.82' E. Supplied by M.T. Zen, No. I1530. This sample seems specifically located, but the locality is much closer to Samarang (Garut) than to Tjitjalengka and there seems little question, chemically, that 200 (114) and 202 (109) are closely related.

## CELEBES

- 203 (101) Obsidian, occurrence uncertain, Kp. Tataāran (Tomohon) near Manado, Celebes (Sulawesi),

Indonesia. Lat 1°16.5' N., long 124°52.42' E. Supplied by P.A. Jezek.

- 204 (112) Obsidian, occurrence uncertain, Pasokan-Menado(sic), Celebes (Sulawesi), Indonesia. The sample has a geochemical signature virtually identical to 203 (101). They are no doubt from the same or very closely related rock units. Supplied by M.T. Zen, No. 51/21965.

## HALMAHERA

- 205 (170) Porphyritic obsidian, lava, coast west of Mount Todoku, northern Halmahera, Indonesia. Lat 1°14' N., long 127°24' E. Supplied by P.A. Jezek, No. NH29.
- 206 (171) Obsidian, porphyritic, lava, near coast west of Mount Rano, northern Halmahera, Indonesia. Lat 1°15.5' N., long 127°26' E. Supplied by P.A. Jezek, No. NH 31.
- 207 (172) Obsidian, porphyritic, lava flow, Mount Popolodio, northern Halmahera, Indonesia. Lat 1°21' N., long 127°30.5' E. Supplied by P.A. Jezek, No. NH 51.
- 208 (173) Obsidian, porphyritic, lava, southwest slope of Mount Alon, northern Halmahera, Indonesia. Lat 1°20' N., long 127°29' E. Supplied by P.A. Jezek, No. NH51.
- 209 (174) Obsidian, porphyritic, lava, from southwestern wall of Mount Rano caldera, northern Halmahera, Indonesia. Lat 1°15' N., long 127°27.6' E. Supplied by P.A. Jezek, No. NH 58.
- 210 (195) Glass separate from 209 (174). Porphyritic obsidian, lava, from southwestern wall of Mount Rano caldera, northern Halmahera, Indonesia. Lat 1°15' N., long 127°27.6' E. Supplied by P.A. Jezek, No. NH 58.

## PAPUA NEW GUINEA

### ADMIRALTY ISLANDS

- 211 (70) Glassy lava, partly crystalline, base of flow making up part of cones 2 and 4, southern coast of Tulum Island, Papua New Guinea. Lat 2°26.67' S., long 147°18.5' E. Supplied by

R.W. Johnson. Major element analyses in Johnson and others (1978, table 1, No. 25NG0011), except F and Cl analyses, which were done for this study.

- 212 (62) Glassy lava, partly crystalline, flow of center 8, directly west of high point marking center 8, southwestern coast of Lou Island, Papua New Guinea. Lat 2°24.83' S., long 147°18.5' E. Supplied by R.W. Johnson. Major element analyses in Johnson and others (1978, table 1, No. 25NG0005), except F and Cl analyses, which were done for this study.
- 213 (58) Glassy lava, partly crystalline, flow of center 3, 1.7 km east of Baun village, southeast coast of Lou Island, Papua New Guinea. Lat 2°24' S., long 147°21.33' E. Supplied by R.W. Johnson. Major element analysis in Johnson and others (1978, table 1, No. 25NG0025), except F and Cl analyses, which were done for this study.
- 214 (64) Glassy lava, partly crystalline, flow, western coast of Pam Lin Island, Papua New Guinea. Lat 2°29.17' S., long 147°20.17' E. Supplied by R.W. Johnson. Major element analysis in Johnson and others (1978, table 1, No. 25NG0059), except F and Cl analyses, which were done for this study.

## NEW BRITAIN

- 215 (60) Obsidian, Garua Harbor area, Talasea, New Britain. Lat 5°18.33' S., long 150°01.33' E. Supplied by R.W. Johnson.

## NEW ZEALAND

- 216 (3) Obsidian, phenocrystic, lava flow, Ongaroto, North Island, New Zealand. Lat 38°23' S., long 175°56' E. Supplied by R.A. Bailey. Major element analyst: Ellen S. Daniels, Denver RAL, USGS. Analysis previously unpublished.
- 217 (71) Obsidian, Tauhara "dacite" flow, quarry, 8 km east of northeast corner of Lake Taupo, North Island, New Zealand. Lat 38°45' S., long 176°9' E. Supplied by P.E. Baker, No. NZ17.

## APPENDIX II.—Chemical analyses of secondarily hydrated subalkaline silicic obsidians

Country/State-----	NEW MEXICO		SOUTH SEAS	ICELAND					
Volcanic field/region---	Taos Plateau	Mount Taylor	South Sandwich Islands	Husafell			Kerlingarfjöll		
Locality-----	Cerro No Agua	Grants Ridge	North S.S.I. 1962	Ulfarsfellsna	Baejargil stream	Reydarfell dome	Lodmunda Mountain		
Specimen-----	218	219	220	221	222	223	224	225	226
Collection No. (RLS)---	28	201	261	179	181	63	59	69	175

## Chemical analyses (weight percent)

SiO <sub>2</sub> -----	73.6	73.5	73.04	67.3	72.9	72.1	69.5	71.3	72.7
Al <sub>2</sub> O <sub>3</sub> -----	13.32	13.00	13.61	13.57	11.68	12.23	12.22	12.31	12.41
Fe <sub>2</sub> O <sub>3</sub> -----	0.45	0.46	0.69	0.88	0.92	0.71	1.25	1.59	0.85
FeO-----	0.22	0.28	2.13	3.18	2.07	1.98	1.00	0.72	1.98
MgO-----	0.05	0.06	0.50	0.84	0.05	0.05	0.20	0.07	0.005
CaO-----	0.84	0.50	3.25	3.56	1.37	1.12	3.74	1.15	0.91
Na <sub>2</sub> O-----	4.06	4.72	4.66	3.71	4.17	4.33	2.26	3.92	5.19
K <sub>2</sub> O-----	4.37	4.08	0.67	1.74	3.03	3.64	1.41	3.94	3.38
H <sub>2</sub> O+-----	2.38	2.33	1.04	3.23	2.51	2.99	7.44	3.63	1.36
TiO <sub>2</sub> -----	0.08	0.02	0.30	0.63	0.28	0.18	0.17	0.17	0.23
P <sub>2</sub> O <sub>5</sub> -----	<0.005	<0.005	0.12	0.13	0.01	0.02	0.02	0.01	0.01
MnO-----	0.10	0.14	0.08	0.09	0.09	0.09	0.08	0.07	0.09
Cl*-----	0.06	0.02	--	0.01	0.08	0.11	0.05	0.12	0.13
Cl**-----	--	0.02	--	--	0.05	--	--	0.12	--
F*-----	0.09	0.50	--	0.04	0.13	0.16	0.08	0.07	0.19
F**-----	--	0.51	--	--	0.11	-	0.08	0.07	--
Subtotal-----	99.62	99.62	100.09	98.91	99.27	99.71	99.42	99.07	99.44
Less O=(F,Cl) <sub>2</sub> -----	0.05	0.22	--	0.02	0.07	0.09	0.05	0.06	0.11
Total-----	99.57	99.40	100.09	98.89	99.20	99.62	99.37	99.01	99.33
FeO <sup>1</sup> -----	0.63	0.69	2.75	3.97	2.90	2.62	2.13	2.15	2.75
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.33	0.38	0.76	0.78	0.69	0.74	0.44	0.31	0.70
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.93	1.16	1.96	2.13	1.38	1.19	1.60	1.00	1.54
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.86	0.93	0.62	0.59	0.87	0.90	0.43	0.87	0.98
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.97	1.00	1.05	1.07	1.08	1.07	0.99	1.04	1.12
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.10	0.06	0.61	0.65	0.19	0.14	1.02	0.15	0.11
Cl/ F <sup>1</sup> -----	0.67	0.04	--	0.25	0.54	0.69	0.63	1.7	0.68

## CIPW norms

Q-----	32.29	30.14	35.21	30.28	34.55	30.81	46.16	32.71	27.86
or-----	26.60	24.92	4.00	10.75	18.54	22.30	9.07	24.44	20.43
ab-----	35.38	41.28	39.81	32.83	36.54	37.99	20.82	34.82	44.92
an-----	4.29	2.31	14.38	15.93	4.35	3.30	20.06	4.57	0.60
c-----	0.40	--	--	--	--	--	0.24	--	--
ac-----	--	--	--	--	--	--	--	(4)	--
ns-----	--	--	--	--	--	--	--	--	--
wo }-----	--	0.11	0.46	0.69	1.09	0.97	--	0.21	1.65
en } di-----	--	0.03	0.14	0.23	0.05	0.05	--	0.18	0.02
fs }-----	--	0.08	0.34	0.47	1.17	1.04	--	0.00	1.85
en } hy-----	0.13	0.12	1.12	1.95	0.08	0.09	0.54	--	0.01
fs }-----	0.09	0.30	2.68	3.96	1.67	1.98	0.73	--	0.93
mt-----	0.67	0.69	1.01	1.33	1.38	1.07	1.97	2.16	1.26
il-----	0.16	0.04	0.58	1.25	0.55	0.35	0.35	0.34	0.45
ap-----	0.00	0.00	0.28	0.32	0.02	0.05	0.05	0.02	0.02

	218	219	220	221	222	223	224	225	226
Trace elements (ppm)									
Ba-----	130.	4.	119.	335.	515.	677.	480.	677.	840.
Be-----	--	21.	--	--	4.4	--	4.4	4.3	--
Co-----	0.2	<0.4	2.8	22.0 <sup>3</sup>	12.8 <sup>3</sup>	0.2	0.3	0.3	21.0 <sup>3</sup>
Cr-----	1.0	<3.0	<4.0	3.8	<4.0	<6.0	2.9	<6.0	5.8
Cs-----	2.2	14.2	0.5	0.3	0.7	1.0	6.3	1.4	0.9
Hf-----	3.3	8.0	3.0	6.9	18.5	13.0	9.8	10.3	18.3
Li-----	--	53.	--	--	10.	--	5.	8.	--
Mo-----	--	1.2	--	--	3.7	--	3.7	4.3	--
Nb**-----	--	170.	0.6	--	--	--	66.	63.	--
Nb***-----	39.	190.	<2.0	14.	90.	97.	69.	78.	151.
Pb-----	19.	40.	9.	5.	26.	15.	23.	10.	13.
Rb**-----	132.	519.	14.	35.	62.	85.	65.	117.	78.
Rb***-----	135.	500.	13.	33.	60.	83.	64.	121.	83.
Sb-----	0.4	1.5	<2.0	<0.5	0.3	0.5	0.7	<0.8	0.3
Sc-----	3.0	2.2	10.2	7.9	1.6	3.3	4.5	4.7	0.57
Sn-----	--	28.	--	--	7.9	--	6.8	4.9	--
Sr-----	40.	5.	110.	225.	110.	92.	110.	390.	75.
Ta-----	3.03	30.50	<0.7	1.73	7.01	6.56	4.86	5.48	9.62
Th-----	9.9	23.2	0.7	6.6	9.4	12.6	12.1	12.9	11.3
U-----	3.4	8.1	<3.0	1.8	3.0	3.5	3.6	4.1	3.3
W-----	--	3.3	--	--	--	--	1.4	1.6	--
Y-----	27.	92.	33.	30.	194.	104.	72.	67.	143.
Zn-----	38.	157.	43.	60.	193.	131.	84.	45.	228.
Zr-----	53.	95.	107.	332.	700.	522.	382.	377.	753.
La-----	13.	7.	5.	39.	80.	85.	72.	74.	96.
Ce-----	25.	18.	11.	69.	172.	163.	140.	140.	192.
Nd-----	12.	12.	7.	23.	90.	79.	64.	69.	90.
Sm-----	2.7	3.9	2.8	5.7	26.0	17.1	13.1	14.2	22.0
Eu-----	0.36	0.05	0.77	1.31	4.44	2.80	2.12	2.27	3.50
Gd-----	2.9	4.3	3.0	4.5	21.9	14.2	10.2	11.1	16.5
Tb-----	0.46	<0.81	0.71	0.63	4.94	2.71	2.07	2.20	3.56
Tm-----	<0.20	0.50	0.57	0.56	3.07	1.27	0.94	1.12	1.79
Yb-----	2.5	7.8	3.4	3.2	18.0	9.4	7.1	7.0	12.6
Lu-----	0.37	1.19	0.53	0.47	2.49	1.28	0.96	1.02	1.67
Nb/Ta-----	12.9	5.9	--	8.1	12.8	14.8	13.9	12.9	15.7
K/Rb-----	269.	68.	428.	438.	419.	364.	183.	270.	338.
Rb/Sr-----	3.4	100.	0.12	0.15	0.55	0.90	0.58	0.31	1.1
Ca/Sr-----	150.	715.	211.	113.	89.	87.	24.3	21.1	87.
Th/U-----	2.9	2.9	--	3.7	3.1	3.6	3.3	3.1	3.4
Zr/Hf-----	16.	12.	36.	48.	38.	40.	39.	37.	41.
Ce/Yb-----	10.0	2.3	3.2	21.6	9.6	17.3	19.7	20.0	15.2
Eu/Eu*-----	0.40	0.04	0.82	0.70	0.58	0.56	0.56	0.55	0.56

\*Analyses performed by the University of Reading.

\*\*Analyses performed by the U.S. Geological Survey.

\*\*\*Analyses performed by the University of Lancaster.

†Cl/F ratios calculated from raw (ppm) data.

<sup>1</sup>By weight<sup>2</sup>Molecular<sup>3</sup>Probably reflects contamination<sup>4</sup>Normative wollastonite, 0.35 percent.

--, not determined

## NORTH AMERICA

### UNITED STATES OF AMERICA

#### NEW MEXICO

- 218 (28) Perlite associated with sample 110 (28), lava dome, Cerros No Agua, Taos County, New Mexico. Lat 36°45.68' N., long 105°56.97' W. Collected by C.S. Ross and R.L. Smith.
- 219 (201) Perlitic glass, possible clast, from pumice quarry, northeast end of Grants Ridge, 8 miles northeast of Grants, Valencia County, New Mexico. Lat 35°12.82' N., long 107°44.5' W. Collected by R.L. Smith.

## ANTARCTICA

### SOUTH SANDWICH ISLANDS

- 220 (261) Glassy pumice, block in pumice raft, collected by H.M.S. *Protector*, 15 March, 1962, northeast of Zavodovski Island, South Sandwich Islands. Probably erupted from seamount. Lat 55°55' S., long 28°6' W. Major element analysis in Gass and others (1963, table 1). Supplied by I.G. Gass.

## EUROPE

### ICELAND

- 221 (179) Rhyolitic glass, clast in silicic tuff, Ulfarsfellsna, Snaefellsnes. Upper Tertiary or lower Quaternary formation, west Iceland. Lat 64°58.5' N., long 22°37' W. Supplied by H. Sigurdsson, No. 477.

- 222 (181) Rhyolitic glass, lower Quaternary flow, Ulfarsfellsna, west Iceland. Lat 64°58.5' N., long 22°37' W. Supplied by H. Sigurdsson, No. 493.
- 223 (63) Rhyolitic glass, margin of dike cutting ash-flow tuff of first silicic phase, but older than second silicic phase, Baejargil stream, Husafell central volcano (Tertiary), west Iceland. Lat 64°41' N., long 20°54' W. Supplied by R.S.J. Sparks, No. H1.
- 224 (59) Rhyolitic glass, Reydarfell lava dome, third silicic phase, Husafell central volcano (Tertiary), west Iceland. Lat 64°41' N., long 20°55' W. Supplied by R.S.J. Sparks, No. H2.
- 225 (69) Rhyolitic glass, large fiamma in densely welded vitrophyre, third silicic phase, underlying Reydarfell dome, Husafell central volcano (Tertiary), west Iceland. Lat 64°41' N., long 22°55' W. Supplied by R.S.J. Sparks, No. H3.
- 226 (175) Obsidian, Lodmundar Mountain (late Quaternary), Kerlingarfjöll central volcano, central Iceland. Lat 64°39' N., long 19°13' W. Supplied by H. Sigurdsson, No. 418.

