CIRCULAR 113

Major-Element Variations in the Potrillo, Carrizozo, and McCartys Basalt Fields, New Mexico

by JACQUES RENAULT

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Abstract

Sixty-two X-ray-fluorescence analyses for nine major oxides in alkaline and subalkaline basalts display considerable lateral variation within closely related genetic units. The number of samples required to characterize the mean compositions of the sampling units with 95 percent confidence was determined. The lower and upper Carrizozo basalts were adequately sampled and require four and seven samples, respectively, to characterize their means; the undifferentiated basalts require more. On the basis of Kuno's differentiation index, the Carrizozo basalts display conspicu ous differentiation, and the Potrillo and McCartys basalts are relatively undifferentiated.

Titanium oxide concentration is correlated with tectonic setting. Within each volcanic field, titanium-rich basalts erupted in upthrown blocks and titanium-poor basalts erupted in downthrown blocks. The presence of deeply penetrating fractures is probably greater in the upthrown blocks, and the higher titanium concentration may be related to higher pressures of magma generation in the mantle.

Introduction

The purpose of this study is to determine areal compositional variations in some New Mexico basalts, characterize their mean compositions, and attempt to correlate their compositions with their tectonic settings. Toward this end, 62 samples of fresh Quaternary basalt from the Potrillo, Carrizozo, and McCartys volcanic fields were analyzed by X-ray-fluorescence spectroscopy for SiO_2, Al_2O_3, MgO, CaO, Na_2O, K_2O, TiO_2, MnO, and total iron as FeO.

The ages of individual basalts are given in Table 1, and the locations of the fields are shown in Figure 1.

All the rocks analyzed are fresh porphyritic olivine basalts with olivine phenocrysts. Augite, the only pyroxene observed, occurs predominately in the groundmass of all the basalts. Sparse augite phenocrysts occur in the rocks of the Potrillo field, and some of these are zoned with pinkish rims. Plagioclase and olivine are close to An_{50} and Fa_{20} in all the basalts, as determined by optical examination.

On the basis of their CIPW norms, and the classification scheme of Chayes (1966), POT-11 from the Potrillo field is an alkaline basalt and CAR-9 and MAC-16 from the Carrizozo and McCartys fields are subalkaline basalts. The incompleteness of the X-ray-fluorescence analyses with regard to Fe_2O_3/FeO ratios renders them unclassifiable on the basis of their norms. However, similarities in SiO_2, MgO, and alkali contents strongly suggest that the Paxton Springs basalt and all the Potrillo basalts are alkaline and that the Laguna, lower McCartys, upper McCartys, Blocky, and all the Carrizozo basalts are subalkaline.

TABLE 1. AGES OF BASALTS ANALYZED

Volcanic Field	Location	Age (m.y.)	Method	Reference
Potrillo	Black Mountain	0.126±0.011	K-Ar	R. E. Denison*
Potrillo	Santo Thomas	0.116±0.116	K-Ar	R. E. Denison*
Potrillo	Kilbourne Hole	0.103±0.084	K-Ar	R. E. Denison*
Potrillo	Aden Crater	>0.011	paleontology	Simons and Alexander (1964)
Carrizozo	Upper Carrizozo	<0.0015	geomorphology	Weber (1964)
McCartys	Upper McCartys	<0.001	archaeology	Nichols (1946)

* Mobil Research and Development Corp.; W. H. Burke, Jr., and J. B. Otto, analysts.

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Figure 1. Index map showing locations of the Potrillo, Carrizozo, and McCartys volcanic fields.

Field Sampling

Compositional variations will occur at the surface of a basalt flow as the result of supergene processes. In addition, Watkins, Gunn, and Coy-Y11 (1970) and Gunn and Watkins (1970) have shown that substantial primary variations in major-element concentrations occur throughout the thicknesses of basalt flows. To avoid as much as possible compositional variations due to differentiation during extrusion and subsequent surficial processes, sampling was confined as nearly as possible to the base of the upper zone of vesiculation at each sample site.

Sample points were selected prior to •field work and modified at the sample location to obtain fresh representative material. Sample points were located on the ground by reference to topographic features and plotted on topographic maps. The principal factors that modified the position of the preselected sample points were availability of fresh outcrop and the availability of helicopter landing sites.

The samples were numbered serially, with the prefixes POT, CAR, and MAC designating the Potrillo, Carrizozo, and McCartys fields respectively.

POTRILLO FIELD

The locations of samples collected in the Potrillo field are shown in Figure 2; in this figure, the boundaries of the effusive rocks were compiled from Dane and Bachman (1965) and Hoffer (1969). North of the international boundary, the field is conveniently divided by a north-south line connecting the East Potrillo Mountains in the south and the Aden Hills in the north. West of this line, the field is dominated by scores of cinder cones peppering a moderately elevated region called the West Potrillo Mountains. East of the line, the field is topographically subdued and lies on a relatively flat plain called La Mesa surface, which extends 20 miles eastward to the west escarpment of the Rio Grande Valley.

The Potrillo field was sampled to obtain an average composition for the Quaternary basalt. The great number of eruptive centers in the area precluded extensive sampling of individual flows, so a grid sampling plan was adopted with sampling points at the corners and centers of townships and a sample interval of 4.3 miles. Samples were taken as near to the preselected points as good rock exposures allowed. Many sample locations are displaced as much as 0.25 mile from the grid points.

CARRIZOZO FIELD

The locations• of samples collected on the Carrizozo field are shown in Figure 3. Flow boundaries are from Dane and Bachman (1965), with the exception of the contact between the upper and lower Carrizozo flows, which was approximately mapped for this study.

The Carrizozo lava field consists of two major eruptive periods: the earlier Broken Back Crater eruptions and the later lower and upper Carrizozo flows. The Broken Back Crater basalts are clearly older and are topographically separated from the Carrizozo flows by a valley containing Triassic sediments. The lower and upper Carrizozo flows are virtually indistinguishable from each other in the field, but are chemically different. The lower Carrizozo flows may have issued from the same vent as the upper flows and extend south of the vicinity of sample CAR-5.