**APPENDIX III.—Compilation of published major-element analyses of subalkaline silicic glasses**

Country/State-----	ALASKA			OREGON							
Volcanic field/region---	Umnak Island	Katmai		Three Sisters	Crater Lake		Newberry Volcano				
Locality-----	Northeast Umnak	Novarupta		South Sister	Grouse Hill	Llao Rock	East Lake	Wall, Big Pumice Cone	Game Hut flow		
Specimen-----	242	243	244	245	246	247	248	249	250	251	252
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	72.36	74.75	77.04	71.94	70.30	70.77	72.5	72.8	72.35	72.8	72.9
Al <sub>2</sub> O <sub>3</sub> -----	13.75	13.01	12.30	14.31	14.52	14.83	14.3	13.9	13.98	14.6	14.0
Fe <sub>2</sub> O <sub>3</sub> -----	0.59	0.82	0.43	0.61	0.37	1.35	0.33	0.67	0.60	0.77	0.77
FeO-----	2.33	1.43	0.97	1.77	2.56	1.25	1.7	1.3	1.78	1.3	1.3
MgO-----	0.09	0.70	0.04	0.41	0.93	0.64	0.33	0.21	0.30	0.34	0.28
CaO-----	1.53	2.12	1.03	1.75	2.94	2.12	1.1	1.4	1.30	1.1	1.0
Na <sub>2</sub> O-----	4.64	4.32	4.56	4.69	4.86	5.07	4.6	4.5	5.04	4.3	4.6
K <sub>2</sub> O-----	4.16	2.62	3.12	3.00	2.66	2.68	4.1	4.1	3.92	4.0	4.2
H <sub>2</sub> O+-----	0.27	0.20	0.18	0.48	0.33	0.33	0.43	0.45	0.45	0.43	0.51
H <sub>2</sub> O-----	0.03	0.05	0.03	0.16	0.14	0.07	0.03	0.05	0.05	0.00	0.02
TiO <sub>2</sub> -----	0.21	0.28	0.18	0.40	0.44	0.38	0.23	0.22	0.25	0.24	0.21
P <sub>2</sub> O <sub>5</sub> -----	0.06	0.09	0.04	0.07	0.09	0.13	0.10	0.02	tr	0.10	0.09
MnO-----	0.09	0.05	0.04	0.05	tr	tr	0.05	0.06	nil	0.04	0.06
Cl-----	--	0.11	0.15	--	--	0.11	--	--	--	--	--
F-----	--	--	--	--	--	--	--	--	--	--	--
Subtotal-----	100.11	100.55	100.11	99.64	100.14	99.73	99.80	99.68	100.02	100.02	99.94
Less O=(F,Cl) <sub>2</sub> -----	--	0.02	0.03	--	--	0.02	--	--	--	--	--
Total-----	100.11	100.53	100.08	99.64	100.14	99.71	99.80	99.68	100.02	100.02	99.94
FeO <sub>t</sub> -----	2.86	2.17	1.36	2.32	2.89	2.47	2.00	1.90	2.32	1.99	1.99
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.80	0.64	0.69	0.74	0.87	0.48	0.84	0.66	0.75	0.63	0.63
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.12	1.65	1.46	1.56	1.83	1.89	1.12	1.10	1.29	1.08	1.10
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.88	0.76	0.88	0.75	0.75	0.76	0.84	0.85	0.90	0.78	0.87
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.09	1.06	1.04	0.99	1.12	1.02	0.98	1.04	1.07	0.92	0.99
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.17	0.31	0.13	0.23	0.39	0.27	0.13	0.16	0.15	0.13	0.11
Cl/ F <sup>1</sup> -----	--	--	--	--	--	--	--	--	--	--	--
CIPW norms											
Q-----	25.21	33.82	36.17	28.31	23.70	25.84	26.49	27.44	24.38	29.37	27.23
or-----	24.63	15.45	18.48	17.91	15.77	15.96	24.39	24.43	23.28	23.73	24.97
ab-----	39.34	36.49	38.68	40.09	41.26	43.24	39.18	38.39	42.85	36.54	39.16
an-----	4.41	8.35	3.89	8.31	9.98	9.74	4.84	5.67	3.96	4.82	4.40
C-----	--	--	--	0.34	--	0.05	0.54	--	--	1.44	0.29
wo }-----	1.17	0.65	0.41	--	1.70	--	--	0.50	1.05	--	--
en } di-----	0.08	0.33	0.03	--	0.67	--	--	0.13	0.27	--	--
fs }-----	1.23	0.30	0.42	--	1.05	--	--	0.40	0.84	--	--
en } hy-----	0.15	1.41	0.07	1.03	1.66	1.61	0.83	0.40	0.48	0.85	0.70
fs }-----	2.39	1.28	0.79	2.20	2.63	0.56	2.58	1.20	1.53	1.44	1.53
mt-----	0.86	1.19	0.63	0.89	0.54	1.97	0.48	0.98	0.87	1.12	1.12
il-----	0.40	0.53	0.34	0.77	0.84	0.73	0.44	0.42	0.48	0.46	0.40
ap-----	0.14	0.21	0.09	0.16	0.21	0.30	0.23	0.05	0.00	0.23	0.21
other-----	--	--	--	--	--	--	--	--	--	--	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	OREGON									CALIFORNIA	
Volcanic field/region---	Newberry Volcano									Medicine Lake Highlands	
Locality-----	Pumice Cone flow		North flow		"Big Obsidian Flow"					Massive lava group	
Specimen-----	253	254	255	256	257	258	259	260	261	262	263
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	72.8	72.9	72.9	73.1	72.22	72.4	72.6	73.40	72.8	71.50	74.10
Al <sub>2</sub> O <sub>3</sub> -----	14.6	14.1	13.9	14.0	14.41	14.4	14.4	14.20	14.4	14.66	13.33
Fe <sub>2</sub> O <sub>3</sub> -----	0.44	0.66	0.56	0.33	0.50	0.64	0.64	0.24	0.54	0.33	tr.
FeO-----	1.6	1.4	1.4	1.7	1.62	1.6	1.6	1.76	1.5	2.28	1.68
MgO-----	0.25	0.27	0.24	0.28	0.18	0.18	0.24	0.18	0.04	0.44	0.38
CaO-----	1.0	0.98	1.6	0.99	0.84	0.87	0.92	1.35	0.84	1.50	1.45
Na <sub>2</sub> O-----	4.2	4.6	4.4	4.6	5.28	4.9	4.7	4.15	4.9	4.53	3.86
K <sub>2</sub> O-----	3.8	4.2	4.1	4.2	4.01	4.1	3.9	4.10	4.0	4.07	4.50
H <sub>2</sub> O+-----	0.76	0.58	0.42	0.45	0.12	0.50	0.63	0.40	0.20	0.20	0.29
H <sub>2</sub> O-----	0.14	0.02	0.06	0.00	0.01	0.06	0.03	0.10	0.10	tr	0.05
TiO <sub>2</sub> -----	0.21	0.22	0.23	0.21	0.23	0.22	0.20	0.20	0.23	0.22	0.20
P <sub>2</sub> O <sub>5</sub> -----	0.09	0.10	0.02	0.09	0.03	0.09	0.09	tr	0.03	nil	nil
MnO-----	0.05	0.05	0.12	0.05	0.06	0.06	0.05	tr	0.07	tr	tr
Cl-----	--	--	--	--	--	--	--	--	--	--	--
F-----	--	--	--	--	--	--	--	--	--	--	--
Subtotal-----	99.94	100.08	99.95	100.00	99.51	100.02	100.00	100.08	99.65	99.73	99.84
Less O=(F,Cl) <sub>2</sub> -----	--	--	--	--	--	--	--	--	--	--	--
Total-----	99.94	100.08	99.95	100.00	99.51	100.02	100.00	100.08	99.65	99.73	99.84
FeO <sub>t</sub> -----	2.00	1.99	1.90	2.00	2.07	2.18	2.18	1.98	1.99	2.58	1.68
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.78	0.68	0.71	0.63	0.76	0.71	0.71	0.88	0.74	0.87	--
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.11	1.10	1.07	1.10	1.32	1.20	1.21	1.01	1.23	1.11	0.86
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.76	0.86	0.84	0.87	0.90	0.87	0.83	0.80	0.86	0.81	0.84
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.89	0.99	1.05	0.99	1.01	0.98	0.95	0.97	0.97	1.00	1.04
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.13	0.11	0.19	0.11	0.09	0.10	0.11	0.16	0.09	0.17	0.17
Cl/ F <sup>1</sup> -----	--	--	--	--	--	--	--	--	--	--	--
CIPW norms											
Q-----	30.81	27.19	27.52	26.93	23.32	25.48	27.45	29.30	26.45	24.20	29.96
or-----	22.67	24.95	24.36	24.93	23.84	24.36	23.20	24.33	23.79	24.16	26.73
ab-----	35.88	39.13	37.43	39.10	44.96	41.69	40.03	35.26	41.73	38.51	32.83
an-----	4.42	4.23	6.10	4.34	3.80	3.75	4.00	6.73	4.00	7.48	5.79
C-----	1.99	0.45	--	0.30	--	0.54	1.00	0.48	0.56	0.08	--
wo } di-----	--	--	0.73	--	0.08	--	--	--	--	--	0.60
en } di-----	--	--	0.18	--	0.02	--	--	--	--	--	0.16
fs } di-----	--	--	0.59	--	0.07	--	--	--	--	--	0.47
en } hy-----	0.63	0.68	0.42	0.70	0.44	0.45	0.60	0.45	0.10	1.10	0.79
fs } hy-----	2.34	1.76	1.37	2.61	2.23	2.17	2.19	2.72	2.07	3.57	2.30
mt-----	0.64	0.96	0.82	0.48	0.73	0.93	0.93	0.35	0.79	0.48	0.00
il-----	0.40	0.42	0.44	0.40	0.44	0.42	0.38	0.38	0.44	0.42	0.38
ap-----	0.21	0.23	0.05	0.21	0.07	0.21	0.21	0.00	0.07	0.00	0.00
other-----	--	--	--	--	--	--	--	--	--	--	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	CALIFORNIA											
Volcanic field/region---	Medicine Lake Highlands											
Locality-----	Big Glass Mountain										Little Glass Mountain	
Specimen-----	264	265	266	267	268	269	270	271	272	273	274	275
Chemical analyses (weight percent)												
SiO <sub>2</sub> -----	72.95	73.00	73.30	73.59	73.60	72.40	72.64	73.15	73.34	73.44	73.22	73.46
Al <sub>2</sub> O <sub>3</sub> -----	13.88	13.87	13.80	13.78	13.70	14.26	14.07	14.08	13.35	13.93	13.65	13.72
Fe <sub>2</sub> O <sub>3</sub> -----	0.44	0.58	0.23	0.60	0.40	0.81	0.77	0.12	0.58	0.49	0.40	0.46
FeO-----	2.37	2.21	2.62	1.30	2.20	2.03	1.45	2.45	1.27	1.24	1.41	1.27
MgO-----	0.14	0.16	0.54	0.33	0.54	0.36	0.49	0.39	0.37	0.33	0.21	0.41
CaO-----	1.80	1.80	1.80	1.39	1.70	1.55	1.60	1.45	1.41	1.22	1.38	1.57
Na <sub>2</sub> O-----	4.05	3.95	3.82	4.19	3.78	3.85	4.25	3.94	4.13	4.19	4.23	4.21
K <sub>2</sub> O-----	3.92	3.85	3.80	4.32	3.98	4.07	4.08	4.00	4.45	4.34	4.30	4.30
H <sub>2</sub> O+-----	nil	0.10	nil	0.14	nil	0.40	0.11	nil	0.33	0.41	0.39	0.33
H <sub>2</sub> O-----	0.10	nil	nil	--	nil	nil	--	0.10	0.03	0.08	0.16	--
TiO <sub>2</sub> -----	0.25	0.25	0.25	0.27	0.20	0.25	0.36	0.25	0.30	0.31	0.29	0.28
P <sub>2</sub> O <sub>5</sub> -----	tr	tr	tr	0.12	tr	tr	0.11	tr	0.18	0.05	0.11	0.13
MnO-----	nil	nil	nil	0.02	nil	nil	0.02	nil	0.02	0.04	0.03	0.02
Cl-----	--	--	--	--	--	--	--	--	0.08	--	0.09	--
F-----	--	--	--	--	--	--	--	--	--	--	--	--
Subtotal-----	99.90	99.77	100.16	100.05	100.10	99.98	99.95	99.93	99.84	100.07	99.87	100.16
Less O=(F,Cl) <sub>2</sub> -----	--	--	--	--	--	--	--	--	0.02	--	0.02	--
Total-----	99.90	99.77	100.16	100.05	100.10	99.98	99.95	99.93	99.82	100.07	99.85	100.16
FeO <sub>t</sub> -----	2.77	2.73	2.83	1.84	2.56	2.76	2.14	2.56	1.79	1.68	1.77	1.68
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.84	0.79	0.92	0.68	0.85	0.71	0.65	0.95	0.69	0.72	0.78	0.73
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.03	1.03	1.01	0.97	0.95	0.95	1.04	0.99	0.93	0.97	0.98	0.98
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.79	0.77	0.75	0.84	0.77	0.75	0.81	0.77	0.87	0.83	0.85	0.84
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.02	1.01	0.99	1.02	0.99	0.95	1.02	0.96	1.06	0.99	1.03	1.05
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.23	0.23	0.24	0.16	0.22	0.20	0.19	0.18	0.16	0.14	0.16	0.18
Cl/ F <sup>1</sup> -----	--	--	--	--	--	--	--	--	--	--	--	--
CIPW norms												
Q-----	28.93	29.89	29.91	28.92	30.37	29.49	27.83	29.47	28.99	29.01	28.71	28.50
or-----	23.21	22.83	22.42	25.55	23.50	24.15	24.15	23.68	26.46	25.77	25.61	25.45
ab-----	34.34	33.53	32.27	35.49	31.95	32.72	36.02	33.40	35.16	35.62	36.07	35.69
an-----	8.13	8.77	8.92	6.04	8.43	7.72	7.23	7.21	4.78	0.24	5.60	5.85
C-----	--	--	0.13	--	0.08	0.71	0.02	0.63	--	0.24	--	--
wo }-----	0.34	0.08	--	0.03	--	--	--	--	0.45	--	0.24	0.46
en } di-----	0.03	0.01	--	0.01	--	--	--	--	0.18	--	0.06	0.19
fs }-----	0.34	0.08	--	0.02	--	--	--	--	0.27	--	0.20	0.28
en } hy-----	0.32	0.39	1.34	0.81	1.34	0.90	1.22	0.97	0.75	0.83	0.47	0.84
fs }-----	3.24	3.10	4.20	1.46	3.38	2.66	1.47	3.99	1.13	1.37	1.65	1.25
mt-----	0.64	0.84	0.33	0.87	0.58	1.18	1.12	0.17	0.85	0.71	0.58	0.67
il-----	0.48	0.48	0.47	0.51	0.38	0.48	0.69	0.48	0.57	0.59	0.56	0.53
ap-----	0.00	0.00	0.00	0.28	0.00	0.00	0.26	0.00	0.42	0.12	0.26	0.30
other-----	--	--	--	--	--	--	--	--	--	--	--	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	CALIFORNIA											
Volcanic field/region---	Medicine Lake Highlands				Clear Lake Volcanic Field		Sonoma Volcanic Field	Inyo Craters		Mono Craters		
Locality-----	Little Glass Mountain				Bottle Rock Rd.	Borax Lake	Napa Glass Mt.	Glass Mountain		South Coulee		
Specimen-----	276	277	278	279	280	281	282	283	284	285	286	287
Chemical analyses (weight percent)												
SiO <sub>2</sub> -----	73.47	73.49	73.53	73.59	74.82	76.53	75.54	72.88	71.25	75.86	76.38	76.09
Al <sub>2</sub> O <sub>3</sub> -----	13.72	13.65	13.71	14.03	13.05	12.82	12.65	13.92	14.60	12.50	12.65	12.54
Fe <sub>2</sub> O <sub>3</sub> -----	0.61	0.60	0.45	0.42	0.19	0.19	0.42	0.54	0.65	0.35	0.39	0.35
FeO-----	1.24	1.29	1.25	1.43	1.05	0.93	0.82	1.08	1.35	0.69	0.68	0.70
MgO-----	0.37	0.40	0.30	0.36	0.22	0.27	0.06	0.17	0.27	0.03	0.01	0.02
CaO-----	1.38	1.40	1.24	1.38	1.09	0.79	0.40	0.76	1.06	0.59	0.56	0.60
Na <sub>2</sub> O-----	4.21	4.17	4.21	4.04	3.52	3.64	4.38	4.31	4.57	4.07	4.06	4.08
K <sub>2</sub> O-----	4.27	4.27	4.39	4.34	4.82	4.64	4.59	5.20	5.08	4.71	4.67	4.70
H <sub>2</sub> O+-----	0.34	0.31	0.36	0.12	0.59	0.17	0.66	0.65	0.56	0.71	0.23	0.55
H <sub>2</sub> O-----	0.12	--	0.05	0.06	0.07	0.05	0.04	0.07	0.07	0.08	0.03	0.16
TiO <sub>2</sub> -----	0.28	0.31	0.29	0.31	0.26	0.11	0.08	0.15	0.26	0.07	0.07	0.07
P <sub>2</sub> O <sub>5</sub> -----	0.22	0.14	0.05	0.09	0.03	0.03	--	0.02	0.06	0.010	0.01	0.008
MnO-----	0.02	0.03	0.04	0.02	0.03	0.02	0.02	0.06	0.06	0.04	0.05	0.05
Cl-----	--	--	--	0.03	--	--	--	--	--	--	0.07	--
F-----	--	--	--	0.03	--	--	--	--	--	--	0.08	--
Subtotal-----	100.25	100.06	99.87	100.25	99.74	100.19	99.66	99.81	99.84	99.71	99.94	99.92
Less O=(F,Cl) <sub>2</sub> -----	--	--	--	0.02	--	--	--	--	--	--	0.05	--
Total-----	100.25	100.06	99.87	100.23	99.74	100.19	99.66	99.81	99.84	99.71	99.89	99.92
FeO <sup>1</sup> -----	1.79	1.83	1.66	1.81	1.22	1.10	1.20	1.57	1.94	1.01	1.03	1.02
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.67	0.68	0.74	0.77	0.85	0.83	0.66	0.67	0.68	0.66	0.64	0.67
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.99	0.97	0.96	0.93	0.73	0.78	0.95	0.83	0.90	0.86	0.87	0.87
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.84	0.84	0.86	0.81	0.84	0.86	0.97	0.91	0.90	0.94	0.93	0.94
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.02	1.03	1.02	0.99	1.00	0.97	1.02	1.01	1.02	1.03	1.01	1.03
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.16	0.17	0.14	0.16	0.13	0.10	0.04	0.08	0.11	0.07	0.06	0.07
Cl/F <sup>1</sup> -----	--	--	--	1.00	--	--	--	--	--	--	0.88	--
CIPW norms												
Q-----	29.20	29.15	28.80	29.42	32.99	34.96	31.54	25.76	22.28	33.01	33.50	33.09
or-----	25.29	25.30	26.08	25.64	28.75	27.41	27.41	31.01	30.26	28.14	27.73	28.00
ab-----	35.70	35.37	35.82	34.18	30.06	30.81	37.45	36.81	38.98	34.82	34.52	34.80
an-----	5.42	5.93	5.58	6.26	5.26	3.72	1.31	3.31	4.36	1.95	2.51	2.04
C-----	0.19	--	--	0.39	0.13	0.45	--	--	--	--	--	--
wo }-----	--	0.05	0.12	--	--	--	0.29	0.15	0.23	0.39	0.09	0.37
en } di-----	--	0.02	0.04	--	--	--	0.04	0.04	0.07	0.03	0.00	0.02
fs }-----	--	0.03	0.08	--	--	--	0.28	0.12	0.17	0.41	0.10	0.40
en } hy-----	0.92	0.98	0.71	0.90	0.55	0.67	0.11	0.39	0.61	0.04	0.02	0.03
fs }-----	1.35	1.39	1.45	1.80	1.41	1.41	0.80	1.29	1.47	0.54	0.81	0.58
mt-----	0.89	0.87	0.66	0.61	0.28	0.28	0.62	0.79	0.95	0.51	0.57	0.51
il-----	0.53	0.59	0.55	0.59	0.50	0.21	0.15	0.29	0.50	0.13	0.13	0.13
ap-----	0.51	0.33	0.12	0.21	0.07	0.07	0.00	0.05	0.14	0.02	0.02	0.02
other-----	--	--	--	--	--	--	--	--	--	--	--	--

See footnotes at end of table.