The sinuous shape of the Carrizozo flows suggested serial sampling, and an average sample interval of 2.7 miles was adopted. The sample locations on the Broken Back Crater flows occupy grid positions with 2.6 miles between samples.

McCARTYS FIELD

The locations of samples collected in the McCartys field are shown in Figure 4. The boundaries of the flows were determined by aerial observation during this study.

The sampled part of the McCartys field consists of older Laguna basalts, which are poorly exposed, and the younger lower and upper McCartys flows. Two additional flows, both younger than the Laguna flows and possibly younger than the lower McCartys flow, were also sampled. They are the. Paxton Springs flow and a flow with a very irregular surface, which I call the Blocky flow. The Blocky flow is younger than the lower McCartys flow, but its age relationship to the upper McCartys flow is unknown.

The sampling plan adopted for the McCartys field was similar to that for the Potrillo flows. The actual locations of sample points depart from the preselected grid pattern more severely than they do for the Potrillo field, mainly because of fewer adequate landing sites and because the distribution of the two major eruptives suggested a more linear sampling plan.

The Paxton Springs flow was serially

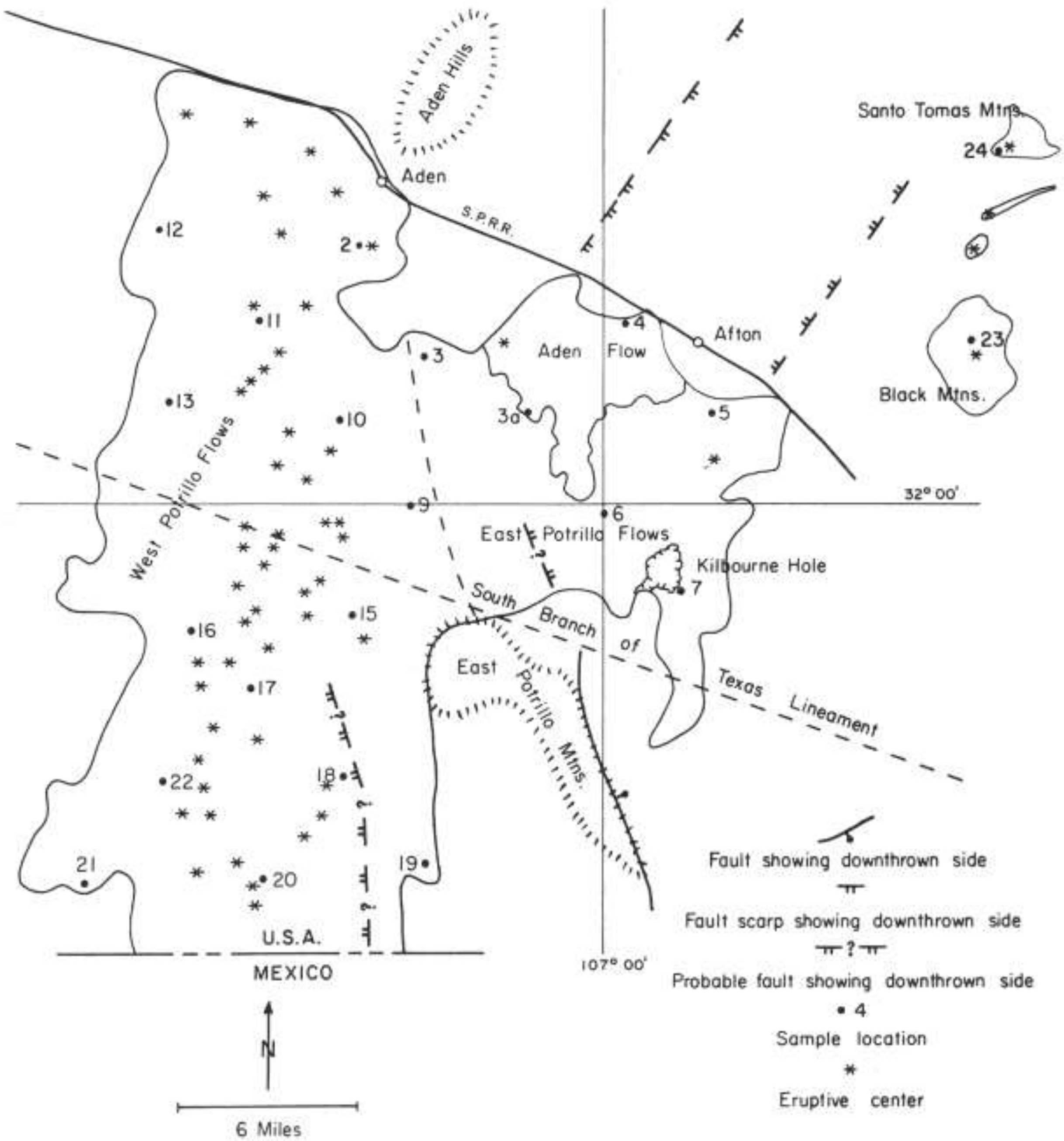

Figure 2. Map of Potrillo volcanic field showing locations of samples sites.