**APPENDIX III.—Compilation of published major-element analyses of subalkaline silicic glasses—Continued**

Country/State-----	CALIFORNIA			NEVADA			WYOMING			
Volcanic field/region---	Mono Craters	Long Valley Complex		Silver Peak Volcanic Center	South Nevada		Yellowstone Volcanic Complex			
Locality-----		Glass Mountain			Shoshone Mountain	Obsidian Butte	Lava Creek Tuff	West Yellowstone		Spring Creek
Specimen-----	288	289	290	291	292	293	294	295	296	297
<b>Chemical analyses (weight percent)</b>										
SiO <sub>2</sub> -----	76.21	77.05	77.10	75.96	74.24	75.53	75.98	76.7	75.8	76.44
Al <sub>2</sub> O <sub>3</sub> -----	12.58	12.58	12.53	13.08	13.46	12.98	12.33	11.9	12.0	12.09
Fe <sub>2</sub> O <sub>3</sub> -----	0.30	0.31	0.30	0.39	0.38	0.37	0.55	0.5	0.8	0.46
FeO-----	0.73	0.45	0.46	0.45	0.92	0.72	1.08	1.2	1.2	1.00
MgO-----	0.03	0.03	0.03	0.13	0.17	0.10	0.00	0.13	0.18	0.03
CaO-----	0.61	0.44	0.45	0.71	0.67	0.70	0.49	0.38	0.57	0.45
Na <sub>2</sub> O-----	4.05	3.96	3.75	3.87	3.97	3.82	3.69	3.4	3.4	3.55
K <sub>2</sub> O-----	4.72	4.68	4.76	4.69	5.33	5.16	5.10	5.0	4.9	5.16
H <sub>2</sub> O+-----	0.39	0.17	0.15	0.22	0.24	0.15	0.13	0.60	0.32	0.26
H <sub>2</sub> O-----	0.13	0.02	0.02	0.01	0.04	0.03	0.00			0.02
TiO <sub>2</sub> -----	0.07	.07	0.08	0.12	0.22	0.12	0.13	0.14	0.20	0.14
P <sub>2</sub> O <sub>5</sub> -----	0.008	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.02
MnO-----	0.04	0.04	0.03	0.06	0.04	0.05	0.04	0.04	0.06	0.04
Cl-----	--	0.05	0.05	--	0.05	0.07	0.12	0.09	0.08	0.08
F-----	--	0.08	0.06	--	0.08	0.07	0.14	0.14	0.14	0.17
Subtotal-----	99.87	99.94	99.78	99.71	99.83	99.89	99.79	100.23	99.67	99.91
Less O=(F,Cl) <sub>2</sub> -----	--	0.05	0.04	--	0.05	0.05	0.09	0.08	0.08	0.09
Total-----	99.87	99.89	99.74	99.71	99.78	99.84	99.70	100.15	99.59	99.82
FeO <sup>1</sup> -----	1.00	0.73	0.73	0.80	1.26	1.05	1.58	1.65	1.92	1.41
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.71	0.59	0.61	0.54	0.71	0.66	0.66	0.71	0.60	0.68
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.86	0.85	0.79	0.83	0.74	0.74	0.72	0.68	0.69	0.69
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.94	0.93	0.90	0.88	0.91	0.91	0.94	0.93	0.91	0.95
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> ---	1.02	0.98	0.97	0.97	1.01	1.01	1.01	0.98	0.99	1.01
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.07	0.05	0.05	0.08	0.07	0.08	0.06	0.05	0.07	0.05
Cl/ F <sup>1</sup> -----	--	0.63	0.83	--	0.63	1.00	0.86	0.64	0.57	0.47
<b>CIPW norms</b>										
Q-----	33.17	35.04	36.03	33.83	28.80	31.76	33.62	36.28	35.54	34.78
or-----	28.07	27.76	28.27	27.86	31.68	30.62	30.32	29.73	29.21	30.68
ab-----	34.49	33.64	31.89	32.92	33.79	32.46	31.41	28.94	29.02	30.23
an-----	2.22	2.13	0.42	3.41	3.18	3.04	2.03	1.83	2.72	1.83
C-----	--	0.23	0.42	0.40	--	--	--	--	0.12	--
wo } di-----	0.32	--	--	--	0.01	0.13	0.15	--	--	0.12
en } di-----	0.02	--	--	--	0.00	0.03	0.00	--	--	0.01
fs } di-----	0.33	--	--	--	0.01	0.11	0.17	--	--	0.13
en } hy-----	0.05	0.08	0.08	0.33	0.42	0.22	0.00	0.33	0.45	0.07
fs } hy-----	0.73	0.53	0.52	0.42	1.08	0.81	1.23	1.64	1.34	1.18
mt-----	0.44	0.45	0.44	0.57	0.55	0.54	0.80	0.73	1.17	0.67
il-----	0.13	0.13	0.15	0.23	0.42	0.23	0.25	0.27	0.38	0.27
ap-----	0.02	0.02	0.02	0.05	0.05	0.05	0.02	0.02	0.05	0.05
other-----	--	--	--	--	--	--	--	--	--	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	WYOMING					UTAH					
Volcanic field/region---	Yellowstone Volcanic Field					Mineral Mountains				Twin Peaks Volcanic Field	
Locality-----	West Yellowstone flow	Cougar Creek flow	Obsidian Cliff flow			Little Bearskin Mountain	North Twin Flat	Wildhorse Canyon	Bailey Ridge	Rhyolite of Cudahy Mine	
Specimen-----	298	299	300	301	302	303	304	305	306	307	308
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	76.39	76.59	76.4	76.71	76.78	76.42	76.45	76.51	76.52	75.24	75.67
Al <sub>2</sub> O <sub>3</sub> -----	11.94	12.42	12.2	12.29	12.09	12.79	12.79	12.29	12.29	12.88	12.94
Fe <sub>2</sub> O <sub>3</sub> -----	0.47	0.30	0.5	0.41	0.56	0.20	0.30	0.23	0.31	0.29	0.22
FeO-----	1.17	0.90	0.84	0.81	0.81	0.38	0.29	0.51	0.46	0.62	0.65
MgO-----	0.01	0.02	0.21	0.01	0.10	0.11	0.12	0.08	0.08	0.07	0.08
CaO-----	0.44	0.56	0.57	0.42	0.57	0.44	0.40	0.65	0.64	0.72	0.72
Na <sub>2</sub> O-----	3.54	3.35	3.0	3.87	3.79	4.42	4.39	3.77	3.80	3.67	3.99
K <sub>2</sub> O-----	5.09	5.20	5.0	4.91	4.93	4.72	4.73	5.28	5.24	5.31	4.90
H <sub>2</sub> O+-----	0.22	0.15 }	0.68	0.15	0.12	0.13	0.10	0.06	0.12	0.03	0.30
H <sub>2</sub> O-----	0.05	0.00 }		0.02	0.08	0.01	--	0.06	0.06	0.05	0.04
TiO <sub>2</sub> -----	0.14	0.11	0.13	0.08	0.08	0.08	0.08	0.12	0.12	0.09	0.12
P <sub>2</sub> O <sub>5</sub> -----	0.01	0.01	0.04	0.01	0.09	tr.	0.06	0.01	0.02	0.01	0.02
MnO-----	0.04	0.02	0.03	0.03	0.02	0.09	0.10	0.05	0.05	0.05	0.04
Cl-----	0.07	0.08	0.08	0.09	0.05	--	--	--	--	--	--
F-----	0.16	0.14	0.12	0.19	0.15	0.42	0.44	0.15	0.16	0.76	0.22
Subtotal-----	99.74	99.85	99.80	100.00	100.22	100.21	100.25	99.77	99.87	99.79	99.91
Less O=(F,Cl) <sub>2</sub> -----	0.08	0.08	0.07	0.10	0.08	0.18	0.18	0.06	0.07	0.32	0.09
Total-----	99.66	99.77	99.73	99.90	100.14	100.03	100.07	99.71	99.80	99.47	99.82
FeO <sub>t</sub> -----	1.59	1.17	1.29	1.18	1.32	0.56	0.56	0.72	0.74	0.88	0.85
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.71	0.75	0.63	0.66	0.59	0.66	0.49	0.69	0.60	0.68	0.75
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.70	0.64	0.60	0.79	0.77	0.94	0.93	0.71	0.73	0.69	0.81
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.95	0.90	0.85	0.95	0.95	0.97	0.96	0.97	0.97	0.92	0.92
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.02	0.98	0.93	1.01	0.96	1.03	1.02	1.07	1.06	1.02	1.02
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.05	0.07	0.07	0.05	0.07	0.05	0.04	0.07	0.07	0.08	0.08
Cl/ F <sup>1</sup> -----	0.44	0.57	0.67	0.47	0.33	--	--	--	--	--	--
CIPW norms											
Q-----	35.03	35.61	38.37	34.27	34.57	31.62	31.97	33.23	33.31	32.02	32.02
or-----	30.31	30.89	29.87	29.15	29.19	27.99	28.03	31.36	31.11	31.71	29.15
ab-----	30.18	28.50	25.66	32.90	32.13	37.53	37.26	32.06	32.31	31.38	33.98
an-----	1.67	2.73	2.59	1.67	1.42	1.12	1.23	1.02	1.01	3.02	2.95
C-----	--	--	0.92	--	--	--	--	--	--	--	--
wo }-----	0.19	--	--	0.15	0.34	0.45	0.15	0.80	0.66	0.22	0.22
en } di-----	0.00	--	--	0.00	0.08	0.15	0.07	0.20	0.20	0.04	0.04
fs }-----	0.22	--	--	0.17	0.29	0.31	0.08	0.65	0.49	0.20	0.19
en } hy-----	0.02	0.05	0.53	0.02	0.17	0.13	0.23	--	--	0.14	0.16
fs }-----	1.40	1.27	0.98	0.91	0.64	0.26	0.26	--	--	0.66	0.70
mt-----	0.69	0.44	0.73	0.60	0.81	0.29	0.44	0.34	0.45	0.43	0.32
il-----	0.27	0.21	0.25	0.15	0.15	0.15	0.15	0.23	0.23	0.17	0.23
ap-----	0.02	0.02	0.09	0.02	0.21	0.00	0.14	0.02	0.05	0.02	0.05
other-----	--	--	--	--	--	--	--	(3)	(4)	--	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	UTAH	ARIZONA	MEXICO				PERU	
Volcanic field/region---	Twin Peaks Volc. Field	Galiuro Volcanics	West	Neovolcanic Central	Zone East			
Locality-----	Rhyolite of Cudahy Mine	Pinal	Tequila	Zinapec- uaro	Zacual- tipan	Tulan- cingo	Macusani	
Specimen-----	309	310	311	312	313	314	315	316
Chemical analyses (weight percent)								
SiO <sub>2</sub> -----	75.86	74.6	74.56	75.43	73.72	73.65	70.67	72.8
Al <sub>2</sub> O <sub>3</sub> -----	12.86	13.5	13.15	13.04	13.32	12.80	16.12	16.3
Fe <sub>2</sub> O <sub>3</sub> -----	0.21	1.3	0.51	0.51	0.85	0.60	1.33	0.29
FeO-----	0.66	0.12	1.00	0.76	0.76	1.76	0.41	0.30
MgO-----	0.07	0.11	0.25	0.15	0.22	0.25	0.18	0.00
CaO-----	0.74	0.38	0.66	0.43	0.66	0.63	2.07	0.16
Na <sub>2</sub> O-----	3.93	4.2	4.10	4.73	3.13	4.28	3.30	4.1
K <sub>2</sub> O-----	4.96	4.5	5.44	4.57	6.60	5.15	5.53	3.7
H <sub>2</sub> O+-----	0.35	0.42	0.25	0.51	0.22	0.23	0.19	0.70
H <sub>2</sub> O-----	0.04	0.10	0.06	0.00	0.03	0.01	0.18	0.00
TiO <sub>2</sub> -----	0.11	0.21	0.25	0.12	0.31	0.29	0.00	0.02
P <sub>2</sub> O <sub>5</sub> -----	0.02	0.03	0.08	0.06	0.09	0.08	0.27	0.55
MnO-----	0.05	0.10	0.02	0.02	0.02	0.02	0.06	0.06
Cl-----	--	--	--	--	--	--	--	--
F-----	0.20	--	--	--	--	--	--	--
Subtotal-----	100.06	99.57	100.33	100.33	99.93	99.75	100.31	98.98 <sup>6</sup>
Less O=(F,Cl) <sub>2</sub> -----	0.08	--	--	--	--	--	--	--
Total-----	99.98	99.57	100.33	100.33	99.93	99.75	100.31	98.98 <sup>6</sup>
FeO <sub>t</sub> -----	0.85	1.29	1.46	1.22	1.53	2.30	1.61	0.56
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.76	0.08	0.66	0.60	0.47	0.75	0.24	0.51
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.79	0.93	0.75	1.04	0.47	0.83	0.60	1.11
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.92	0.87	0.96	0.98	0.92	0.99	0.71	0.66
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.03	0.92	1.05	1.04	1.01	1.08	0.94	0.68
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.08	0.04	0.07	0.05	0.07	0.07	0.23	0.02
Cl/ F <sup>1</sup> -----	--	--	--	--	--	--	--	--
CIPW norms								
Q-----	32.28	32.36	28.14	29.33	28.76	27.04	26.39	35.22
or-----	29.47	26.85	32.14	27.05	39.13	30.58	32.70	22.25
ab-----	33.43	35.88	34.69	40.10	26.57	36.40	27.94	35.30
an-----	2.82	1.71	1.41	0.85	2.70	0.51	8.51	0.00
C-----	--	1.11	--	--	0.04	--	1.59	5.65
wo } di-----	0.31	--	0.56	0.37	--	0.88	--	--
en } di-----	0.05	--	0.21	0.12	--	0.20	--	--
fs } di-----	0.28	--	0.36	0.26	--	0.74	--	--
en } hy-----	0.12	0.28	0.41	0.25	0.55	0.43	0.45	0.00
fs } hy-----	0.67	0.00	0.68	0.55	0.22	1.57	0.00	0.40
mt-----	0.31	0.11	0.74	0.74	1.24	0.87	1.52	0.43
il-----	0.21	0.40	0.48	0.23	0.59	0.55	0.00	0.04
ap-----	0.05	0.07	0.19	0.14	0.21	0.19	0.63	0.29
other-----	--	--	--	--	--	--	(5)	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	ICELAND					ITALY					
Volcanic field/region---					Gaesafjöll complex	Vulcano				Lipari	
Locality-----	Hrafninn- uhryggur	Vatnajökull		Berufjor- dur	Little Krafla	Monte Lentia				Forgia Vecchia	Rocche Rosse
Specimen-----	317	318	319	320	321	322	323	324	325	326	327
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	75.4	75.06	73.63	75.0	73.44	71.37	71.16	70.85	70.69	73.86	74.22
Al <sub>2</sub> O <sub>3</sub> -----	11.9	13.84	12.75	12.4	11.82	14.90	14.07	13.70	14.54	12.49	12.98
Fe <sub>2</sub> O <sub>3</sub> -----	0.7	0.31	1.33	0.8	1.97	1.34	1.80	1.36	0.84	0.60	0.40
FeO-----	2.5	1.91	1.80	1.2	1.56	1.15	1.00	1.46	1.29	1.40	1.60
MgO-----	0.21	0.28	nil	0.16	0.01	0.36	0.93	1.10	0.74	0.11	0.04
CaO-----	1.7	1.62	1.12	0.92	1.74	1.54	1.95	2.32	2.28	0.75	0.67
Na <sub>2</sub> O-----	4.4	3.16	4.96	5.1	4.70	4.15	4.08	4.63	4.99	4.05	4.13
K <sub>2</sub> O-----	2.7	3.22	3.15	3.6	3.68	5.18	4.78	4.44	4.32	4.81	4.97
H <sub>2</sub> O+-----	0.21	0.17	0.49	0.23	0.63	0.27	0.23	0.39	0.26	0.92	0.27
H <sub>2</sub> O-----	0.03	0.06	0.22	0.04	0.14	0.06	0.08	0.02	0.03	0.09	0.04
TiO <sub>2</sub> -----	0.27	0.12	0.24	0.20	0.31	--	0.20	0.18	0.32	0.12	0.11
P <sub>2</sub> O <sub>5</sub> -----	0.03	tr	0.26	0.03	0.44	tr	0.10	0.12	0.15	tr	0.14
MnO-----	0.10	tr	0.06	0.06	0.09	0.07	0.06	0.08	0.05	tr	0.01
Cl-----	--	--	--	--	--	--	--	--	--	0.26	0.03
F-----	--	--	--	--	--	--	--	--	--	--	--
Subtotal-----	100.15	99.75	100.01	99.74	100.53	100.39	100.44	100.65	100.50	99.46	99.61
Less O=(F,Cl) <sub>2</sub> -----	--	--	--	--	--	--	--	--	--	0.06	0.01
Total-----	100.15	99.75	100.01	99.74	100.53	100.39	100.44	100.65	100.50	99.40	99.60
FeO <sup>1</sup> -----	3.13	2.19	3.00	1.92	3.33	2.36	2.62	2.69	2.05	1.94	1.96
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.78	0.86	0.58	0.60	0.44	0.46	0.36	0.52	0.61	0.70	0.80
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.63	0.98	1.57	1.42	1.28	0.80	0.85	1.04	1.16	0.84	0.83
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.86	0.63	0.91	0.99	0.99	0.84	0.84	0.91	0.91	0.94	0.95
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.11	0.84	1.07	1.13	1.26	1.02	1.10	1.21	1.21	1.06	1.03
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.24	0.25	0.14	0.11	0.21	0.17	0.22	0.26	0.24	0.08	0.07
Cl/F <sup>1</sup> -----	--	--	--	--	--	--	--	--	--	--	--
CIPW norms											
Q-----	34.68	39.22	30.53	29.87	30.37	23.24	24.42	21.53	20.22	30.25	29.22
or-----	15.97	19.14	18.75	21.39	21.80	30.59	28.21	26.17	25.47	28.95	29.59
ab-----	37.27	26.90	42.27	43.39	39.87	35.10	34.48	39.08	42.14	34.90	35.20
an-----	4.75	8.09	3.25	0.31	0.29	6.73	5.95	3.48	4.51	1.73	2.22
C-----	--	2.22	--	--	--	--	--	--	--	--	--
wo }-----	1.46	--	0.27	1.64	0.82	0.38	1.28	3.02	2.42	0.86	0.09
en } di-----	0.20	--	0.00	0.40	0.03	0.17	1.06	1.87	1.39	0.12	0.00
fs }-----	1.40	--	0.30	1.33	0.90	0.21	0.06	0.96	0.93	0.82	0.10
en } hy-----	0.33	0.70	0.00	--	--	0.73	1.26	0.86	0.45	0.16	0.10
fs }-----	2.36	3.27	1.63	--	--	0.92	0.07	0.44	0.31	1.09	2.37
mt-----	1.02	0.45	0.94	1.17	2.86	1.94	2.61	1.97	1.22	0.89	0.58
il-----	0.51	0.00	0.46	0.38	0.59	0.00	0.38	0.34	0.61	0.23	0.21
ap-----	0.07	0.00	0.61	0.07	1.02	0.00	0.23	0.28	0.35	0.00	0.33
other-----	--	--	--	(7)	(8)	--	--	--	--	--	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	HUNGARY		CZECHOSLOVAKIA	GREECE			U.S.S.R.		
Volcanic field/region---	Tokaj			Melos			Kamchatka	Great Kurile Arc	
Locality-----	Mad	Tolcsva	Vinicky	Bombardha			Uzon	Medvezcja caldera	
Specimen-----	328	329	330	331	332	333	334	335	336
Chemical analyses (weight percent)									
SiO <sub>2</sub> -----	73.06	74.67	75.10	76.56	74.59	74.75	73.03	74.82	74.87
Al <sub>2</sub> O <sub>3</sub> -----	14.04	13.47	14.07	13.47	13.37	13.00	13.42	12.89	12.78
Fe <sub>2</sub> O <sub>3</sub> -----	0.52	0.29	0.37	0.20	0.53	0.63	1.51	0.80	1.40
FeO-----	1.76	1.29	0.84	1.01	0.95	1.03	1.31	1.31	0.76
MgO-----	0.29	0.38	0.36	0.08	0.53	0.55	0.58	0.67	0.59
CaO-----	1.51	1.25	1.23	1.47	0.67	1.35	2.13	2.37	2.25
Na <sub>2</sub> O-----	3.40	3.73	3.54	3.76	4.47	3.65	4.43	4.31	4.52
K <sub>2</sub> O-----	4.99	4.25	4.37	3.51	4.51	4.56	2.43	1.57	1.57
H <sub>2</sub> O+-----	0.27	0.31	0.19	0.27	0.32	0.31	0.40	0.61	0.47
H <sub>2</sub> O-----	0.08	0.04	0.01	0.22	0.04	0.09	0.20	0.16	0.20
TiO <sub>2</sub> -----	0.10	0.07	tr	0.10	0.11	0.18	0.47	0.55	0.63
P <sub>2</sub> O <sub>5</sub> -----	0.02	0.01	tr	--	0.02	0.22	0.08	0.04	0.08
MnO-----	0.02	0.02	0.04	0.06	0.02	0.06	0.07	0.10	0.10
Cl-----	0.06	0.12	--	--	--	--	0.08	--	--
F-----	--	--	--	--	--	--	0.03	--	--
Subtotal-----	100.12	99.90	100.12	100.71	100.13	100.38	100.17	100.20	100.22
Less O=(F,Cl) <sub>2</sub> -----	0.01	0.03	--	--	--	--	0.03	--	--
Total-----	100.11	99.87	100.12	100.71	100.13	100.38	100.14	100.20	100.22
FeO <sub>t</sub> -----	2.23	1.55	1.17	1.19	1.43	1.60	2.67	2.03	2.02
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.77	0.82	0.69	0.84	0.64	0.62	0.46	0.62	0.35
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	0.68	0.88	0.81	1.07	0.99	0.80	1.82	2.75	2.98
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.78	0.80	0.75	0.74	0.92	0.84	0.74	0.68	0.72
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.98	0.97	0.91	0.94	1.01	1.03	1.03	1.02	1.04
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.18	0.16	0.16	0.20	0.07	0.16	0.31	0.40	0.37
Cl/ F <sup>1</sup> -----	--	--	--	--	--	--	2.67	--	--
CIPW norms									
Q-----	29.44	32.75	34.04	37.16	28.72	32.44	32.81	37.59	37.41
or-----	29.57	25.26	25.84	20.70	26.71	26.95	14.44	9.33	9.32
ab-----	28.85	31.74	29.98	31.75	37.91	20.89	37.69	36.68	38.42
an-----	7.38	6.17	6.11	7.28	3.10	5.26	9.61	11.25	9.99
C-----	0.35	0.49	1.28	0.81	--	0.13	--	--	--
wo } di-----	--	--	--	--	0.04	--	0.21	0.13	0.29
en } di-----	--	--	--	--	0.02	--	0.14	0.08	0.25
fs } di-----	--	--	--	--	0.02	--	0.05	0.05	0.00
en } hy-----	0.72	0.95	0.90	0.20	1.30	1.37	1.31	1.60	1.22
fs } hy-----	2.68	2.06	1.31	1.63	1.15	1.19	0.47	0.98	0.00
mt-----	0.76	0.42	0.54	0.29	0.77	0.91	2.20	1.17	0.95
il-----	0.19	0.13	0.00	0.19	0.21	0.34	0.90	1.05	1.20
ap-----	0.05	0.02	0.00	0.00	0.05	0.51	0.19	0.09	0.19
other-----	--	--	--	--	--	--	--	--	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----		JAPAN									
Volcanic field/region---		Hokkaido			Honshu					Nagano Prefecture	Huzi volc. zone
Locality-----		Atosan- upuri	Tokachi	Usu	Asama Volcano					Wada- toge	Kasiwa- toge
Specimen-----		338	339	340	341	342	343	344	345	346	347
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	72.80	72.64	76.59	70.60	73.7	73.0	72.7	72.01	71.76	75.65	75.63
Al <sub>2</sub> O <sub>3</sub> -----	14.80	12.92	12.76	15.00	14.2	14.1	14.3	14.37	14.20	12.81	12.80
Fe <sub>2</sub> O <sub>3</sub> -----	1.58	1.52	0.28	1.37	0.39	0.65	0.42	0.73	0.74	0.32	0.47
FeO-----	3.07	1.93	0.98	2.49	1.62	1.58	1.79	1.81	1.71	0.85	1.95
MgO-----	0.43	1.14	0.48	0.77	0.63	0.58	0.60	0.57	0.22	0.23	0.28
CaO-----	0.74	2.53	1.11	3.30	2.49	2.59	2.80	2.56	2.94	0.56	2.20
Na <sub>2</sub> O-----	3.36	4.03	4.05	4.42	4.47	4.12	4.19	4.35	4.43	3.73	3.71
K <sub>2</sub> O-----	1.51	1.62	3.47	0.98	2.30	2.07	2.33	2.39	2.03	4.40	2.35
H <sub>2</sub> O+-----	0.50	0.61	0.48	0.69	0.42	0.37	0.38	0.26	0.49	0.74	0.25
H <sub>2</sub> O-----	0.30	0.15	0.22	0.12							
TiO <sub>2</sub> -----	0.32	0.68	tr	0.36	0.47	0.47	0.51	0.41	0.73	0.13	0.26
P <sub>2</sub> O <sub>5</sub> -----	--	0.04	0.12	0.21	0.09	0.09	0.09	0.07	0.05	0.12	tr
MnO-----	0.16	0.07	0.04	0.09	0.06	0.06	0.06	0.08	0.20	0.05	0.06
Cl-----	--	--	--	--	--	--	--	--	--	--	--
F-----	--	--	--	--	--	--	--	--	--	--	--
Subtotal-----	99.57	99.88	100.58	100.40	100.84	99.68	100.17	99.69	99.50	99.72	100.03
Less O=(F,Cl) <sub>2</sub> -----	--	--	--	--	--	--	--	--	--	--	--
Total-----	99.57	99.88	100.58	100.40	100.84	99.68	100.17	99.69	99.50	99.72	100.03
FeO <sup>1</sup> -----	4.49	3.30	1.23	3.72	1.97	2.17	2.17	2.47	2.38	1.14	2.37
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.66	0.56	0.78	0.65	0.81	0.71	0.81	0.71	0.70	0.73	0.81
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	2.23	2.49	1.17	4.51	1.94	1.99	1.80	1.82	2.18	0.85	1.58
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.48	0.65	0.82	0.56	0.69	0.64	0.66	0.68	0.67	0.85	0.68
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.57	1.01	0.97	0.96	1.01	0.97	1.01	1.00	1.04	0.93	0.99
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.15	0.45	0.15	0.75	0.37	0.42	0.43	0.38	0.46	0.07	0.36
Cl/ F <sup>1</sup> -----	--	--	--	--	--	--	--	--	--	--	--
CIPW norms											
Q-----	43.92	35.72	36.29	32.27	31.84	34.42	31.83	30.62	31.58	35.79	38.73
or-----	9.03	9.66	20.53	5.82	13.53	12.32	13.80	14.22	12.12	26.30	13.93
ab-----	28.79	34.40	34.31	37.56	37.67	35.11	35.53	37.05	37.86	31.93	31.48
an-----	3.72	12.40	4.73	15.06	11.72	12.35	13.33	12.32	12.99	2.02	10.95
C-----	6.37	0.03	0.61	1.18	0.05	0.59	0.01	0.14	--	1.19	0.15
wo } di-----	--	--	--	--	--	--	--	--	0.59	--	--
en } di-----	--	--	--	--	--	--	--	--	0.15	--	--
fs } di-----	--	--	--	--	--	--	--	--	0.47	--	--
en } hy-----	1.08	2.86	1.20	1.93	1.56	1.46	1.50	1.43	0.40	0.58	0.70
fs } hy-----	4.15	1.31	1.65	3.03	1.98	1.71	2.21	2.21	1.24	1.19	2.88
mt-----	2.32	2.22	0.41	2.00	0.56	0.95	0.61	1.07	1.08	0.47	0.68
il-----	0.62	1.30	0.00	0.69	0.89	0.90	0.97	0.78	1.40	0.25	0.50
ap-----	0.00	0.09	0.28	0.49	0.21	0.21	0.21	0.16	0.12	0.28	0.00
other-----	--	--	--	--	--	--	--	--	--	--	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	JAPAN										
Volcanic field/region---	Kanagawa Prefecture	Hakone Prefecture	Huzi volcanic zone		Izu-Mariana Arc			Oki-Dogo Islands		Kumamoto Prefecture	Kagoshima Prefecture
Locality-----	Yugawara- machi	Young somma	Amagi Volcano		Kozu- shima	Ombasi- zima	Higashi- yama	Kumi		Aso	Aira
Specimen-----	348	349	350	351	352	353	354	355	356	357	358
Chemical analyses (weight percent)											
SiO <sub>2</sub> -----	75.63	75.78	71.16	71.36	75.35	74.93	73.42	74.40.	74.53	72.50	76.84
Al <sub>2</sub> O <sub>3</sub> -----	11.68	12.71	14.72	14.35	13.49	13.52	12.35	12.71	12.84	13.91	11.39
Fe <sub>2</sub> O <sub>3</sub> -----	1.08	0.40	1.12	0.97	0.95	0.76	0.79	0.69	0.45	0.40	0.80
FeO-----	1.70	1.93	2.15	1.95	0.55	0.72	4.03	1.23	1.76	1.38	0.79
MgO-----	0.66	0.39	1.30	1.38	0.36	0.32	0.28	0.06	0.05	0.02	0.35
CaO-----	2.74	2.64	3.50	3.73	1.61	0.93	3.02	0.48	0.39	1.34	1.40
Na <sub>2</sub> O-----	3.22	3.92	3.61	2.72	4.28	4.50	3.41	4.06	3.71	4.17	4.28
K <sub>2</sub> O-----	2.46	1.27	2.06	2.24	2.52	3.39	1.96	5.18	5.44	5.01	3.11
H <sub>2</sub> O+-----	0.51	0.64	0.27	0.78	0.61	0.46	0.53	0.55	0.16	0.60	0.24
H <sub>2</sub> O-----	0.04	0.15	0.10	0.35	0.06	0.33	0.07	0.08	0.02	0.16	0.20
TiO <sub>2</sub> -----	0.26	0.41	0.36	0.35	0.20	0.13	0.27	0.13	0.15	0.40	0.17
P <sub>2</sub> O <sub>5</sub> -----	0.28	0.15	0.08	0.33	--	0.08	0.13	tr	tr	0.13	0.20
MnO-----	0.11	0.12	0.08	0.06	0.08	0.08	0.12	0.06	0.06	0.06	0.06
Cl-----	--	--	--	--	--	--	--	--	--	--	--
F-----	--	--	--	--	--	--	--	--	--	--	--
Subtotal-----	100.37	100.51	100.51	100.57	100.06	100.15	100.38	99.63	99.56	100.08	99.83
Less O=(F,Cl) <sub>2</sub> -----	--	--	--	--	--	--	--	--	--	--	--
Total-----	100.37	100.51	100.51	100.57	100.06	100.15	100.38	99.63	99.56	100.08	99.83
FeO <sub>t</sub> -----	2.67	2.29	3.16	2.82	1.41	1.40	4.74	1.85	2.17	1.74	1.51
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.61	0.83	0.66	0.67	0.37	0.49	0.84	0.64	0.80	0.78	0.50
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.31	3.09	1.75	1.21	1.70	1.33	1.74	0.78	0.68	0.83	1.38
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.68	0.62	0.55	0.48	0.72	0.82	0.63	0.97	0.93	0.88	0.91
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.11	0.99	0.99	0.95	0.94	0.94	1.07	1.04	0.99	1.06	1.14
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.48	0.51	0.62	0.75	0.24	0.12	0.56	0.05	0.04	0.15	0.19
Cl/ F <sup>1</sup> -----	--	--	--	--	--	--	--	--	--	--	--
CIPW norms											
Q-----	40.93	41.16	31.85	37.00	37.03	33.47	37.00	29.68	30.17	26.26	37.67
or-----	14.56	7.53	12.16	13.31	14.98	20.16	11.61	30.92	32.35	29.81	18.49
ab-----	27.30	33.26	30.50	23.15	36.44	38.32	28.92	34.70	31.59	35.53	36.44
an-----	10.17	12.15	16.82	16.44	8.04	4.12	12.63	1.17	1.95	4.47	2.70
C-----	--	0.45	0.38	1.47	0.80	0.96	--	--	0.14	--	--
wo }-----	0.68	--	--	--	--	--	0.64	0.52	--	0.57	1.24
en } di-----	0.30	--	--	--	--	--	0.07	0.05	--	0.02	0.70
fs }-----	0.37	--	--	--	--	--	0.64	0.52	--	0.62	0.50
en } hy-----	1.34	0.97	3.23	3.46	0.90	0.80	0.63	0.10	0.13	0.03	0.18
fs }-----	1.64	2.77	2.57	2.33	0.04	0.63	5.90	1.08	2.74	1.04	0.13
mt-----	1.57	0.58	1.62	1.41	1.39	1.11	1.15	1.01	0.66	0.58	1.17
il-----	0.50	0.78	0.68	0.67	0.38	0.25	0.51	0.25	0.29	0.77	0.33
ap-----	0.65	0.35	0.19	0.77	0.00	0.19	0.30	0.00	0.00	0.30	0.47
other-----	--	--	--	--	--	--	--	--	--	--	--