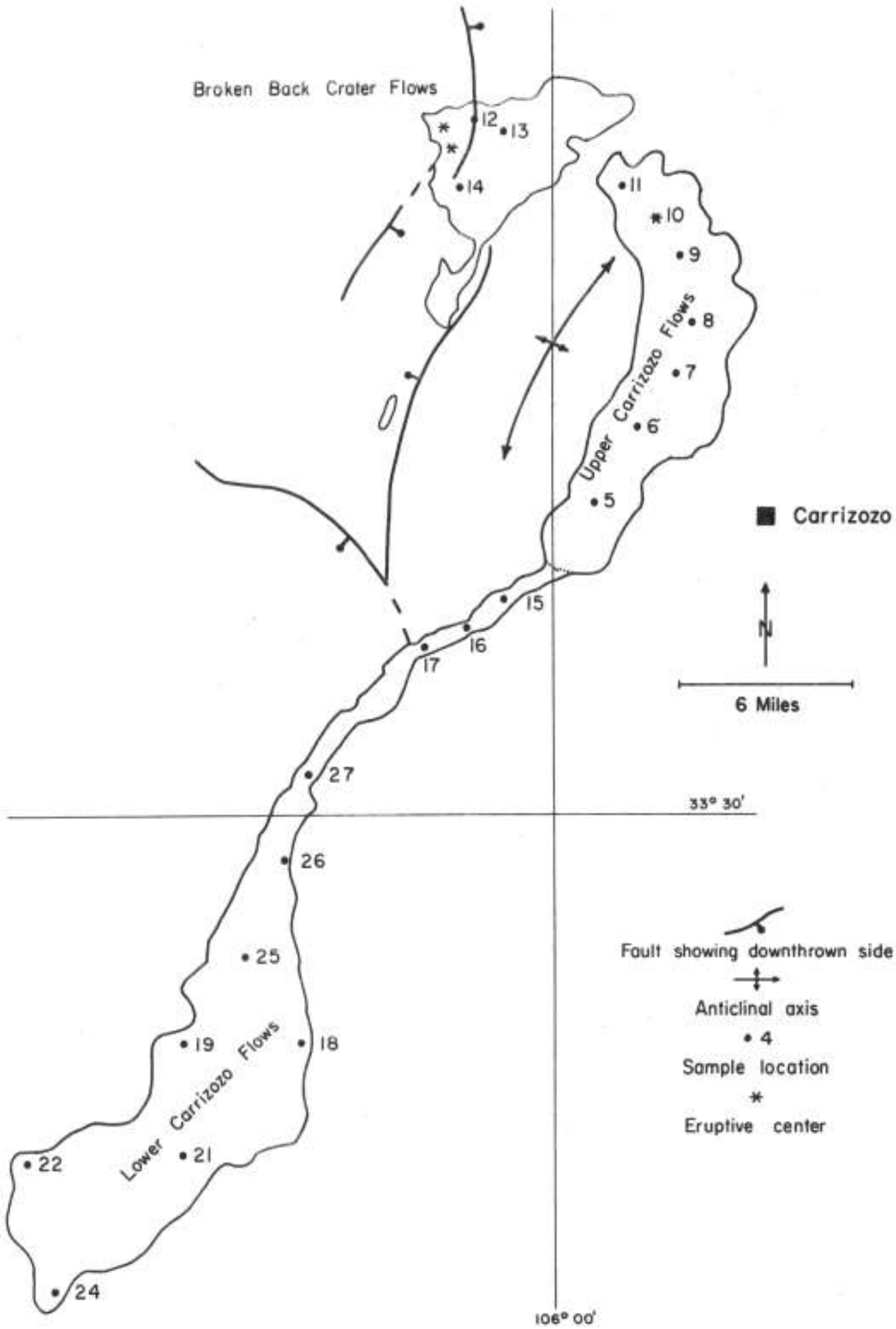

Figure 3. Map of Carrizozo volcanic field showing locations of sample sites.

sampled with an average spacing of 1. 9 miles. The spacing on the upper McCartys flow is about 3.5 miles. The average spacing on the lower McCartys basalt is 5. 1 miles. The distribution of sampling points on the Laguna and Blocky flows is essentially random.