See footnotes at end of table.

APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	PAPUA NEW GUINEA						NEW BRITAIN	NEW ZEALAND	
Volcanic field/region---	D'Entrecasteaux Island		St. Andrew Strait		Witu Islands				
Locality-----	Moresby Strait		Lou Island		Garove Island		Talasea	Tairua River	Fanal Island
Specimen-----	359	360	361	362	363	364	365	366	367
Chemical analyses (weight percent)									
SiO <sub>2</sub> -----	72.30	72.77	73.66	71.39	71.71	70.3	75.6	76.89	75.66
Al <sub>2</sub> O <sub>3</sub> -----	14.20	14.19	14.05	13.95	14.01	13.4	12.8	12.72	12.86
Fe <sub>2</sub> O <sub>3</sub> -----	0.38	0.42	0.39	0.58	0.43	0.90	0.33	0.43	0.26
FeO-----	0.95	0.94	0.90	1.88	1.86	3.00	0.84	0.70	1.01
MgO-----	0.22	0.22	0.18	0.55	0.39	0.73	0.26	0.17	0.35
CaO-----	0.72	0.71	0.63	1.29	1.21	2.60	1.22	0.57	0.97
Na <sub>2</sub> O-----	5.19	5.05	5.01	5.06	5.04	5.7	3.95	3.48	3.65
K <sub>2</sub> O-----	4.45	4.44	4.51	3.93	3.99	1.68	3.85	4.39	4.70
H <sub>2</sub> O+-----	0.52	0.41	0.38	0.15	0.21	0.11	0.56	0.47	0.28
H <sub>2</sub> O-----	0.16	0.11	0.09	0.21	0.10	0.25	0.02	0.02	0.07
TiO <sub>2</sub> -----	0.26	0.26	0.24	0.31	0.30	0.66	0.27	0.08	0.21
P <sub>2</sub> O <sub>5</sub> -----	0.04	0.04	0.03	0.04	0.04	0.14	0.03	nil	0.06
MnO-----	0.06	0.05	0.04	0.07	0.07	0.15	0.07	0.07	0.02
Cl-----	--	--	--	--	--	--	--	tr	--
F-----	--	--	--	--	--	--	--	--	--
Subtotal-----	99.45	99.61	100.11	99.41	99.36	99.62	99.80	99.99	100.10
Less O=(F,Cl) <sub>2</sub> -----	--	--	--	--	--	--	--	--	--
Total-----	99.45	99.61	100.11	99.41	99.36	99.62	99.80	99.99	100.10
FeO <sup>1</sup> -----	1.29	1.32	1.25	2.40	2.25	3.81	1.14	1.09	1.24
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.71	0.73	0.70	0.76	0.81	0.77	0.72	0.62	0.80
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.17	1.14	1.11	1.29	1.26	3.39	1.03	0.79	0.78
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.94	0.92	0.93	0.90	0.90	0.84	0.83	0.82	0.86
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.03	1.02	1.02	1.07	1.06	1.19	1.01	0.90	1.00
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.07	0.07	0.07	0.14	0.13	0.35	0.16	0.07	0.12
Cl/ F <sup>1</sup> -----	--	--	--	--	--	--	--	--	--
CIPW norms									
Q-----	23.32	24.49	25.44	23.00	23.47	24.12	34.82	38.14	33.49
or-----	26.62	26.48	26.75	23.45	23.80	10.00	22.93	26.07	27.84
ab-----	44.46	43.12	42.55	43.23	43.06	48.59	33.69	29.60	30.96
an-----	2.34	2.97	2.54	3.78	3.86	6.06	5.87	2.84	4.43
c-----	--	--	--	--	--	--	--	1.21	0.15
wo }-----	0.42	0.14	0.17	1.01	0.81	2.51	0.01	--	--
en } di-----	0.14	0.05	0.05	0.36	0.23	0.82	0.01	--	--
fs }-----	0.29	0.09	0.12	0.68	0.62	1.78	0.01	--	--
en } hy-----	0.41	0.51	0.40	1.03	0.76	1.01	0.65	0.43	0.87
fs }-----	0.83	0.96	0.89	1.94	2.10	2.21	0.95	0.93	1.33
mt-----	0.56	0.62	0.57	0.85	0.63	1.32	0.48	0.63	0.38
il-----	0.50	0.50	0.46	0.59	0.58	1.26	0.52	0.15	0.40
ap-----	0.09	0.09	0.07	0.09	0.09	0.33	0.07	0.00	0.14
other-----	--	--	--	--	--	--	--	--	--

See footnotes at end of table.



APPENDIX III.—*Compilation of published major-element analyses of subalkaline silicic glasses—Continued*

Country/State-----	NEW ZEALAND			TONGA
Volcanic field/region---	Haroharo complex		Taupo Complex	
Locality-----	Okataina center		Tuhin-gamata	Metis Shoal
Specimen-----	368	369	370	371
Chemical analyses (weight percent)				
SiO <sub>2</sub> -----	75.55	75.76	76.7	73.38
Al <sub>2</sub> O <sub>3</sub> -----	12.78	12.87	12.1	12.66
Fe <sub>2</sub> O <sub>3</sub> -----	0.34	0.29	0.4	1.11
FeO-----	1.07	0.89	0.9	2.84
MgO-----	0.22	0.16	0.2	0.84
CaO-----	1.45	1.29	1.1	3.79
Na <sub>2</sub> O-----	3.98	4.38	4.25	3.09
K <sub>2</sub> O-----	3.64	3.11	3.55	1.52
H <sub>2</sub> O+-----	0.35	0.46	0.2	<0.13
H <sub>2</sub> O-----	0.04	0.12	0.0	0.03
TiO <sub>2</sub> -----	0.21	0.19	0.16	0.45
P <sub>2</sub> O <sub>5</sub> -----	0.02	0.03	0.04	0.00
MnO-----	0.05	0.07	<0.01	0.06
Cl-----	--	0.14	--	--
F-----	--	--	--	--
Subtotal-----	99.70	99.76	99.60	99.77
Less O=(F,Cl) <sub>2</sub> -----	--	0.03	--	--
Total-----	99.70	99.73	99.60	99.77
FeO <sup>1</sup> -----	1.38	1.15	1.26	3.84
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	0.76	0.75	0.69	0.72
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	1.09	1.41	1.20	2.03
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	0.82	0.82	0.90	0.53
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.03	1.00	1.06	1.08
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	0.19	0.17	0.14	0.82
Cl/ F <sup>1</sup> -----	--	--	--	--
CIPW norms				
Q-----	34.85	35.25	35.96	39.21
or-----	21.66	18.56	21.10	9.01
ab-----	33.91	37.42	36.18	26.22
an-----	6.30	6.26	3.48	16.23
C-----	--	0.03	--	--
wo }-----	0.34	--	0.73	1.10
en } di-----	0.10	--	0.24	0.41
fs }-----	0.26	--	0.51	0.71
en } hy-----	0.45	0.40	0.26	1.69
fs }-----	1.18	1.22	0.55	2.97
mt-----	0.50	0.43	0.58	1.61
il-----	0.40	0.36	0.31	0.86
ap-----	0.05	0.07	0.09	0.00
other-----	--	--	--	--

<sup>1</sup>By weight.

<sup>2</sup>Molecular.

<sup>3</sup>Normative wollastonite, 0.10 percent.

<sup>4</sup>Normative wollastonite, 0.20 percent.

<sup>5</sup>Normative hematite, 0.28 percent.

<sup>6</sup>Low total due to non-analysis for fluorine.

<sup>7</sup>Normative wollastonite, 0.07 percent.

<sup>8</sup>Normative wollastonite, 1.47 percent.

## NORTH AMERICA

## UNITED STATES OF AMERICA

## ALASKA

- 242 Rhyolitic obsidian, flow, northeastern Umnak Island. Lat 53°29.5' N., long 168°10'3" W. Analyst: F.M. Byers, Jr. (Reference: Byers, 1959, table 2, No. 19, colln. 46 A By 30 a.)
- 243 Siliceous soda rhyolite, light band in Novarupta composite lava, Valley of Ten Thousand Smokes. Analyst: C.N. Fenner. (Reference: Fenner, 1923, p. 57, colln. 153 c.)
- 244 Glassy rhyolite, Novarupta, Valley of Ten Thousand Smokes. Analyst: E.G. Zies. (Reference: Zies, 1929, p. 56, colln. Fenner No. 406.)

## OREGON

- 245 Obsidian, north edge of Newberry flow, South Sister, at 6,800 ft elevation. Analyst: K. Aoki. (Reference: McBirney, 1968, table 2, No. 7. Phenocrysts: no data.)
- 246 Glassy dacite, south edge of Grouse Hill dome, Crater Lake. Analyst: W.H. Herdsman. (Reference: Williams, 1942, p. 151, No. 22.)
- 247 Hypersthene-dacite, vitrophyric type, south edge of Llao Rock flow, Crater Lake. Analyst: H.N. Stokes. (Reference: Diller and Patton, 1902, p. 140, No. 102.)
- 248 Rhyolitic obsidian, East Lake obsidian flow, Newberry Volcano. Analysts: G. Riddle, P. Elmore, G. Chloe, J. Glenn, L. Artis, H. Smith, J. Kelsey, and S. Botts. (Reference: Higgins, 1973, table 5, No. 40.)
- 249 Obsidian, wall obsidian in caldera pumice cone, Newberry Volcano. Analysts: same as 248. (Reference: Higgins, 1973, table 5, No. 42. Phenocrysts: not specified.)
- 250 Obsidian, massive, black flow on north wall of crater, Big Pumice Cone, between the lakes, Newberry Volcano. Analyst: F. Herdsman. (Reference: Williams, 1935, table, No. 10, colln. 44.)
- 251, 252 Obsidians, Game Hut flow, Newberry Volcano. Analysts: same as 248. (Reference:

- Higgins, 1973, table 5, Nos. 48 and 49. Phenocrysts: not specified.)
- 253, 254 Obsidians, Pumice Cone obsidian flow, Newberry Volcano. Analysts: same as 248. (Reference: Higgins, 1973, table 5, Nos. 50 and 51. Phenocrysts: not specified.)
- 255, 256 Obsidians, north obsidian flow, Newberry Volcano. Analysts: same as 248. (Reference: Higgins, 1973, table 5, Nos. 52 and 53. Phenocrysts: not specified.)
- 257-259 Obsidians, "Big Obsidian Flow," Newberry Volcano. Analysts: same as 248. (Reference: Higgins, 1973, table 5, Nos. 54, 55, and 56. Phenocrysts: not specified.)
- 260 Pumiceous obsidian, plug-dome at head of "Big Obsidian Flow," Newberry Volcano. Analyst: F. Herdsman. (Reference: Williams, 1935, table, No. 11, colln. 101.)
- 261 Obsidian, "Big Obsidian Flow," Newberry caldera. Analyst: T. Cook. (Reference: Green, 1965, p. 1131, No. 3.)

## CALIFORNIA

- 262 Trachytic obsidian, massive lava group, north slope Medicine Lake Highlands. Analyst: F. Herdsman. (Reference: Powers, 1932, table 1, colln. 19044.)
- 263 Rhyolitic obsidian, massive lava group, south slope Medicine Lake Highlands. Analyst: F. Herdsman. (Reference: Powers, 1932, table 1, colln. 19007.)
- 264 Rhyolitic obsidian, near ridge of pumice breccia in rhyolite-dacite composite lava field, Glass Mountain, Medicine Lake Highlands. Analyst: F. Herdsman. (Reference: Anderson, 1933, table 1, No. 6. Phenocrysts: not specified.)
- 265 Rhyolitic obsidian, from dome south of Glass Mountain, Medicine Lake Highlands, representing last extrusion of lava into the rhyolite-dacite composite flow. Analyst: F. Herdsman. (Reference: Anderson, 1933, table 1, No. 7. Phenocrysts: not specified.)
- 266 Rhyolitic obsidian, south of ridge of pumice breccia in rhyolite-dacite composite lava field, Glass Mountain, Medicine Lake Highlands. Analyst: F. Herdsman. (Reference: Anderson, 1933, table 1, No. 5. Phenocrysts: not specified.)
- 267 Rhyolitic obsidian, obsidian group, Big Glass Mountain, Medicine Lake Highlands. Analyst: E.S. Shepherd. (Reference: Powers, 1932, table 1, colln. 19103.)
- 268 Rhyolitic obsidian, associated with dacite in northeastern tongue of rhyolite-dacite composite flow, Glass Mountain, Medicine Lake Highlands. Analyst: F. Herdsman. (Reference: Anderson, 1933, table 1, No. 4. Phenocrysts: not specified.)
- 269 Finely vesicular rhyolitic glass, part of large dome, summit of Glass Mountain, Medicine Lake Highlands. Analyst: F. Herdsman. (Reference: Anderson, 1933, table 1, No. 10. Phenocrysts: not specified.)
- 270 Rhyolitic obsidian, obsidian group, fourth terrace from top, eastern slope of Big Glass Mountain, Medicine Lake Highlands. Analyst: E.S. Shepherd. (Reference: Powers, 1932, table 1, colln. 19103 c.)
- 271 Rhyolitic obsidian, from younger obsidian flow, Glass Mountain, Medicine Lake Highlands. Analyst: F. Herdsman. (Reference: Anderson, 1933, table 1, No. 8. Phenocrysts: not specified.)
- 272 Rhyolitic obsidian, third terrace from top, obsidian group, Big Glass Mountain, Medicine Lake Highlands. Analyst: E.S. Shepherd. (Reference: Powers, 1932, table 1, colln. 19103 b.)
- 273 Obsidian, Glass Mountain, Medicine Lake. Analyst: I.S.E. Carmichael. (Reference: Carmichael, 1967, table 5, No. 14, colln. CAM 66.)
- 274-277 Obsidians, Little Glass Mountain, Medicine Lake Highlands. Analyst: E.S. Shepherd. (Reference: Shepherd, 1938, table 3. Phenocrysts: not specified.)
- 278 Porphyritic obsidian, Little Glass Mountain, Medicine Lake. Analyst: I.S.E. Carmichael. (Reference: Carmichael, 1967, table 5, No. 12, colln. CAM 49.)
- 279 Rhyolitic obsidian, obsidian group, Little Glass Mountain, Medicine Lake Highlands. Analyst: E.S. Shepherd. (Reference: Powers, 1932, table 1, colln. 19033 a, except F value—Shepherd, 1938, table 3.)
- 280 Obsidian, Bottle Rock Road, Clear Lake volcanic field, Lake County. Analyst: I.S.E. Carmichael. (Reference: Carmichael, 1967, table 5, No. 21, colln. CAM 118.)
- 281 Rhyolitic obsidian, south of Borax Lake, Clear Lake volcanic field. Analyst: S. Goldich. (Reference: Anderson, 1936, table 1, No. 13. Sample 13 composite and free from inclusions. Nevertheless, some of phenocrysts may, in fact, be xenocrystic from dismembered mafic inclusions.)

- 282 Rhyolitic obsidian, plug underlying Little Glass Mountain, Napa County. Analyst: A.G. Loomis. (Reference: Lofgren, 1971.)
- 283 Porphyritic rhyolitic obsidian, Glass Mountain, Inyo Craters. Analyst: I.S.E. Carmichael. (Reference: Carmichael, 1967, table 5, No. 22, colln. CAM 81.)
- 284 Porphyritic rhyolitic obsidian, extrusion south of Glass Mountain, Inyo Craters. Analyst: I.S.E. Carmichael. Reference: Carmichael, 1967, table 5, No. 23, colln. CAM 86.
- 285 Obsidian, north of pumice mine, Mono Craters. Analyst: I.S.E. Carmichael. (Reference: Carmichael, 1967, table 5, No. 17, colln. CAM 104.)
- 286 Aphyric obsidian, southern Coulee, Mono Craters. Analysts: G. Riddle and V.C. Smith. (Reference: Noble and others, 1972, table 1, No. 5, lab. D101110.)
- 287 Rhyolitic obsidian, circular extrusion by Route 120, Mono Craters. Analyst: I.S.E. Carmichael. (Reference: Carmichael, 1967, table 5, No. 19, colln. CAM 110.)
- 288 Rhyolitic obsidian, flow, south of Route 120, Mono Craters. Analyst: I.S.E. Carmichael. (Reference: Carmichael, 1967, table 5, No. 18, colln. CAM 108.)
- 289 Aphyric obsidian, from near crest of Glass Mountain, Long Valley volcanic complex. Analysts: G. Riddle and V.C. Smith. (Reference: Noble and others, 1972, table 1, No. 1, lab. D101113.)
- 290 Obsidian, near crest of Glass Mountain, Long Valley volcanic complex. Analysts: G. Riddle and V.C. Smith. (Reference: Noble and others, 1972, table 1, No. 2, lab. D101114. Phenocrysts: not specified, but less than or equal to 1 percent modally.)

## NEVADA

- 291 Rhyolitic obsidian, Silver Peak volcanic center. Analyst: U.S. Geological Survey. (Reference: Robinson, 1972, table 3, No. 0b, colln. 430160. Phenocrysts: not specified.)
- 292 Obsidian, core in perlite, rhyolite of Shoshone Mountain. Analysts: V.C. Smith and C.L. Parker. (Reference: Jezek and Noble, 1978, table 2, lab. D100425.)
- 293 Obsidian, core in perlite, rhyolite of Obsidian Butte. Analyst: V.C. Smith. (Reference: Jezek and Noble, 1978, table 4, lab. D100319.)

## WYOMING

- 294 Obsidian, from glassy, densely welded base of member B, Lava Creek Tuff, east end of dam on Grassy Lake Reservoir, Yellowstone. Analyst: G. Riddle. (Reference: R.L. Christiansen, written commun., 1988, table 4, No. 4, lab. D101806. Phenocrysts said to include "accessory minerals.")
- 295 Rhyolitic obsidian, from block in obsidian breccia at top of rhyolite flow, collected along Black Canyon forest access road, 10.6 mi west of south from West Yellowstone. Analysts: P. Elmore, I. Barlow, S. Botts, G. Chloe, and V.C. Smith. (Reference: Hamilton, 1963, table, No. 11, lab. 158048.)
- 296 Rhyolitic obsidian, from block in breccia at top of a rhyolite flow front, 2.3 mi south of West Yellowstone. Analysts: same as 295. (Reference: Hamilton, 1963, table, No. 9, lab. 158049.)
- 297 Glassy rhyolite, Spring Creek flow of Central Plateau Member. Just west of trail to Divide Lookout, 0.8 km southwest of Norris Pass, Yellowstone. Analyst: G. Riddle. (Reference: R.L. Christiansen, written commun., 1988, table 4, No. 12, lab. D101812. Phenocrysts said to include "accessory minerals.")
- 298 Glassy rhyolite, West Yellowstone flow, Central Plateau Member. Lumbering road on west side of Madison Plateau, about 0.5 km south-southwest of West Yellowstone. Analyst: G. Riddle. (Reference: R.L. Christiansen, written commun., 1988, table 4, No. 15, lab. D102472. Phenocrysts said to include "accessory minerals.")
- 299 Glassy rhyolite, Cougar Creek flow, Roaring Mountain Member. From south side of outcrop area of flow, south of Cougar Creek, Yellowstone. Analyst: G. Riddle. (Reference: R.L. Christiansen, written commun., 1988, table 4, No. 18, lab. D101808. Phenocrysts said to include "accessory minerals.")
- 300 Rhyolitic obsidian, obsidian dome (hill 7085, Madison Junction quadrangle) 6.5 mi east-northeast of West Yellowstone. Analysts: same as 295. (Reference: Hamilton, 1963, table, No. 10, lab. 158045.)
- 301 Glassy rhyolite, Obsidian Cliff flow, Roaring Mountain Member, Yellowstone, from 0.6 km east of Lake of the Woods. Analyst: G. Riddle. (Reference: R.L. Christiansen, written commun., 1988, table 4, No. 19, lab. D101810.)

- 302 Obsidian, Obsidian Cliff, Yellowstone. Analyst: E.S. Shepherd. (Reference: Bowen, 1935, table 1, No. 3. Phenocrysts: not specified.)

## UTAH

- 303 Obsidian, Little Bearskin Mountain dome, Mineral Mountains. Analyst: S.H. Evans, Jr. (Reference: Lipman and others, 1978, table 2, colln. MR 75-14.)
- 304 Obsidian, North Twin Flat Mountain dome, Mineral Mountains. Analyst: S.H. Evans, Jr. (Reference: Lipman and others, 1978, table 2, colln. MR 75-20.)
- 305 Obsidian, Wildhorse Canyon flow, Mineral Mountains. Analyst: S.H. Evans, Jr. (Reference: Lipman and others, 1978, table 2, colln. MR 74-8.)
- 306 Obsidian, Bailey Ridge flow, Mineral Mountains. Analyst: S.H. Evans, Jr. (Reference: Lipman and others, 1978, table 2, colln. 74-3A.)
- 307-309 Obsidians, rhyolite of Cudahy mine, Twin Peaks volcanic field. Analyst: not specified. (Reference: Crecraft and others, 1981, table 3, Nos. 9, 18, and 19.)

## ARIZONA

- 310 Flow-banded rhyolite obsidian, upper rhyolite-obsidian unit, Galiuro Volcanics, Holy Joe Peak quadrangle. Analysts: P. Elmore, S. Botts, H. Smith, and D. Taylor. (Reference: Creasey and Krieger, 1978, table 2, lab. M101317W.)

## MEXICO

- 311 Obsidian, near Tequila, on highway from Guadalajara to Tepic. Analyst: A. Obregon-Perez. (Reference: Heizer and others, 1965, table 3, No. 4. Phenocrysts: not specified.)
- 312 Obsidian, just south of Zinapécuaro, on highway from Zinapécuaro to Ciudad Hidalgo, Michoacan. Analyst: A. Obregon-Perez. (Reference: Heizer and others, 1965, table 3, No. 5. Phenocrysts: not specified.)
- 313 Obsidian, small cut on road from Pachuca to Zacualtipan, at turnoff east to Huayacocotla, Hidalgo. Analyst: A. Obregon-Perez. (Reference: Heizer and others, 1965, table 3, No. 3. Phenocrysts: not specified.)
- 314 Obsidian, exposed in cut between 145- and 146-km markers on highway from Tulancingo to Posa Rica,

Veracruz. Analyst: A. Obregon-Perez. (Reference: Heizer and others, 1965, table 3, No. 1. Phenocrysts: not specified.)

## SOUTH AMERICA

### PERU

- 315 Macusanite, Macusani. Analyst: C. de Sitter-Koomans. (Reference: Martin and de Sitter-Koomans, 1955, p. 158.)
- 316 Macusanite, Macusani. Analysts: P. Elmore, S. Botts, and L. Artis. (Reference: Barnes and others, 1970, table 3, lab. 164364. Phenocrysts: not specified.)

## EUROPE

### ICELAND

- 317 Obsidian, postglacial, Hrafninnuhryggur. Analyst: I.S.E. Carmichael. (Reference: Carmichael, 1962, table 3, No. J. Phenocrysts: not specified.)
- 318 Obsidian, Pálsfjall, Vatnajökull. Analyst: W.H. Herdsman. (Reference: Noe-Nygaard, 1952, table 2, No. 2.)
- 319 Glassy liparite, Mid-Bergvatnsá, just south of Vatnajökull. Analyst: Me. Mouritzen. (Reference: Noe-Nygaard, 1952, table 5.)
- 320 Obsidian pebbles, top of acid lava, Bondolfur, Berufjörður. Analyst: I.S.E. Carmichael. (Reference: Carmichael, 1962, table 3, No. N. Phenocrysts: not specified.)
- 321 Hypersthene hyalo-andesite (rhyolite), south flank of Little Krafla, Gaesafjöll complex. Analyst: A.C.W.C. Bot. (Reference: van Bemmelen and Rutten, 1955, table 5, colln. 309.)

### ITALY

- 322-325 Rhyolitic obsidians, Monte Lentia, Vulcano. Analyst: not specified. (Reference: Baldanza and others, 1973, table 3, collns. L72, L70, L73, and L74, respectively. Phenocrysts: not specified.)
- 326 Obsidian, Forgia Vecchia, Lipari. Analyst: H.S. Washington. (Reference: Washington, 1920, table, No. 2.)
- 327 Obsidian, Rocche Rosse, Lipari. Analyst: H.S. Washington. (Reference: Washington, 1920, table, No. 1.)

## HUNGARY

- 328 Grey obsidian, Mád, Tokaj. Analyst: A. Vendl. (Reference: Vendl, 1927, p. 217.)
- 329 Black obsidian, Tolcsva, Tilalmas, Tokaj. Analyst: A. Vendl. (Reference: Vendl, 1927, p. 221.)

## CZECHOSLOVAKIA

- 330 Obsidian, Vinický. Analyst: not known. (Reference: Salát and Ončáková, 1964, p. 50. Phenocrysts: not known.)

## GREECE

- 331 Rhyolitic obsidian, Bombardo, Milos. Analyst: H.S. Washington. (Reference: Washington, 1920, table 4, No. 1.)
- 332 Obsidian, Bombardha Peninsula, Milos. Analyst: B. Simó. (Reference: Szàdeczky-Kardoss and others, 1964, table 2. Phenocrysts: not specified.)
- 333 Obsidian, Milos. Analyst: Th. Monrampas. (Reference: Georgiades, 1956 table 1, colln. 511. Phenocrysts: not specified.)

## FORMER USSR

- 334 Vitreous rhyolite, eastern caldera rim, Uzon Volcano, Kamchatka. Analyst: E.A. Sverzhinskaya. (Reference: Vlodavetz and Piip, 1959, p. 53. Phenocrysts: not specified.)
- 335, 336 Rhyolites, extrusive dome, Medvezjja caldera, Iturup Islands, Great Kurile Arc. Analyst: not known. (Reference: Ostapenko and others, 1967, table 3.)

## AFRICA

### CAMEROON

- 337 Rhyolitic obsidian, blocks, town of N'kongsamba, lower slopes of Mount Manengouba. Analyst: not stated. (Reference: Tchoua, 1970, p. 28.)

## ASIA

### JAPAN

- 338 Augite hypersthene dacite, Atosanupuri lava dome, Atosanupuri Volcano, Hokkaido. Analyst: Y. Katsui. (Reference: Katsui, 1958.)