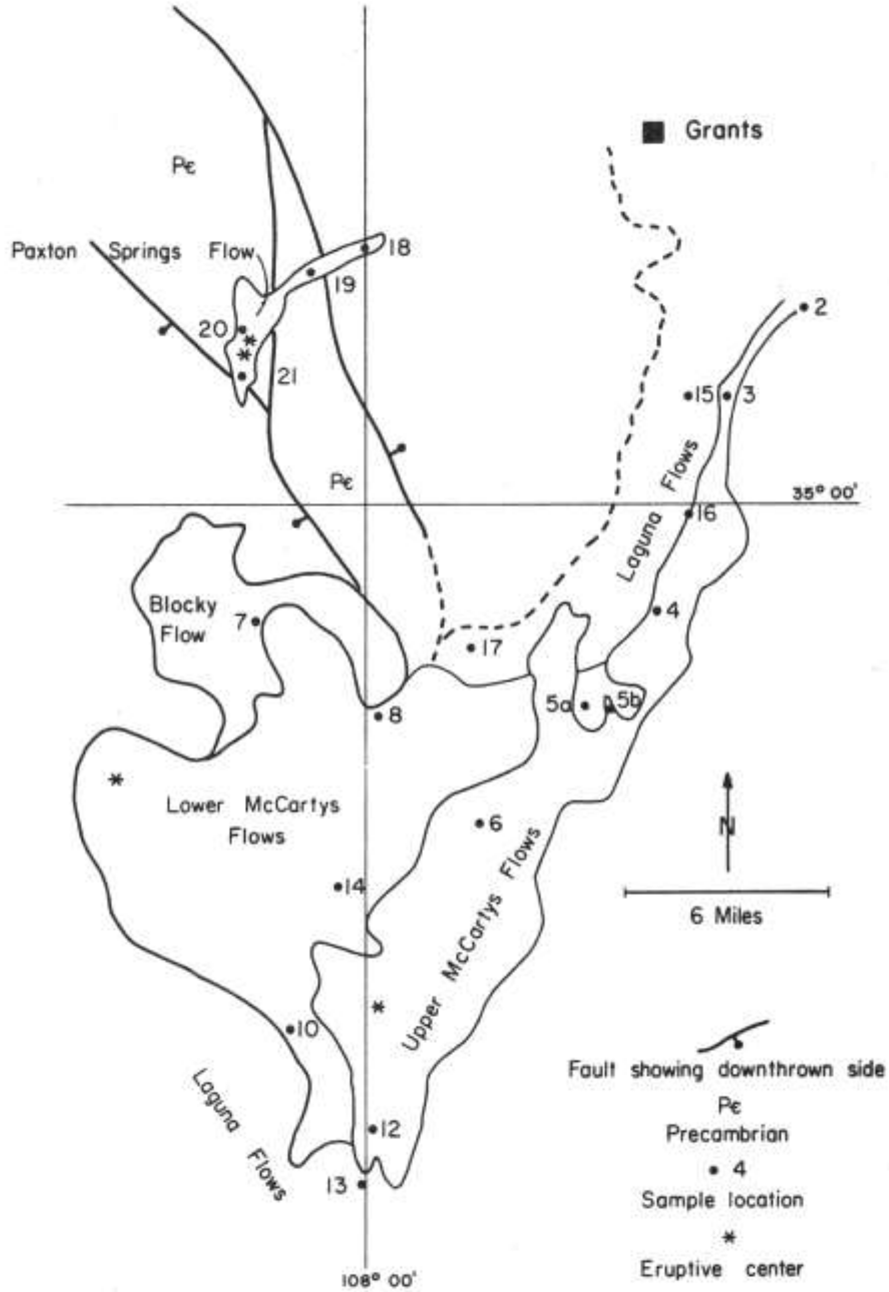

Figure 4. Map of McCartys volcanic field showing locations of sample sites.

Analytical Procedures

SAMPLE PREPARATION

Samples were first crushed to pea-size granules and hand picked to eliminate vesicle fillings and weathered material. Five grams of the cleaned basalt was then ground under acetone in an automatic mortar for 30 minutes. After drying, undiluted briquettes were made according to the method of Volborth (1963), except that, in place of the fragile glass anvil Volborth used, we inlaid a polished carbide disc into the base of the press.

X-RAY FLUORESCENCE

X-ray-fluorescence data were obtained on a Norelco 8-position vacuum spectrograph. Counting was done in fixed-time mode, with counting statistics better than 3.3 percent. U. S. Geological Survey geochemical standard W-1 was kept in one position of the spectrograph and counted prior to running each set of seven unknowns. Count rates for unknowns were divided by the appropriate count rate for W-1 to obtain a count ratio, and straight-line calibration curves were constructed' using the three wet-analyzed standards given in Table 2. Some difficulty was experienced in obtaining a satisfactory calibration curve for FeO, so this oxide was reanalyzed for the three standard basalts by Lynn Brandvold, chemist of the Bureau. Brandvold's results are included in Table 2.

The calibration curves were drawn through triplicate determinations of the standard basalts and determined by passing a straight line through the grand mean of the data and choosing its slope to be the ratio of the standard deviations of count ratio to composition. Thus, where Y and X are the respective count ratios and compositions of the standards, and s_y and s_x are their standard deviations, and B is the intercept on the Y axis, the equation of the calibration curve is

$$X = (Y - B)(s_x / s_y)$$

As this method of curve-fitting is not generally used, it is worthwhile to show its relationship to regression and correlation coefficients. Following the notation of Snedecor (1956), where r is the Pearson correlation co-

TABLE 2. CHEMICAL AND NORMAL ANALYSES OF BASALT STANDARDS

	Wet Chemical Analyses* (weight percent)		
	CAR-9	MAC-16	POT-11
SiO_2	51.07	49.93	44.00
TiO_2	1.58	1.38	2.35
Al_2O_3	17.65	16.62	14.76
Fe_2O_3	2.01	1.54	4.46
FeO	7.76	9.25	7.33
MnO	0.15	0.17	0.22
MgO	5.98	8.45	10.44
CaO	8.23	8.90	10.40
Na_2O	3.90	2.89	3.07
K_2O	1.21	0.75	1.40
P_2O_5	0.33	0.25	0.58
H_2O^+	0.02	0.02	0.65
H_2O^-	0.09	0.04	0.18
CO_2	0.00	0.00	0.00
S	0.0	0.0	0.0
Cr_2O_3	0.051	0.073	0.068
Ni	0.0095	0.0250	0.0225
Co	0.0058	0.0074	0.0070
Cu	0.0243	0.0181	0.0169
	100.07	100.32	99.96
Total iron as FeO	10.64	10.48	9.21
	Normative Minerals		
Albite	33.01	24.63	11.53
Orthoclase	6.67	4.45	8.34
Anorthite	27.24	30.02	22.24
Olivine	12.02	11.82	15.94
Diopside	9.52	10.20	20.63
Hypersthene	4.22	13.48	--
Quartz	--	--	--
Nepheline	--	--	7.95
Magentite	3.02	2.09	6.50
Ilmenite	3.04	2.74	4.41
Apatite	0.67	0.67	1.34

* Analyses by H. Wiik; total iron by L. Brandvold.

efficient, b12 and $b2_1$ are the regression coefficients of X on Y and Y on X, and s_x and s are the standard deviations of X and Y populations,

$$s_y/s_x = b_{21}/r$$

$$r = (b_{21}b_{12})^{1/2}$$

$$s_y/s_x = (b_{21}/b_{12})^{1/2}$$

If m is the slope of a regression line measured from the X axis,

$$m_{yx} = b_{21}$$

$$m_{xy} = 1/b_{12}$$

$$s_y/s_x = (m_{yx}m_{xy})^{1/2}$$

Thus the slope defined as the ratio of the standard deviations is the geometric mean of the two possible regression lines.

The calibration curve determined in this way gives the best correlation between composition and count ratio. For straight-line calibration curves, it has an advantage over the least-squares regression on composition in that it does not assume that the standard compositions are accurate.