- 339 Obsidian, Kamishihoro-machi?, Tokachi Volcano, Hokkaido. Analyst: K. Endo. (Reference: Kôzu, 1929, table 6. Phenocrysts: not specified.)
- 340 Hypersthene dacite, glassy part of the Ô-usu dome lava, Usu Volcano, Hokkaido. Analyst: K. Yagi. (Reference: Yagi, 1953, table 3, No. D.)
- 341, 342 Hypersthene-dacite obsidians, from cliff facing southwest of dry valley of Okubo-sawa at height of ~1,300 m a.s.l., Asama Volcano, Honshu. Analyst: Y. Matsui. (Reference: Minami and Matsui, 1960, Nos. 241 and 240A, respectively. See also Aramaki, 1963, table 21, Nos. 24 and 25.)
- 343 Hypersthene dacite, lowermost part of eastward-facing cliff, about 150 m south of Sengataki Falls, Asama Volcano, Honshu. Analyst: Y. Matsui. (Reference: Minami and Matsui, 1960, table 4, No. 232. See also Aramaki, 1963, table 21, No. 23.)
- 344 Dacite obsidian, Mugenno-tani obsidian, high cliff of Hotoke-iwa (Midagajô-iwa), Asama Volcano, Honshu. Analyst: S. Tanaka. (Reference: Tsuya, 1933, table 6, No. v.)
- 345 Hornblende-bearing hypersthene-dacite obsidian, from cliff on western bank of gorge at Sengataki, Asama Volcano, Honshu. Analyst: not known. (Reference: Aramaki, 1963, table 21, No. 12. Phenocrysts: not known.)
- 346 Nonporphyritic obsidian, Wada-toge, Nagano Prefecture, Honshu. Analyst: K. Tanida. (Reference: Tanida, 1961, No. 90.)
- 347 Two pyroxene plagioliparite, Kasiwa-toge, midway between Ito-mati and Hiye-kawa, north Idu, Huzi volcanic zone, Honshu. Analyst: S. Tanaka. (Reference: Tsuya, 1937, table 7, No. 22.)
- 348 Augite-bearing hypersthene-dacite obsidian, Kajiya dacite, Yugawara-machi, Kanagawa Prefecture, Honshu. Analyst: M. Chiba. (Reference: Ono, 1962, No. 374. Phenocrysts: not known.)
- 349 Augite-bearing hypersthene-dacite obsidian, lava of young somma, Hakone Volcano, Kanagawa Prefecture, Honshu. Analyst: M. Chiba. (Reference: Ono, 1962, No. 401. Phenocrysts: not specified, but rock said to be "nearly aphyric.")
- 350 Olivine-bearing, two pyroxene-hornblende dacite, Iwano-yama lava, east side of Iwano-yama parasitic lava dome on northern flank (near base) of Amagi Volcano, about 3 km southeast of Hiye-kawa, Honshu. Analyst: S. Tanaka. (Reference: Tsuya, 1937, table 17, No. 40.)

- 351 Obsidian, lava of Omuro-yama volcanic group, Nakaizu-machi, Amagi Volcano, Shizuoka Prefecture, Honshu. Analyst: T. Kushida. (Reference: Kawano, 1950, table 7. Phenocrysts: not specified.)
- 352 Hypersthene plagioliparite, lava of first period, Kozu-sima Volcano, Hinmashi-hana, southwestern point of Kozu-sima Island, Izu-Mariana Arc. Analyst: S. Tanaka. (Reference: Tsuya, 1929, table 4.)
- 353 Aphanitic liparite, Ombasi-zima, 4 km southwest of Kozu-sima, Izu-Mariana Arc. Analyst: S. Tanaka. (Reference: Tsuya, 1937, table 40, No. 111.)
- 354 Ferroaugite-fayalite-quartz dacite obsidian, fragment in pumice flow deposit(?) exposed on northwest flank of precaldera cone, Higashi-yama Volcano, Hachijo-jima volcano group, Seven Izu Islands, Izu-Mariana Arc. Analyst: H. Haramura. (Reference: Isshiki, 1963, colln. N153011301.)
- 355 Rhyolitic obsidian, block in ash-fall deposits of Oki trachyte-rhyolite group, 1.5 km south of Kumi, Dôgo, Oki Islands. Analyst: H. Haramura. (Reference: Uchimizu, 1966, table 15, No. 33.)
- 356 Anorthoclase liparite obsidian, block in ash-fall deposits of Oki trachyte-rhyolite group, south of Kumi, Goka village, Oki-Dôgo Island. Analyst: M. Teshima. (Reference: Tomita, 1935, p. 260. Phenocrysts: not specified.)
- 357 Two pyroxene-andesine obsidian, central zone lava, Aso Volcano, Chôyô-mura, Kumamoto Prefecture, Kyusu. Analyst: T. Oyama. (Reference: Ono, 1962, No. 770. Phenocrysts: not known.)

- 358 Hypersthene-hornblende plagioliparite obsidian, near Aira Volcano, Kagoshima-shi, Kyushu. Termed "clear obsidian from the Mifune rhyolite" by Aramaki and Haramura, 1966. Analyst: K. Yamaguchi. (Reference: Ono, 1962, No. 885. Phenocrysts: not specified.)

## INDONESIA

### PAPUA NEW GUINEA

- 359-361 Rhyolitic obsidians, Moresby Strait area, Papua New Guinea. Analyst: not specified. (Reference: Smith and Johnson, 1981, table 3, Nos. 33-680, 33-682, and 33-683. Phenocrysts: generalized assemblage given as  $Pl+Ox\pm Bi\pm Ab\pm Q$ .)
- 362 Glassy rhyolite flow, from center 3, 700 m northeast of Solang village, northwestern coast of Lou Island. Analyst: I.E. Smith. (Reference: Johnson and others, 1978, table 1, colln. 25NG0002.)
- 363 Obsidian, rhyolite lava flow of centre 8, 2 km northwest of southern tip of Lou Island. Analyst: I.E. Smith. Reference: Johnson and others, 1978, table 1, colln. 25NG0006. Phenocrysts: not specified.
- 364 Rhyolite, lava flow, Garove Island, Witu Islands, Bismarck Sea. Analysts: Australian Mineral Development Laboratories. (Reference: Johnson and Arculus, 1978, table 1, No. 20, colln. 48NG0532.)

- 365 Rhyolitic obsidian, Garua Harbour area, Talasea, New Britain. Analyst: not specified. (Reference: Smith and Johnson, 1981, table 1, No. Gs 3/4.)

## NEW ZEALAND

- 366 Obsidian, marekanite cores, volcanic ash beds, Tairua River. Analyst: E.J. Dunn. (Reference: Washington, 1917, p. 72. Phenocrysts: not specified.)
- 367 Dacite glass, stream flowing south on Fanal Island, Mokohinau Islands. Analyst: F.T. Seelye. (Reference: Challis, 1971, No. 41, colln. P10284.)
- 368 Obsidian, older rhyolite of Okataina center, Whakapoungakau Mountain, E. Lake Rotorua. Analyst: F.T. Seelye. (Reference: Grange, 1937, p. 66, No. 3, colln. P6113.)
- 369 Banded spherulitic obsidian, younger rhyolite, Okataina center, south side of Lake Rotoiti, 15 chains east of turnoff to Lake Okataina. Analyst: F.T. Seelye. (Reference: Grange, 1937, p. 73, No. 2, colln. P17480.)
- 370 Obsidian, 7.5 mi northwest of Taupo on west boundary of Tuhingamata. Analyst: J.A. Ritchie. (Reference: Steiner, 1963, No. VII, colln. P12851.)

## TONGA

- 371 Glass separated from dacite pumice, Metis Shoal, Tonga. Analyst: E. Jarosewich. (Reference: Melson and others, 1970, table 2, No. 2.)

## APPENDIX IV.—Trace-element determinations in obsidians for which major-element analyses are not available

[Values in parts per million. --, not determined; v.f., volcanic field]

Country/State-----	OREGON		CALIFORNIA		ARIZONA	PERU						ITALY	GREECE	TIBET	U.S.S.R.
Volcanic field/region---	Crater Lake		Northeast California		San Francisco v.f.							Sardinia			East Siberia
Locality-----	Subaqueous dome	Thorn Lake	Steele Swamp	Annie Lake	Sugar Loaf	Macusani						Mount Arci	Milos	Unknown	Marekanka River
Specimen-----	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241
Collection No. (RLS)---	260	258	251	257	259	119	120	121	122	123	124	255	254	256	253
Ba-----	916.	821.	1130.	--	23.	--	--	--	--	--	--	155.	522.	156.	--
Co-----	4.1	0.2	<0.3	0.2	<0.2	--	--	--	--	--	--	0.4	0.6	0.6	0.2
Cr-----	4.8	0.4	--	0.7	<2.0	<20.0	<20.0	<20.0	<20.0	<20.0	<20.0	0.5	0.5	<3.0	0.6
Cs-----	4.8	6.0	2.5	2.2	9.9	507.	523.	539.	530.	528.	545.	4.0	3.7	85.7	5.8
Hf-----	5.3	8.8	9.5	4.5	6.0	1.2	1.3	1.3	1.3	1.2	1.3	3.4	3.3	5.4	2.2
Nb**-----	--	--	--	--	119.	--	--	--	--	--	--	--	--	22.	--
Nb***-----	6.5	20.	21.	--	140.	--	--	--	--	--	--	57.	11.	28.	--
Pb-----	17.	26.	19.	--	55.	--	--	--	--	--	--	37.	16.	178.	--
Rb**-----	87.	119.	60.	89.	275.	1166.	1206.	1219.	1202.	1181.	1242.	242.	117.	464.	117.
Rb***-----	90.	125.	59.	--	290.	--	--	--	--	--	--	280.	127.	466.	--
Sb-----	1.1	1.7	0.8	--	5.1	3.6	3.7	3.9	4.0	3.6	3.9	0.5	0.4	0.7	0.9
Sc-----	5.0	8.6	10.7	2.7	4.8	2.4	2.5	2.5	2.4	2.4	2.5	3.8	1.6	1.1	2.2
Sr-----	307.	2.0	0.6	--	0.5	--	--	--	--	--	--	30.	107.	198.	--
Ta-----	0.64	1.27	1.00	1.21	20.0	25.5	26.7	27.7	26.2	27.7	27.6	3.98	1.01	1.98	1.52
Th-----	9.0	12.3	6.9	8.8	30.7	1.4	1.3	1.3	1.3	1.5	1.5	16.6	14.2	84.2	6.6
U-----	3.8	4.7	2.6	3.7	17.0	20.5	20.9	21.1	23.4	21.6	23.1	5.9	4.0	32.2	4.7
Y-----	23.	58.	78.	--	75.	--	--	--	--	--	--	48.	22.	18.	--
Zn-----	29.	87.	187.	--	120.	--	--	--	--	--	--	101.	23.	34.	--
Zr-----	205.	347.	364.	--	92.	--	--	--	--	--	--	101.	118.	134.	--
La-----	24.	39.	44.	33.	10.	1.	0.	1.	1.	1.	0.	23.	26.	42.	14
Ce-----	43.	75.	89.	56.	23.	3.	3.	3.	4.	3.	3.	48.	46.	57.	26.
Nd-----	21.	38.	45.	24.	15.	<30.	<30.	<30.	<30.	<30.	<30.	26.	15.	14.	11.
Sm-----	4.0	8.5	10.7	4.5	5.1	1.8	1.8	1.9	2.0	1.9	2.0	7.3	2.7	2.1	2.2
Eu-----	0.72	0.67	1.89	0.55	<0.03	<7.0	<7.0	<7.0	<7.0	<7.0	<7.0	0.30	0.43	0.25	0.31
Gd-----	3.9	9.1	10.4	2.8	6.6	<0.70	<0.70	<0.70	<0.60	<0.70	<0.70	7.2	3.1	<4.0	1.7
Tb-----	0.51	1.14	1.8	0.63	1.08	<0.70	<0.70	<0.70	<0.60	<0.70	<0.70	1.05	<0.20	<0.30	0.32
Tm-----	0.37	0.85	1.1	0.42	<0.30	<0.80	<0.80	<0.80	<0.80	<0.80	<0.80	--	0.56	<0.20	0.14
Yb-----	2.0	6.0	8.8	3.2	6.5	<0.9	<0.9	<0.8	<0.8	<0.8	<0.8	2.8	2.2	0.4	1.0
Lu-----	0.31	0.86	1.25	0.50	1.01	<0.10	<0.20	<0.20	<0.10	<0.20	<0.20	0.38	0.36	0.05	0.15
Nb/Ta-----	10.2	15.7	21.0	--	6.5	--	--	--	--	--	--	14.3	10.9	12.6	--
Rb/Sr-----	0.29	62.5	98.3	--	580.	--	--	--	--	--	--	9.3	1.2	2.4	--
Th/U-----	2.4	2.6	2.7	2.4	1.8	0.07	0.06	0.06	0.06	0.07	0.06	2.8	3.6	2.6	1.4
Zr/Hf-----	39.	39.	38.	--	15.	--	--	--	--	--	--	30.	36.	25.	--
Ce/Yb-----	21.5	12.5	10.1	17.5	3.5	6.0	--	--	--	--	10.0	17.1	20.9	14.3	26.0
Eu/Eu*-----	0.56	0.23	0.56	0.47	--	--	--	--	--	--	--	.13	0.45	--	0.49

\*\*Analyses performed by the U.S. Geological Survey.  
 \*\*\*Analyses performed by the University of Lancaster.

APPENDIX IV.—*Sample localities*

**NORTH AMERICA**

**UNITED STATES OF AMERICA**

**OREGON**

- 227 (260) Porphyritic obsidian, top of subaqueous dome, east slope of Wizard Island, Crater Lake, Oregon. Lat 42°56.75' N., long 122°07.75' W. Supplied by C.H. Nelson.
- 228 (258) Obsidian, residual pebble litter on Thorn Lake alkali flat, Deschutes County, Oregon. Lat 43°8.78' N., long 120°49.43' W. These pebbles probably were first deposited as clasts in air-fall deposits from an unknown source, were rounded by wave action in ancestral Thorn Lake, were perhaps chemically pitted by alkali solution at a later lake stage, and today are sand-blasted and polished by wind during the dry season. Collected by R.L. Smith and G.W. Walker.

**CALIFORNIA**

- 229 (251) Obsidian, flakes from a chipping ground for ancient artifacts and probable obsidian source. Known to archaeologists as the Steele Swamp source, NW1/4 sec. 24, T. 46 N., R. 9 E., MDBM, Modoc County, California. Lat 41°49.19' N., long 120°53.67' W. Supplied by W.A. Duffield.

- 230 (257) Obsidian, Apache tears, margin of lava dome, 1-1/4 mi northeast of Annie Lake, Modoc County, California. Lat 41°55.14' N., long 120°05.06' W. Collected by R.L. Smith and G.W. Walker.

**ARIZONA**

- 231 (259) Phenocrystic, fractured, and partly hydrated obsidian. Sugarloaf, rhyolite dome on northeast flank of San Francisco Peaks, Coconino County, Arizona. Lat 35°22.03' N., long 111°36.76' W. Collected by R.L. Smith and P.E. Damon.

**SOUTH AMERICA**

**PERU**

- 232-237 (119-124) Obsidians, 6 samples of Macusanite, highly peraluminous rhyolite, Macusani, Peru. Approx. lat 14°4' S, approx. long 70°27' W. Glass powders supplied by P.A. Jezek.

**EUROPE**

**ITALY**

**SARDINIA**

- 238 (255) Obsidian, occurrence uncertain, Conca Cannas, MTE, Arci, Sardinia, Italy. Approx lat 39°45' N., approx long 8°35' E. Supplied by the

Smithsonian Institution, USNM No. 99249-1. Courtesy of W.G. Melson, Curator.

**GREECE**

- 239 (254) Obsidian, occurrence uncertain, Bombardha, Milos, Greece. Lat 36°44' N, long 24°27' E. Supplied by the Smithsonian Institution, USNM No. 100076. Courtesy of W.G. Melson, Curator.

**ASIA**

**TIBET**

- 240 (256) Obsidian occurrence and source unknown. Museum label reads "From a loose stone 3 1/2 inches high found in a plain on the high plateau of Tibet. Exact locality not known." Supplied by the British Museum. Registered No. 1946, 30. Courtesy of A.R. Woolley.

**FORMER USSR**

**EASTERN SIBERIA**

- 241 (253) Obsidian, Apache tears ("Marekanite"). Presumably from the archetypical "Marekanite" deposits on the river Marekanka, Okhotsk, Siberia. Approx lat 59°23' N., approx long 143°35' E. Supplied by the British Museum Reg. No. 67438. Courtesy of A.R. Woolley.