RESULTS

The reproducibility expressed as coefficients of variation ($C = \frac{\text{standard deviation}}{\text{mean composition}}$ mean composition 100) of the samples run in triplicate is given in Table 3. The relatively poor precision of the Na_20 and MgO analyses is attributed to insufficiently fine grain size and the possibility of surface imperfections on the sample briquettes (Volborth, 1963). Poor reproducibility of MnO may be due to the low concentrations involved.

The chemical analyses of rocks from the Potrillo, Carrizozo, and McCartys basalt fields are given in Table 4. In these tables, "Given D" is the deviation from the mean, or tolerance, used to calculate "Number," the number of samples required for the mean composition to lie within plus or minus "Given D" with 95-percent confidence. The "Given D's" are also the class intervals used by Manson (1967) in his study of the frequency distributions of the major-element compositions of basalts. "Number" is calculated from the formula given by Krumbein and Graybill (1965):

$$n = st/d \qquad (1)$$

where n is "Number, " s is the standard deviation, t is the tabulated value of the t distribution at a half probability of 0.025 for the appropriate degrees of freedom, and d is "Given D. " "Calc D" is the deviation of the mean determined by substituting N, the actual number of samples collected, for n in equation (1) and solving for d. Thus for the west Potrillo samples (table 4), the mean SiO_2 concentration is 44.46+0.79 percent for 14 samples, but only three samples need have been taken to achieve the given tolerance of +1. 0 percent. For Na_2O, on the other hand, the mean is 3. 31+0. 11 percent, and four additional samples would have to be taken in order to achieve a tolerance of +0.2 percent. In practice the sampling program would have to be adjusted to give the best results for the most significant elements.

TABLE 3. COEFFICIENTS OF VARIATION OF X-RAY-FLUORESCENCE ANALYSES (percent)

SiO_2	0.71
Al_2O_3	2.23
FeO	2.28
MgO	4.44
CaO	1.97
Na_2O	4.84
K_2O	2.08
TiO_2	2.74
MnO	4.01

Most analyses in Table 4 total less than 100 percent because we did not analyze for water and P_2O_5 and because total iron is expressed as FeO. Analyses that exceed 100 percent contain some degree of unknown error.

As a consequence of the statistics of small sample size, some of the values for "Number" are unrealistically high. If the sample size (N) is increased, the standard deviation will probably decrease, and, even if it does not, the tabulated value of the t distribution will decrease, thus reducing the value of "Number. " For example, "Number" for the silica analysis of the lower McCartys flows is 55; if N is doubled and the standard deviation remains the same, "Number" becomes 30.

TABLE 4. CHEMICAL ANALYSES AND STATISTICS OF POTRILLO, CARRIZOZO, AND McCARTYS BASALTS, N. MEX.

West Potrillo Basalts

GIVEN D	SIO2 1.000	AL 2O3 0.500	FEO 0.500	MGO 0.500	CAO 0.500	NA2O 0.200	K2O 0.150	TIO2 0.200	MNO 0.030	SUM
POT- 2	43.917	15.133	9.435	11.348	10.980	2.700	1.663	2.254	0.173	97.603
POT- 9	44.378	15.856	9.236	10.137	10.020	3.146	1.669	2.495	0.170	97.107
POT- 10	43.134	15.703	9.467	10.167	10.630	3.358	1.529	2.373	0.172	96.533
POT- 11	44.055	14.316	10.293	10.392	10.250	3.112	1.392	2.288	0.217	96.315
POT- 12	46.083	15.228	8.839	11.191	10.570	3.823	0.780	1.972	0.183	98.669
POT- 13	43.502	15.646	10.063	9.103	11.160	2.931	1.548	2.514	0.178	96.645
POT- 15	44.977	15.285	9.822	9.078	10.120	4.231	1.175	2.152	0.198	97.038
POT- 16	45.484	16.217	9.446	10.172	9.660	3.596	1.444	2.229	0.172	98.420
POT- 17	44.240	14.487	9.927	10.838	9.750	3.292	1.493	2.354	0.186	96.567
POT- 18	44.700	15.304	9.467	10.980	10.730	3.408	0.981	2.276	0.178	98.024
POT- 19	45.161	15.665	9.948	8.971	9.840	3.396	1.741	2.202	0.185	97.109
POT- 20	44.470	15.494	10.293	10.377	10.560	3.050	1.514	2.342	0.177	98.277
POT- 21	43.871	15.475	9.414	10.814	10.820	2.862	1.582	2.175	0.170	97.183
POT- 22	44.424	15.437	9.927	10.917	10.720	3.377	1.543	2.338	0.176	98.859
MEAN	44.457	15.375	9.684	10.320	10.415	3.306	1.432	2.283	0.181	
CALC D	0.454	0.288	0.242	0.454	0.274	0.230	0.158	0.081	0.007	
STD DEV	0.786	0.499	0.420	0.787	0.475	0.399	0.273	0.140	0.013	
STD ERR	0.210	0.133	0.112	0.210	0.127	0.107	0.073	0.037	0.003	
NUMBER	2.884	4.646	3.291	11.557	4.213	18.548	15.463	2.278	0.860	
N = 14										

East Potrillo Basalts

GIVEN D	SIO2 1.000	AL 2O3 0.500	FEO 0.500	MGO 0.500	CAO 0.500	NA2O 0.200	K2O 0.150	TIO2 0.200	MNO 0.030	SUM
POT- 3	45.484	15.741	9.990	9.554	10.730	3.308	0.869	2.191	0.172	98.039
POT- 3	45.484	15.228	10.439	9.863	10.420	2.208	1.103	2.129	0.186	97.060
POT- 4	44.147	15.894	9.948	9.260	10.270	2.688	1.432	2.244	0.180	96.063
POT- 5	43.502	14.677	10.136	10.191	11.000	2.746	1.469	2.073	0.186	95.980
POT- 6	45.346	16.141	9.833	9.505	9.790	2.754	1.569	2.169	0.182	97.289
POT- 7	43.226	14.411	10.335	9.814	11.000	2.108	1.184	2.051	0.187	94.316
POT- 23	46.958	15.894	8.285	9.078	10.980	3.112	1.627	2.007	0.154	98.095
POT- 24	48.802	15.856	8.682	9.475	9.730	3.100	1.584	1.937	0.150	99.316
MEAN	45.369	15.480	9.706	9.592	10.490	2.753	1.355	2.100	0.175	
CALC D	1.545	0.533	0.658	0.296	0.440	0.357	0.228	0.085	0.012	
STD DEV	1.848	0.637	0.787	0.354	0.526	0.427	0.273	0.102	0.015	
STD ERR	0.653	0.225	0.278	0.125	0.186	0.151	0.096	0.036	0.005	
NUMBER	19.103	9.077	13.874	2.808	6.196	25.462	18.469	1.458	1.362	
N = 8										