APPENDIX V.—*Additional analyses of rhyolites of primitive island arcs*  
[—, not determined]

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CHEMISTRY OF THE SUBALKALIC SILICIC OBSIDIANS

Sample -----	A	B	C	D	E	F	G	H	I	J	K	L	M
Chemical analyses (weight percent)													
SiO <sub>2</sub> -----	70.5	70.7	70.25	73.60	73.50	73.04	70.10	75.1	77.8	79.4	70.7	70.3	71.19
Al <sub>2</sub> O <sub>3</sub> -----	13.51	12.5	12.76	12.29	11.90	13.61	14.31	13.5	11.4	10.4	15.4	14.9	15.06
Fe <sub>2</sub> O <sub>3</sub> -----	1.57	—	1.14	1.31	.76	.69	—	—	—	—	—	—	—
FeO -----	2.17	5.1*	4.22	2.71	4.84	2.13	3.89*	2.38*	1.55*	2.24*	3.49*	4.8*	2.76*
MgO -----	.93	1.1	1.01	1.07	.63	.50	.90	.34	.81	.28	.80	1.2	.49
CaO -----	3.66	4.0	4.61	3.61	3.80	3.25	3.46	2.45	2.50	1.76	2.41	4.1	4.01
Na <sub>2</sub> O -----	4.55	—	3.10	3.17	2.81	4.66	4.88	4.71	4.01	4.08	5.33	4.5	5.25
K <sub>2</sub> O -----	.64	1.4	.79	1.47	.75	.67	.65	.64	1.45	1.17	.87	.30	.93
H <sub>2</sub> O <sup>+</sup> -----	—	—	.73	—	.46	1.04	—	—	—	—	—	—	—
H <sub>2</sub> O <sup>-</sup> -----	1.30	—	.05	.13	—	.04	—	1.85 <sup>†</sup>	1.66 <sup>†</sup>	2.32 <sup>†</sup>	3.25 <sup>†</sup>	—	—
TiO <sub>2</sub> -----	.55	.4	.53	.52	.58	.30	.50	.50	.30	.20	.38	.70	.20
P <sub>2</sub> O <sub>5</sub> -----	.12	—	.12	.07	.09	.12	.08	.14	.07	.18	.11	—	.13
MnO -----	.13	.1	.14	.06	—	.08	.13	.01	.03	.05	.09	—	.22
Total -----	99.63	—	99.45	100.01	100.12	100.13	—	101.62	101.58	102.08	102.83	—	—
FeO <sup>1</sup> -----	3.58	5.1	5.25	3.89	5.52	2.75	3.89	2.38	1.55	2.24	3.49	4.8	2.76
FeO/(FeO+Fe <sub>2</sub> O <sub>3</sub> ) <sup>1</sup> -----	.58	—	.79	.67	.86	.76	—	—	—	—	—	—	—
Na <sub>2</sub> O/K <sub>2</sub> O <sup>1</sup> -----	7.11	—	3.92	2.16	3.75	6.96	7.51	7.36	2.77	3.49	6.13	15.0	5.65
(Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	.61	—	.47	.55	.46	.62	.61	.63	.72	.77	.63	.51	.64
(CaO+Na <sub>2</sub> O+K <sub>2</sub> O)/Al <sub>2</sub> O <sub>3</sub> <sup>2</sup> -----	1.10	—	1.12	1.09	1.04	1.05	1.05	.96	1.12	1.07	.92	1.01	1.12
CaO/(Na <sub>2</sub> O+K <sub>2</sub> O) <sup>1</sup> -----	.71	—	1.19	.99	1.07	.61	.65	.46	.46	.34	.39	.85	.65
Trace elements (parts per million)													
Ba -----	345	—	—	610	—	119	68	90	138	123	214	148	—
Co -----	7	—	—	10	—	2.8	—	—	< 5	< 5	< 5	10	—
Cr -----	—	—	—	7	—	< 4	20	—	3	3	2	5	—
Hf -----	—	—	—	—	—	3.0	—	3.0	2.1	2.9	—	—	—
Nb -----	—	10	—	2.3	—	.6	3	1.2	1.2	1.3	—	—	—
Pb -----	5.1	10	—	4.24	—	9	9	1	4	3	2	—	—
Rb -----	6.8	23	—	21	—	13	14	8	12	6	6	3	19
Sc -----	—	—	—	12	—	10.2	—	—	7	9	6	22	—
Sr -----	175	255	—	130	—	110	117	108	94	97	203	176	284
Th -----	2.1	4	—	—	—	.7	2	.5	.4	.4	.8	.44	—
U -----	.84	—	—	.39	—	.68	—	.4	.4	.4	.5	.31	—



APPENDIX V.—Additional analyses of rhyolites of primitive island arcs—Continued

Sample -----	A	B	C	D	E	F	G	H	I	J	K	L	M
Trace elements—Continued													
Y -----	41	—	—	25	—	33	36	560	34	52	47	34	25
Zn -----	84	—	—	46	—	43	101	—	—	—	—	—	—
Zr -----	84	51	—	68	—	107	178	177	142	119	162	54	196
La -----	4.8	—	—	—	—	5	10	76	4.3	7.8	—	—	—
Ce -----	14.0	—	—	—	—	11	22	—	12.7	23	—	—	—
Nd -----	10.5	—	—	—	—	7	—	210	5.8	17.0	—	—	—
Sm -----	—	—	—	—	—	2.8	—	71	1.6	6.8	—	—	—
Eu -----	—	—	—	—	—	.77	—	8.4	.45	2.0	—	—	—
Gd -----	—	—	—	—	—	3.0	—	81	2.3	5.8	—	—	—
Tb -----	—	—	—	—	—	.71	—	12	.37	.89	—	—	—
Tm -----	—	—	—	—	—	.57	—	—	—	—	—	—	—
Yb -----	—	—	—	—	—	3.4	—	27	1.9	3.0	—	—	—
Lu -----	—	—	—	—	—	.53	—	—	—	—	—	—	—
K/Rb -----	781	505	—	601	—	428	385	664	1003	1619	1204	830	406
Rb/Sr -----	.04	.09	—	.16	—	.12	.12	.07	.13	.06	.03	.02	.07
Ca/Sr -----	149	112	—	198	—	211	211	162	190	130	85	166	101
Th/U -----	2.5	—	—	—	—	1.0	—	1.3	1.0	1.0	1.6	1.4	—
Zr/Hf -----	—	—	—	—	—	36	—	59	68	41	—	—	—
Ce/Yb -----	—	—	—	—	—	3.2	—	—	6.7	7.7	—	—	—
Eu/Eu* -----	—	—	—	—	—	.82	—	.38	.80	.97	—	—	—

†Values given are for loss on ignition.

\*Total iron as FeO.

<sup>1</sup>By weight.

<sup>2</sup>Molecular.

Sample localities and references:

- A, Dacite, Curtis Island, Kermadec Islands (Ewart and others, 1977, table 2).
- B, Obsidian, Tafahi Volcano, Tongan Islands (Smith and others, 1977, table 2).
- C, Pumice, Eua Islands, Tonga (Bryan, 1971, table 2, No. 2).
- D, Glass, 1967-68 Metis Shoal dacite, Tongan Islands (Ewart and others, 1973, table 8; Pb and U data from Oversby and Ewart, 1972; Nb value from David Gottfried, oral commun., 1980).
- E, Light pumice, Herald Cays, Queensland (Bryan, 1968).
- F, Pumice, South Sandwich Islands (Gass and others, 1963; this paper, spec. 220).
- G, Rhyodacite, Deception Island, South Shetland Islands (Weaver and others, 1979, table 1).
- H, Porphyritic obsidian clast, Undu Group, Fiji (Gill and Stork, 1979, tables 2 and 3, No. H26).
- I, Lapilli tuff, Undu Group, Fiji (Gill and Stork, 1979, tables 2 and 3, No. B535).
- J, Crystal tuff, Undu Group, Fiji (Gill and Stork, 1979, tables 2 and 3, No. M96).
- K, Porphyritic lava, Wainimala Group, Viti Levu, Fiji (Gill and Stork, 1979, table 2, No. 856).
- L, Dacite, Louisenhoj Formation, Virgin Islands, NE. Caribbean (Donnelly and Rogers, 1980, table 1).
- M, Average rhyolite, The Quill, Statia, Lesser Antilles (Smith and others, 1980, table 4).

## APPENDIX VI.—Correlation matrix

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CHEMISTRY OF THE SUBALKALIC SILICIC OBSIDIANS

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	H <sub>2</sub> O <sup>+</sup>	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	MnO	Cl	F	FeO <sub>t</sub>	Na <sub>2</sub> O/K <sub>2</sub> O
SiO <sub>2</sub> -----	1.00	-.83	-.57	-.77	-.74	-.71	-.70	.51	-.04	-.79	-.67	-.48	-.28	.012	-.79	-.62
Al <sub>2</sub> O <sub>3</sub> -----	-.83	1.00	.31	.41	.66	.61	.57	-.42	.02	.59	.62	.40	.06	-.26	.42	.49
Fe <sub>2</sub> O <sub>3</sub> -----	-.57	.31	1.00	.54	.47	.42	.56	-.43	-.15	.58	.45	.24	.22	.02	.73	.45
FeO-----	-.77	.41	.54	1.00	.61	.72	.56	-.61	-.11	.78	.54	.43	.32	-.08	.97	.67
MgO-----	-.74	.66	.47	.61	1.00	.91	.41	-.71	-.01	.87	.82	.30	.12	-.21	.63	.70
CaO-----	-.71	.61	.42	.72	.91	1.00	.35	-.80	-.07	.85	.77	.40	.09	-.29	.70	.73
Na <sub>2</sub> O-----	-.70	.57	.56	.56	.41	.35	1.00	-.57	.04	.48	.36	.47	.29	.04	.62	.71
K <sub>2</sub> O-----	.51	-.42	-.43	-.61	-.71	-.80	-.57	1.00	-.04	-.67	-.61	-.45	-.05	.25	-.62	-.90
H <sub>2</sub> O <sup>+</sup> -----	-.04	.02	-.15	-.11	-.01	-.07	.04	-.04	1.00	-.08	.15	.03	-.04	.04	-.13	.02
TiO <sub>2</sub> -----	-.79	.59	.58	.78	.87	.85	.48	-.67	-.08	1.00	.84	.39	.13	-.28	.80	.70
P <sub>2</sub> O <sub>5</sub> -----	-.67	.62	.45	.54	.82	.77	.36	-.61	.15	.84	1.00	.31	-.02	-.21	.56	.55
MnO-----	-.48	.40	.24	.43	.30	.40	.47	-.45	.03	.39	.31	1.00	.14	-.15	.42	.52
Cl-----	-.28	.06	.22	.32	.12	.09	.29	-.05	-.04	.13	-.02	.14	1.00	.21	.32	.12
F-----	.12	-.26	.02	-.08	-.21	-.29	.04	.25	.04	-.28	-.21	-.15	.21	1.00	-.06	-.16
Fe as FeO-----	-.79	.42	.73	.97	.63	.70	.62	-.62	-.13	.80	.56	.42	.32	-.06	1.00	.67
Na <sub>2</sub> O/K <sub>2</sub> O-----	-.62	.49	.45	.67	.70	.73	.71	-.90	.02	.70	.55	.52	.12	-.16	.67	1.00
Ba-----	-.37	.46	.14	.26	.30	.41	.17	-.31	-.14	.34	.28	.11	.03	-.45	.25	.19
Be-----	.14	-.24	-.01	-.17	-.35	-.38	.13	.23	.15	-.33	-.23	-.05	.10	.82	-.14	-.10
Co-----	-.63	.50	.34	.56	.69	.66	.37	-.47	.02	.66	.58	.16	.15	-.02	.55	.49
Cr-----	.13	-.18	-.11	-.11	-.11	-.16	-.13	.22	.08	-.22	-.17	.01	-.03	.48	-.12	-.21
Cs-----	.29	-.23	-.33	-.29	-.31	-.29	-.37	.34	.18	-.35	-.26	-.14	.08	.22	-.33	-.36
Hf-----	-.52	.10	.57	.71	.17	.18	.59	-.21	-.14	.38	.10	.28	.37	.32	.75	.34
Li-----	.21	-.13	-.17	-.27	-.39	-.32	-.05	.25	.13	-.34	-.18	-.15	-.13	.58	-.26	-.19
Mo-----	.04	-.18	.20	-.08	-.20	-.29	.11	.29	-.11	-.04	-.22	.13	.15	.05	-.01	-.12
Nb-----	.05	-.23	.09	-.00	-.27	-.31	.20	.19	-.01	-.22	-.21	-.05	.12	.72	.03	-.06
Pb-----	.32	-.29	-.19	-.34	-.45	-.41	-.21	.41	-.02	-.45	-.33	-.24	-.06	.63	-.33	-.35
Rb-----	.47	-.44	-.32	-.49	-.53	-.61	-.32	.59	.13	-.58	-.42	-.31	.07	.72	-.49	-.52
Sb-----	.01	-.02	.00	-.02	.02	-.05	.12	-.05	.25	-.02	-.03	-.01	.09	.02	-.02	.07
Sc-----	-.51	.36	.33	.63	.65	.72	.32	-.67	.02	.71	.55	.44	.07	-.28	.61	.64
Sn-----	.05	-.31	.07	.07	-.24	-.26	.11	.15	.05	-.20	-.20	-.20	.20	.76	.08	-.05
Sr-----	-.65	.73	.42	.43	.80	.83	.36	-.69	.07	.71	.71	.28	-.02	-.40	.46	.59
Ta-----	.13	-.25	.02	-.11	-.35	-.35	.15	.20	.03	-.29	-.22	-.12	.06	.75	-.08	-.11
Th-----	.40	-.44	-.19	-.38	-.46	-.54	-.27	.56	-.01	-.47	-.43	-.29	.19	.65	-.36	-.45
U-----	.35	-.34	-.20	-.38	-.38	-.47	-.17	.41	.09	-.43	-.32	-.21	.11	.63	-.37	-.34
W-----	.31	-.39	-.24	-.22	-.37	-.38	-.26	.40	.15	-.35	-.35	-.13	.16	.52	-.24	-.36
Y-----	-.03	-.30	.20	.26	-.14	-.13	.21	.02	-.06	-.06	-.18	.03	.33	.69	.27	.06
Zn-----	-.28	-.04	.35	.47	-.00	.01	.43	-.12	-.08	.11	.01	.23	.23	.48	.48	.22
Zr-----	-.66	.28	.61	.81	.28	.35	.64	-.33	-.17	.54	.22	.38	.36	.06	.83	.43
La-----	-.20	-.09	.27	.32	-.10	-.09	.05	.27	-.19	.10	-.17	-.02	.34	.14	.34	-.12
Ce-----	-.21	-.12	.30	.37	-.10	-.09	.09	.23	-.19	.12	-.16	.00	.36	.20	.40	-.08
Nd-----	-.27	-.13	.40	.52	-.02	.01	.25	.03	-.16	.19	-.08	.06	.41	.27	.54	.09
Sm-----	-.21	-.20	.38	.51	-.06	-.02	.27	-.01	-.14	.14	-.09	.08	.37	.42	.53	.11
Eu-----	-.61	.28	.55	.81	.41	.54	.57	-.55	-.15	.61	.33	.47	.23	-.13	.82	.56
Gd-----	-.24	-.10	.39	.39	.08	.06	.29	-.11	-.06	.16	.00	.08	.33	.41	.43	.20
Tb-----	-.03	-.36	.27	.33	-.14	-.14	.21	.01	-.11	-.02	-.19	-.00	.35	.61	.35	.06
Tm-----	.00	-.33	.18	.24	-.13	-.13	.17	.02	-.07	-.06	-.12	.04	.31	.70	.25	.04
Yb-----	.01	-.33	.19	.22	-.13	-.13	.18	.01	-.08	-.07	-.18	-.02	.33	.71	.24	.05
Lu-----	-.01	-.32	.20	.24	-.11	-.11	.18	-.00	-.10	-.06	-.16	.01	.35	.72	.25	.07

APPENDIX VI.—*Correlation matrix*—Continued

	Ba	Be	Co	Cr	Cs	Hf	Li	Mo	Nb	Pb	Rb	Sb	Sc	Sn	Sr	Ta
SiO <sub>2</sub> -----	-0.37	0.14	-0.63	0.13	0.29	-0.52	0.21	0.04	0.05	0.32	0.47	0.01	-0.51	0.05	-0.65	0.13
Al <sub>2</sub> O <sub>3</sub> -----	.46	-.24	.50	-.18	-.23	.10	-.13	-.18	-.23	-.29	-.44	-.02	.36	-.31	.73	-.25
Fe <sub>2</sub> O <sub>3</sub> -----	.14	-.01	.34	-.11	-.33	.57	-.17	.20	.09	-.19	-.32	.00	.33	.07	.42	.02
FeO-----	.26	-.17	.56	-.11	-.29	.71	-.27	-.08	-.00	-.34	-.49	-.02	.63	.07	.43	-.11
MgO-----	.30	-.35	.69	-.11	-.31	.17	-.39	-.20	-.27	-.45	-.53	.02	.65	-.24	.80	-.35
CaO-----	.41	-.38	.66	-.16	-.29	.18	-.32	-.29	-.31	-.41	-.61	-.05	.72	-.26	.83	-.35
Na <sub>2</sub> O-----	.17	.13	.37	-.13	-.37	.59	-.05	.11	.20	-.21	-.32	.12	.32	.11	.36	.15
K <sub>2</sub> O-----	-.31	.23	-.47	.22	.34	-.21	.25	.29	.19	.41	.59	-.05	-.67	.15	-.69	.20
H <sub>2</sub> O <sup>+</sup> -----	-.14	.15	.02	.08	.18	-.14	.13	-.11	-.01	-.02	.13	.25	.02	.05	.07	.03
TiO <sub>2</sub> -----	.34	-.33	.66	-.22	-.35	.38	-.34	-.04	-.22	-.45	-.58	-.02	.71	-.20	.71	-.29
P <sub>2</sub> O <sub>5</sub> -----	.28	-.23	.58	-.17	-.26	.10	-.18	-.22	-.21	-.33	-.42	-.03	.55	-.20	.71	-.22
MnO-----	.11	-.05	.16	.01	-.14	.28	-.15	.13	-.05	-.24	-.31	-.01	.44	-.20	.28	-.12
Cl-----	.03	.10	.15	-.03	.08	.37	-.13	.15	.12	-.06	.07	.09	.07	.20	-.02	.06
F-----	-.45	.82	-.02	.48	.22	.32	.58	.05	.72	.63	.72	.02	-.28	.76	-.40	.75
Fe as FeO-----	.25	-.14	.55	-.12	-.33	.75	-.26	-.01	.03	-.33	-.49	-.02	.61	.08	.46	-.08
Na <sub>2</sub> O/K <sub>2</sub> O-----	.19	-.10	.49	-.21	-.36	.34	-.19	-.12	-.06	-.35	-.52	.07	.64	-.05	.59	-.11
Ba-----	1.00	-.48	.20	-.31	-.25	.03	-.34	-.16	-.38	-.38	-.54	-.16	.20	-.37	.56	-.40
Be-----	-.48	1.00	-.28	.37	.27	.28	.68	.13	.88	.74	.75	.23	-.35	.82	-.43	.91
Co-----	.20	-.28	1.00	-.01	-.22	.32	-.32	-.23	.01	-.35	-.40	.04	.45	-.08	.52	-.09
Cr-----	-.31	.37	-.01	1.00	.04	.02	.26	.20	.28	.36	.33	-.08	-.17	.18	-.26	.29
Cs-----	-.25	.27	-.22	.04	1.00	-.25	.35	-.28	-.00	.24	.64	.36	-.17	.37	-.30	.12
Hf-----	.03	.28	.32	.02	-.25	1.00	-.00	.27	.48	.01	-.10	-.00	.18	.44	.02	.36
Li-----	-.34	.68	-.32	.26	.35	-.00	1.00	-.14	.59	.63	.62	.36	-.26	.52	-.30	.65
Mo-----	-.16	.013	-.23	.020	-.28	.27	-.14	1.00	.18	-.02	-.00	.02	-.25	0.00	-.022	0.09
Nb-----	-.38	.88	.01	.28	-.00	.48	.59	.18	1.00	.64	.48	.10	-.35	.72	-.37	.96
Pb-----	-.38	.74	-.35	.36	.24	.01	.63	-.02	.64	1.00	.64	.08	-.40	.53	-.43	.68
Rb-----	-.54	.75	-.40	.33	.64	-.10	.62	-.00	.48	.64	1.00	.19	-.54	.65	-.60	.57
Sb-----	-.16	.23	.04	-.08	.36	-.00	.36	.02	.10	.08	.19	1.00	-.02	.11	-.01	.17
Sc-----	.20	-.35	.45	-.17	-.17	.18	-.26	-.25	-.35	-.40	-.54	-.02	1.00	-.25	.46	-.37
Sn-----	-.37	.82	-.08	.18	.37	.44	.52	.00	.72	.53	.65	.11	-.25	1.00	-.44	.73
Sr-----	.56	-.43	.52	-.26	-.30	.02	-.30	-.22	-.37	-.43	-.60	-.01	.46	-.44	1.00	-.38
Ta-----	-.40	.91	-.09	.29	.12	.36	.65	.09	.96	.68	.57	.17	-.37	.73	-.38	1.00
Th-----	-.53	.67	-.30	.17	.56	.01	.50	.18	.44	.55	.89	.22	-.53	.59	-.55	.52
U-----	-.49	.70	-.27	.20	.60	-.05	.44	.13	.43	.47	.84	.20	-.44	.65	-.44	.56
W-----	-.25	.49	-.29	.14	.49	.06	.27	.25	.37	.47	.67	.03	-.34	.51	-.44	.36
Y-----	-.25	.68	.02	.27	.10	.63	.26	.12	.68	.40	.38	-.02	-.07	.84	-.33	.64
Zn-----	-.09	.54	.15	.25	-.20	.78	.24	.17	.74	.38	.08	.01	-.01	.55	-.12	.61
Zr-----	.19	.01	.39	-.02	-.36	.94	-.19	.25	.25	-.21	-.35	-.05	.31	.19	.18	.11
La-----	-.00	.03	.10	.02	-.17	.61	-.24	.41	.28	-.04	-.03	-.16	-.18	.20	-.17	.12
Ce-----	-.02	.08	.10	.03	-.16	.68	-.21	.38	.31	-.02	-.00	-.17	-.14	.28	-.19	.16
Nd-----	-.02	.13	.14	.05	-.17	.80	-.15	.26	.34	-.04	-.02	-.11	-.01	.40	-.13	.21
Sm-----	-.10	.30	.13	.08	-.10	.83	-.01	.21	.47	.11	.09	-.08	.02	.55	-.22	.36
Eu-----	.36	-.21	.37	-.22	-.47	.73	-.32	.09	.04	-.42	-.58	-.15	.45	.00	.36	-.09
Gd-----	-.08	.34	.16	-.02	.01	.60	.03	.06	.37	.08	.12	.06	.05	.49	.01	.33
Tb-----	-.18	.54	-.01	.08	.01	.72	.16	.16	.61	.31	.29	-.07	-.06	.74	-.33	.54
Tm-----	-.25	.69	-.01	.35	.10	.58	.24	.13	.67	.39	.38	-.09	-.06	.81	-.36	.72
Yb-----	-.26	.66	.01	.15	.11	.59	.24	.09	.63	.44	.41	-.06	-.05	.82	-.35	.61
Lu-----	-.24	.65	.02	.25	.11	.59	.22	.08	.60	.42	.40	-.07	-.04	.80	-.33	.59