Broken Back Crater Basalts

GIVEN D	SIO2 1.000	AL 2O3 0.500	FEO 0.500	MGO 0.500	CAO 0.500	NA2O 0.200	K2O 0.150	TIO2 0.200	MNO 0.030	SUM
CAR- 12	51.751	17.510	9.195	6.730	8.060	3.527	1.520	1.745	0.152	100.190
CAR- 13	51.152	17.053	8.954	7.314	8.210	3.231	1.505	1.669	0.145	99.233
CAR- 14	52.120	18.764	9.038	5.941	8.090	3.438	1.602	1.850	0.150	100.993
MEAN	51.674	17.776	9.062	6.662	8.120	3.399	1.542	1.755	0.149	
CALC D	1.213	2.201	0.304	1.712	0.197	0.377	0.130	0.226	0.009	
STD DEV	0.488	0.886	0.122	0.689	0.079	0.152	0.052	0.091	0.004	
STD ERR	0.282	0.511	0.071	0.398	0.046	0.088	0.030	0.052	0.002	
NUMBER	4.416	58.118	1.107	35.164	0.466	10.676	2.243	3.823	0.267	
N = 3										

Lower Carrizozo Basalts

GIVEN D	SIO2 1.000	AL 2O3 0.500	FEO 0.500	MGO 0.500	CAO 0.500	NA2O 0.200	K2O 0.150	TIO2 0.200	MNO 0.030	SUM
CAR- 15	50.323	16.920	9.676	5.931	8.710	3.581	1.339	1.764	0.155	98.399
CAR- 16	48.157	17.034	9.697	6.814	9.110	3.142	1.578	1.927	0.166	97.625
CAR- 17	50.507	17.167	9.592	6.784	8.340	3.369	1.377	1.694	0.152	98.982
CAR- 18	50.092	17.471	9.854	6.657	8.460	3.454	1.333	1.712	0.160	99.193
CAR- 19	50.276	17.262	9.927	6.319	8.570	3.473	1.304	1.750	0.163	99.044
CAR- 21	49.309	17.072	9.467	6.917	9.320	3.592	1.387	1.747	0.163	98.974
CAR- 22	50.461	16.559	9.958	7.123	8.750	3.458	1.277	1.688	0.167	99.441
CAR- 24	48.802	16.141	9.571	7.250	8.900	3.485	1.463	1.748	0.159	97.519
CAR- 25	50.829	16.464	9.592	6.711	8.530	3.896	1.316	1.691	0.156	99.185
CAR- 26	50.415	16.578	9.958	7.480	8.790	3.604	1.205	1.653	0.165	99.848
CAR- 27	49.124	16.578	9.508	7.152	8.940	3.600	1.640	1.902	0.164	98.608
MEAN	49.845	16.841	9.709	6.831	8.765	3.514	1.384	1.752	0.161	
CALC D	0.575	0.271	0.124	0.294	0.195	0.124	0.087	0.059	0.003	
STD DEV	0.856	0.403	0.184	0.437	0.291	0.185	0.130	0.087	0.005	
STD ERR	0.258	0.122	0.056	0.132	0.088	0.056	0.039	0.026	0.001	
NUMBER	3.638	3.228	0.673	3.796	1.681	4.228	3.720	0.942	0.133	
N = 11										

Upper Carrizozo Basalts

	SIO2	AL203	FEO	MGO	CAO	NA2O	K2O	TIO2	MNO	SUM
GIVEN D	1.000	0.500	0.500	0.500	0.500	0.200	0.150	0.200	0.030	
CAR- 5	51.060	17.700	9.111	7.211	8.440	3.796	1.407	1.692	0.140	100.557
CAR- 6	51.659	17.243	9.686	6.426	8.340	3.885	1.283	1.722	0.151	100.395
CAR- 7	50.783	17.034	9.812	6.083	8.250	3.850	1.292	1.732	0.152	98.988
CAR- 8	51.106	16.749	9.833	5.819	8.230	3.462	1.295	1.711	0.153	98.358
CAR- 9	51.014	17.776	9.351	6.623	8.290	3.604	1.175	1.586	0.152	99.571
CAR- 10	52.719	16.331	9.958	5.627	8.120	3.731	1.297	1.822	0.159	99.764
CAR- 11	52.857	17.605	9.864	6.279	8.130	3.658	1.193	1.735	0.157	101.478
MEAN	51.600	17.205	9.659	6.295	8.257	3.712	1.277	1.714	0.152	
CALC D	0.790	0.497	0.288	0.490	0.105	0.138	0.071	0.065	0.006	
STD DEV	0.855	0.537	0.311	0.529	0.113	0.149	0.077	0.070	0.006	
STD ERR	0.323	0.203	0.118	0.200	0.043	0.056	0.029	0.026	0.002	
NUMBER	4.373	6.917	2.319	6.713	0.308	3.330	1.567	0.733	0.244	
N = 7										

Laguna Basalts

	SIO2	AL203	FEO	MGO	CAO	NA2O	K2O	TIO2	MNO	SUM
GIVEN D	1.000	0.500	0.500	0.500	0.500	0.200	0.150	0.200	0.030	
MAC- 13	51.751	16.388	10.272	8.828	9.400	2.354	0.507	1.120	0.162	100.782
MAC- 15	48.387	16.179	11.015	10.995	9.040	2.450	0.832	1.590	0.194	100.682
MAC- 16	49.539	16.654	10.544	8.373	9.090	2.912	0.762	1.366	0.166	99.406
MAC- 17	48.940	16.426	11.454	9.554	8.790	2.488	0.720	1.440	0.190	100.002
MEAN	49.654	16.412	10.821	9.437	9.080	2.551	0.705	1.379	0.178	
CALC D	2.346	0.309	0.830	1.824	0.398	0.393	0.223	0.312	0.026	
STD DEV	1.475	0.194	0.522	1.147	0.250	0.247	0.140	0.196	0.016	
STD ERR	0.737	0.097	0.261	0.573	0.125	0.124	0.070	0.098	0.008	
NUMBER	22.023	1.527	11.022	53.244	2.540	15.466	8.821	9.745	3.000	
N = 4										

Lower McCartys Basalts

	SIO2	AL203	FEO	MGO	CAO	NA2O	K2O	TIO2	MNO	SUM
GIVEN D	1.000	0.500	0.500	0.500	0.500	0.200	0.150	0.200	0.030	
MAC- 5B	46.774	14.582	11.799	10.975	8.820	2.769	0.812	1.566	0.190	98.287
MAC- 8	50.645	15.095	10.795	9.740	9.120	2.604	0.578	1.228	0.182	99.987
MAC- 10	52.258	16.521	9.906	8.093	9.520	2.869	0.612	1.257	0.159	101.195
MAC- 14	49.170	17.490	9.404	8.402	9.920	2.373	0.540	1.133	0.152	98.584
MEAN	49.712	15.922	10.476	9.302	9.345	2.654	0.635	1.296	0.171	
CALC D	3.706	2.114	1.675	2.107	0.762	0.345	0.193	0.299	0.029	
STD DEV	2.329	1.329	1.053	1.324	0.479	0.217	0.121	0.188	0.018	
STD ERR	1.165	0.664	0.526	0.662	0.239	0.108	0.061	0.094	0.009	
NUMBER	54.937	71.505	44.903	71.043	9.281	11.889	6.620	8.911	3.700	
N = 4										

Upper McCartys Basalts

	SIO2	AL203	FEO	MGO	CAO	NA2O	K2O	TIO2	MNO	SUM
GIVEN D	1.000	0.500	0.500	0.500	0.500	0.200	0.150	0.200	0.030	
MAC- 2	51.889	16.236	10.774	8.289	8.970	2.646	0.702	1.361	0.172	101.039
MAC- 3	50.783	15.285	11.213	9.377	9.030	2.431	0.653	1.344	0.188	100.304
MAC- 4	50.000	14.316	11.370	9.789	8.870	2.515	0.686	1.458	0.175	99.179
MAC- 5A	50.138	15.342	10.941	9.098	9.380	2.581	0.655	1.345	0.178	99.658
MAC- 6	50.415	15.589	11.255	8.755	8.950	2.735	0.663	1.346	0.181	99.889
MAC- 12	51.705	16.236	10.010	8.328	9.280	2.700	0.609	1.250	0.162	100.280
MEAN	50.822	15.501	10.927	8.939	9.080	2.601	0.661	1.351	0.176	
CALC D	0.843	0.752	0.525	0.624	0.213	0.121	0.034	0.069	0.009	
STD DEV	0.803	0.716	0.500	0.595	0.203	0.115	0.032	0.066	0.009	
STD ERR	0.328	0.292	0.204	0.243	0.083	0.047	0.013	0.027	0.004	
NUMBER	4.267	13.560	6.610	9.356	1.087	2.197	0.300	0.722	0.567	
N = 6										

Blocky Basalt

	SIO2	AL203	FEO	MGO	CAO	NA2O	K2O	TIO2	MNO	SUM
GIVEN D	1.000	0.500	0.500	0.500	0.500	0.200	0.150	0.200	0.030	
MAC- 7	46.774	13.840	11.412	11.951	9.310	2.546	0.885	1.642	0.195	98.555

Paxton Springs Basalt

	SIO2	AL203	FEO	MGO	CAO	NA2O	K2O	TIO2	MNO	SUM
GIVEN D	1.000	0.500	0.500	0.500	0.500	0.200	0.150	0.200	0.030	
MAC- 18	45.161	14.493	10.743	9.794	9.820	2.450	1.181	2.316	0.187	96.145
MAC- 19	45.253	15.000	11.004	10.451	9.490	2.735	1.344	2.399	0.193	97.869
MAC- 20	45.300	14.791	11.381	10.951	9.430	2.154	1.194	2.400	0.202	97.803
MAC- 21	45.069	15.076	11.224	9.005	9.080	3.700	1.542	2.879	0.181	97.756
MEAN	45.196	14.840	11.088	10.050	9.455	2.760	1.315	2.498	0.191	
CALC D	0.162	0.415	0.441	1.341	0.482	1.066	0.268	0.408	0.014	
STD DEV	0.102	0.261	0.277	0.843	0.303	0.670	0.168	0.257	0.009	
STD ERR	0.051	0.130	0.139	0.421	0.152	0.335	0.084	0.128	0.004	
NUMBER	0.105	2.755	3.110	28.757	3.722	113.702	12.745	16.680	0.903	
N = 4										

Oxide Variation in the Basalts

The compositional variation of the various basalt flows is presented as histograms in Figures 5 through 13; the volcanic fields are arranged upward from south to north, and, within the fields, the histograms are arranged upward from older to younger units (where relative ages are known).