	Th	U	W	Y	Zn	Zr	La	Ce	Nd	Sm	Eu	Gd	Tb	Tm	Yb	Lu
SiO <sub>2</sub> -----	0.40	0.35	0.31	- 0.03	- 0.28	- 0.66	- 0.20	- 0.21	- 0.27	- 0.21	- 0.61	- 0.24	- 0.03	0.00	0.01	- 0.01
Al <sub>2</sub> O <sub>3</sub> -----	- .44	- .34	- .39	- .30	- .04	.28	- .09	- .12	- .13	- .20	.28	- .10	- .36	- .33	- .33	- .32
Fe <sub>2</sub> O <sub>3</sub> -----	- .19	- .20	- .24	.20	.35	.61	.27	.30	.40	.38	.55	.39	.27	.18	.19	.20
FeO -----	- .38	- .38	- .22	.26	.47	.81	.32	.37	.52	.51	.81	.39	.33	.24	.22	.24
MgO -----	- .46	- .38	- .37	- .14	- .00	.28	- .10	- .10	- .02	- .06	.41	.08	- .14	- .13	- .13	- .11
CaO -----	- .54	- .47	- .38	- .13	.01	.35	- .09	- .09	.01	- .02	.54	.06	- .14	- .13	- .13	- .11
Na <sub>2</sub> O -----	- .27	- .17	- .26	.21	.43	.64	.05	.09	.25	.27	.57	.29	.21	.17	.18	.18
K <sub>2</sub> O -----	.56	.41	.40	.02	- .12	- .33	.27	.23	.03	- .01	- .55	- .11	.01	.02	.01	- .00
H <sub>2</sub> O <sup>+</sup> -----	- .01	.09	.15	- .06	- .08	- .17	- .19	- .19	- .16	- .14	- .15	- .06	- .11	- .07	- .08	- .10
TiO <sub>2</sub> -----	- .47	- .43	- .35	- .06	.11	.54	.10	.12	.19	.14	.61	.16	- .02	- .06	- .07	- .06
P <sub>2</sub> O <sub>5</sub> -----	- .43	- .32	- .35	- .18	.01	.22	- .17	- .16	- .08	- .09	.33	.00	- .19	- .12	- .18	- .16
MnO -----	- .29	- .21	- .13	.03	.23	.38	- .02	.00	.06	.08	.47	.08	- .00	.04	- .02	.01
Cl -----	.19	.11	.16	.33	.23	.36	.34	.36	.41	.37	.23	.33	.35	.31	.33	.35
F -----	.65	.63	.52	.69	.48	.06	.14	.20	.27	.42	- .13	.41	.61	.70	.71	.72
Fe as FeO -----	- .36	- .37	- .24	.27	.48	.83	.34	.40	.54	.53	.82	.43	.35	.25	.24	.25
Na <sub>2</sub> O/K <sub>2</sub> O -----	- .45	- .34	- .36	.06	.22	.43	- .12	- .08	.09	.11	.56	.20	.06	.04	.05	.07
Ba -----	- .53	- .49	- .25	- .25	- .09	.19	- .00	- .02	- .02	- .10	.36	- .08	- .18	- .25	- .26	- .24
Be -----	.67	.70	.49	.68	.54	.01	.03	.08	.13	.30	- .21	.34	.54	.69	.66	.65
Co -----	- .30	- .27	- .29	.02	.15	.39	.10	.10	.14	.13	.37	.16	- .01	- .01	.01	.02
Cr -----	.17	.20	.14	.27	.25	- .02	.02	.03	.05	.08	- .22	- .02	.08	.35	.15	.25
Cs -----	.56	.60	.49	.10	- .20	- .36	- .17	- .16	- .17	- .10	- .47	.01	.01	.10	.11	.11
Hf -----	.01	- .05	.06	.63	.78	.94	.61	.68	.80	.83	.73	.60	.72	.58	.59	.59
Li -----	.50	.44	.27	.26	.24	- .19	- .24	- .21	- .15	- .01	- .32	.03	.16	.24	.24	.22
Mo -----	.18	.13	.25	.12	.17	.25	.41	.38	.26	.21	.09	.06	.16	.13	.09	.08
Nb -----	.44	.43	.37	.68	.74	.25	.28	.31	.34	.47	.04	.37	.61	.67	.63	.60
Pb -----	.55	.47	.47	.40	.38	- .21	- .04	- .02	- .04	.11	- .42	.08	.31	.39	.44	.42
Rb -----	.89	.84	.67	.38	.08	- .35	- .03	- .00	- .02	.09	- .58	.12	.29	.38	.41	.40
Sb -----	.22	.20	.03	- .02	.01	- .05	- .16	- .17	- .11	- .08	- .15	.06	- .07	- .09	- .06	- .07
Sc -----	- .53	- .44	- .34	- .07	- .01	.31	- .18	- .14	- .01	.02	.45	.05	- .06	- .06	- .05	- .04
Sn -----	.59	.65	.51	.84	.55	.19	.20	.28	.40	.55	.00	.49	.74	.81	.82	.80
Sr -----	- .55	- .44	- .44	- .33	- .12	.18	- .17	- .19	- .13	- .22	.36	.01	- .33	- .36	- .35	- .33
Ta -----	.52	.56	.36	.64	.61	.11	.12	.16	.21	.36	- .09	.33	.54	.72	.61	.59
Th -----	1.00	.84	.65	.36	.06	- .23	.20	.21	.16	.20	- .45	.21	.34	.36	.39	.39
U -----	.84	1.00	.59	.45	.05	- .27	- .04	- .02	.01	.10	- .46	.20	.30	.46	.47	.47
W -----	.65	.59	1.00	.38	.18	- .12	.13	.17	.13	.22	- .28	.16	.35	.39	.43	.42
Y -----	.36	.45	.38	1.00	.75	.41	.36	.46	.62	.78	.29	.65	.93	.95	.96	.96
Zn -----	.06	.05	.18	.75	1.00	.64	.47	.54	.65	.76	.50	.55	.78	.68	.68	.67
Zr -----	- .23	- .27	- .12	.41	.64	1.00	.60	.64	.74	.72	.85	.49	.52	.37	.36	.36
La -----	.20	- .04	.13	.36	.47	.60	1.00	.98	.87	.72	.41	.46	.52	.29	.28	.27
Ce -----	.21	- .02	.17	.46	.54	.64	.98	1.00	.93	.82	.48	.53	.63	.41	.39	.38
Nd -----	.16	.01	.13	.62	.65	.74	.87	.93	1.00	.94	.62	.65	.79	.57	.56	.55
Sm -----	.20	.10	.22	.78	.76	.72	.72	.82	.94	1.00	.60	.70	.91	.74	.74	.73
Eu -----	- .45	- .46	- .28	.29	.50	.85	.41	.48	.62	.60	1.00	.42	.43	.28	.25	.26
Gd -----	.21	.20	.16	.65	.55	.49	.46	.53	.65	.70	.42	1.00	.70	.60	.62	.61
Tb -----	.34	.30	.35	.93	.78	.52	.52	.63	.79	.91	.43	.70	1.00	.89	.91	.90
Tm -----	.36	.46	.39	.95	.68	.37	.29	.41	.57	.74	.28	.60	.89	1.00	.96	.96
Yb -----	.39	.47	.43	.96	.68	.36	.28	.39	.56	.74	.25	.62	.91	.96	1.00	1.00
Lu -----	.39	.47	.42	.96	.67	.36	.27	.38	.55	.73	.26	.61	.90	.96	1.00	1.00

APPENDIX VII.—*Phenocryst assemblages and modal analyses of porphyritic obsidians*

[Compositions given in appendixes I, II, III, and IV. +, mineral present but no modal data available; (?), uncertain identification; —, not recorded. All accessories < 0.1 percent. Al, allanite; ap, apatite; gr, granophyric intergrowths of quartz and alkali feldspar; po, pyrrhotite; z, zircon; s, sphene

Sample number -----	1	2	3	4	6	8	9	11	13
Collection number -----	190	56	214	39	45	187	189	8-3Av	9-2v
<b>Phenocrysts:</b>									
Quartz -----	—	—	.3	—	—	—	—	—	—
Alkali feldspar -----	—	—	?	—	—	—	—	—	—
Plagioclase -----	4.7	.7	5.4	2.7	<.1	9.6	6.1	+	+
Olivine -----	—	<.1	—	—	—	—	—	?	?
Clinopyroxene -----	—	.4	.4	—	<.1	—	—	+	+
Orthopyroxene -----	—	—	.3	—	—	1.3	.8	+	+
Amphibole -----	<.1	—	—	—	—	—	—	—	+
Biotite -----	.8	—	—	.5	—	—	—	—	—
Fe-Ti-oxides -----	<.1	—	.2	.3	—	<0.1	<.1	+	+
Others -----	z?	—	ap	ap,z	—	—	—	—	—
Total -----	5.5	1.1	6.6	3.5	<.1	10.9	6.9	—	—
Xenoliths -----	—	<.1	—	—	—	—	—	+	—

Sample number -----	15	17	19	20	21	22	24	31	36
Collection number -----	9-16v	9-19v	222	223	224	144	159	161	52
<b>Phenocrysts:</b>									
Quartz -----	—	—	—	—	—	—	—	—	—
Alkali feldspar -----	—	—	—	—	—	—	—	—	—
Plagioclase -----	+	+	7.5	10.0	6.1	<.1	1.1	<.1	<.1
Olivine -----	?	?	—	—	—	—	—	—	—
Clinopyroxene -----	+	+	—	.8	.3	<.1	—	—	—
Orthopyroxene -----	+	+	.8	.4	.6	<.1	<.1	—	—
Amphibole -----	+	+	<.1	—	—	—	—	<.1	—
Biotite -----	—	—	—	—	—	—	—	—	<.1
Fe-Ti-oxides -----	+	+	.2	.4	.3	<.1	<.1	—	—
Others -----	—	—	—	—	—	—	—	gr	—
Total -----	—	—	8.5	11.6	7.3	<.1	1.1	<.1	<.1
Xenoliths -----	+	—	—	—	—	—	—	—	—



APPENDIX VII.—*Phenocryst assemblages and modal analyses of porphyritic obsidians*—Continued[illegible]





APPENDIX VII.—*Phenocryst assemblages and modal analyses of porphyritic obsidians*—Continued[illegible][illegible]

APPENDIX VII.—*Phenocryst assemblages and modal analyses of porphyritic obsidians*—Continued

Sample number -----	172	173	174	176	178	179	183	184	185
Collection number -----	177	178	176	61	57	209	67	66	211
<b>Phenocrysts:</b>									
Quartz -----	—	—	—	—	—	—	—	—	—
Alkali feldspar -----	—	—	—	—	—	—	—	—	—
Plagioclase -----	+	+	+	1.5	1.1	.1	.8	.8	—
Olivine -----	+	—	+	—	<.1	—	—	—	—
Clinopyroxene -----	+	+	+	.7	<.1	<.1	—	<.1	—
Orthopyroxene -----	—	—	—	.1	—	—	—	—	—
Amphibole -----	+	+	—	—	—	—	—	—	—
Biotite -----	—	—	—	—	—	<.1	—	.2	—
Fe-Ti-oxides -----	+	—	+	<.1	<.1	<.1	<.1	<.1	<.1
Others -----	—	—	—	—	—	—	—	—	—
<b>Total -----</b>	—	—	—	2.3	1.1	.1	.8	1.0	<.1
<b>Xenoliths -----</b>	—	—	—	3.5	—	—	—	—	—

[illegible]

APPENDIX VII.—*Phenocryst assemblages and modal analyses of porphyritic obsidians*—Continued

Sample number -----	198	199	200	201	202	203	204	205	206
Collection number -----	108	107	114	113	109	101	112	170	171
<b>Phenocrysts:</b>									
Quartz -----	1.2	—	—	1.2	—	—	—	—	—
Alkali feldspar -----	.5	—	—	—	.3	—	—	—	—
Plagioclase -----	.8	.1	.7	1.8	.1	1.3	.4	6.9	4.5
Olivine -----	—	—	—	—	—	—	—	<.1	—
Clinopyroxene -----	—	—	<.1	<.1	—	.1	—	.2	—
Orthopyroxene -----	<.1	—	—	<.1	—	—	<.1	.3	.3
Amphibole -----	.2	.2	—	.3	—	—	—	—	—
Biotite -----	—	—	—	—	—	—	—	—	—
Fe-Ti-oxides -----	<.1	<.1	.3	<.1	<.1	<.1	<.1	<.1	.2
Others -----	z?	z?	ap	—	z?	—	—	—	—
Total -----	2.7	.3	1.0	3.3	.4	1.4	.4	7.4	5.0
Xenoliths -----	—	.2	—	—	—	—	—	2.0	—

Sample number -----	207	208	209	211	213	214	216
Collection number -----	172	173	174	70	58	64	3
<b>Phenocrysts:</b>							
Quartz -----	—	—	—	—	—	—	—
Alkali feldspar -----	—	—	—	—	—	—	0.8
Plagioclase -----	18.3	7.5	4.4	<.1	.4	<.1	1.3
Olivine -----	—	—	—	—	—	<.1	—
Clinopyroxene -----	<.1	—	<.1	—	—	—	—
Orthopyroxene -----	1.6	.3	<.1	—	—	—	<.1
Amphibole -----	.2	.2	—	—	—	—	—
Biotite -----	—	—	—	—	—	—	—
Fe-Ti-oxides -----	.5	<.1	.2	<.1	<.1	<.1	.2
Others -----	—	—	—	—	z?	—	z?
Total -----	20.6	8.0	4.6	<.1	.4	<.1	2.3
Xenoliths -----	—	0.3	—	—	—	—	—



APPENDIX VII.—*Phenocryst assemblages and modal analyses of porphyritic obsidians*—Continued

Sample number -----	284	285	287	288	294	295	296	297	298	299
Phenocrysts:										
Quartz -----	.2	—	—	—	+	—	+	+	+	+
Alkali feldspar -----	1	—	—	—	+	+	+	+	+	+
Plagioclase -----	1	—	—	—	+	—	—	—	—	—
Olivine -----	—	—	—	—	—	—	—	—	—	—
Clinopyroxene -----	<.1	—	—	—	—	—	—	—	—	—
Orthopyroxene -----	<.1	<.1	<.1	<.1	—	—	—	—	—	—
Amphibole -----	.1	—	—	—	—	—	—	—	—	—
Biotite -----	.1	—	—	—	—	—	—	—	—	—
Fe-Ti-oxides -----	.3	<.1	<.1	<.1	—	—	—	—	—	—
Others -----	—	—	—	—	+	—	—	+	+	+
Total -----	2.8	.1	.1	.1	—	—	—	—	—	—
Xenoliths -----	—	—	—	—	+	—	—	—	—	—
Sample number -----	300	303	304	305	306	307	308	309	310	315
Phenocrysts:										
Quartz -----	—	+	+	—	—	<.1	<.1	<.1	+	—
Alkali feldspar -----	+	+	+	6.0	3.1	<.1	<.1	<.1	+	—
Plagioclase -----	+	+	+	—	—	<.1	<.1	<.1	+	—
Olivine -----	+	—	—	—	—	<.1	<.1	<.1	—	—
Clinopyroxene -----	—	—	—	—	—	<.1	<.1	<.1	?	—
Orthopyroxene -----	—	—	—	—	—	<.1	<.1	<.1	?	—
Amphibole -----	—	—	—	—	—	<.1	<.1	<.1	+	—
Biotite -----	—	+	+	.8	.2	<.1	<.1	<.1	—	—
Fe-Ti-oxides -----	—	+	+	1.5	—	<.1	<.1	<.1	+	—
Others -----	gr	—	—	—	—	—	—	—	s	+*
Total -----	—	—	—	8.3	3.3	<1	<1	<1	—	—
Xenoliths -----	—	—	—	—	—	—	—	—	+	—

\* Spec. 315 — andalusite, zircon, sillimanite, mica and cordierite.

APPENDIX VII.—*Phenocryst assemblages and modal analyses of porphyritic obsidians*—Continued

Sample number -----	319	321	328	329	335	336	337	338	340	341
<b>Phenocrysts:</b>										
Quartz -----	—	—	—	—	+	+	—	+	+	—
Alkali feldspar -----	—	—	—	—	—	—	+	—	—	—
Plagioclase -----	+	+	+	+	+	+	—	+	—	+
Olivine -----	+	—	—	—	—	—	—	—	—	—
Clinopyroxene -----	+	+	—	—	—	—	—	+	—	+
Orthopyroxene -----	—	—	—	—	+	+	—	+	—	+
Amphibole -----	—	—	—	—	—	—	—	—	+	+
Biotite -----	—	—	+	+	—	—	—	—	—	+
Fe-Ti-oxides -----	—	+	?	—	—	—	—	+	—	+
Others -----	—	—	—	—	—	—	—	—	—	—
Total -----	—	—	—	—	c.15	c.15	—	—	—	<20
Xenoliths -----	+	—	—	—	—	—	—	—	—	—

Sample number -----	342	343	344	347	350	352	354	364	367	368
<b>Phenocrysts:</b>										
Quartz -----	—	—	—	+	+	+	—	—	—	—
Alkali feldspar -----	—	—	—	—	—	—	—	—	—	—
Plagioclase -----	+	+	8.78	+	+	+	+	14	+	+
Olivine -----	—	—	—	—	+	—	+	—	—	—
Clinopyroxene -----	+	+	.29	+	+	—	+	+	—	—
Orthopyroxene -----	+	+	.21	+	+	+	—	<1	+	—
Amphibole -----	+	+	.25	—	+	—	—	—	—	+
Biotite -----	+	+	—	—	—	—	—	—	—	—
Fe-Ti-oxides -----	+	+	.56	+	—	—	+	<1	—	—
Others -----	—	—	—	—	—	—	—	ap	—	—
Total -----	<20	<20	10.1	—	—	—	—	15	—	—
Xenoliths -----	—	—	—	—	—	—	—	—	—	—

Note: Samples 290, 317, 320, 322–325, 345, 348, and 356–361 are reported as being porphyritic, but the phenocryst assemblages are not specified.

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