SILICA

Silica displays rather high dispersion, which is most prominent in the Potrillo and the McCartys fields. The distributions of silica content in the Broken Back Crater and upper and lower Carrizozo flows are narrow, with the mean composition for the upper Carrizozo significantly higher at the 95-percent confidence level than that of the lower. This is consistent with a normal differentiation trend.

Although the means of silica content for the lower and upper McCartys flows are also consistent with a normal differentiation trend, the dispersion of silica in the lower McCartys is too great to distinguish with confidence between the two populations of analyses. The wide distribution of silica in the Laguna and east Potrillo analyses is expectable, considering that these flows are old and poorly exposed; more than one genetic unit may be represented by the samples. However, the wide distribution in the lower McCartys flow is unusual and may be due to compositional heterogeneity in the magma chamber. The narrow distribution of the Paxton Springs flow is expectable, as the flow is a localized product of a brief volcanic event.

ALUMINA

In the Potrillo field, alumina content has a smaller range than it has in either the Carrizozo or McCartys fields. This suggests, as opposed to the silica analyses, that differentiation was rather limited. The relatively large dispersion of Al_2O_3 analyses in the upper Carrizozo, lower McCartys, and upper McCartys suggests that these lavas issued from rather heterogeneous magmas as opposed to those of the Broken Back Crater, lower Carrizozo, Laguna, and Paxton Springs lavas.

IRON AND MANGANESE

The compositional range of FeO and MnO among the various fields is limited, and, with the exception of the east Potrillo and the lower and upper McCartys units, the dispersions are narrow. Secondary processes cannot be used to explain the behavior of iron in these two units, as the older Laguna and Potrillo flows have relatively narrow distributions. Secondary processes, however, may account for the dispersion of MnO.

MnO is a more sensitive discriminator among the sampling units than is FeO. There is no significant difference in iron content among the Carrizozo flows and the flows of the McCartys field, but there is a significant difference in MnO between the lower Carrizozo flow and the Broken Back Crater and upper Carrizozo flows. The difference in MnO of the upper McCartys and Paxton Springs flows and the east and west Potrillo flows is noticeable if not significant at the same level.

MAGNESIA

The magnesia distributions have moderate dispersion and show strong family resemblances within each field. The means of the lower Carrizozo and upper Carrizozo flows are displaced from one another in a direction consistent with a normal differentiation history, as are the means of the lower and upper McCartys; although the differences are not significant at the 95-percent confidence level. The difference in MgO in the east and west Potrillo fields is almost significant at 95-percent confidence, with only 0. 02 percent overlap in their "Calc D's. " The high mean value of MgO for the west Potrillo flow, in particular, suggests derivation from a parental mantle material with minimal differentiation between partial melting of the mantle and extrusion. The high MgO concentrations in the McCartys field also suggest close affinity to primary basaltic magma.

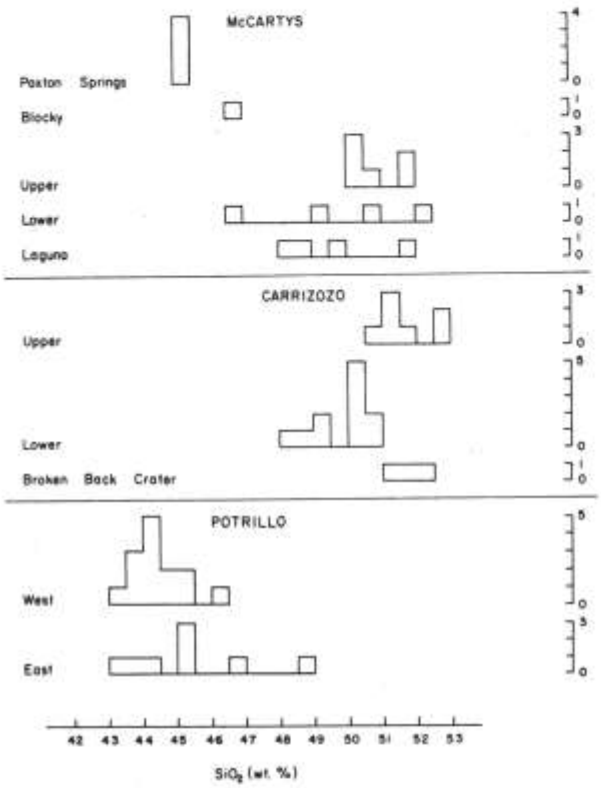

Figure 5. Distribution of silica content.

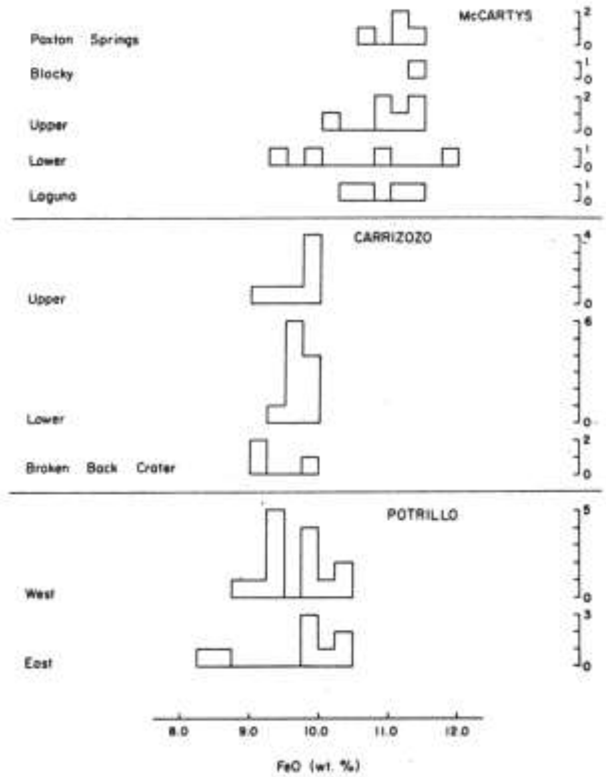

Figure 7. Distribution of iron content.

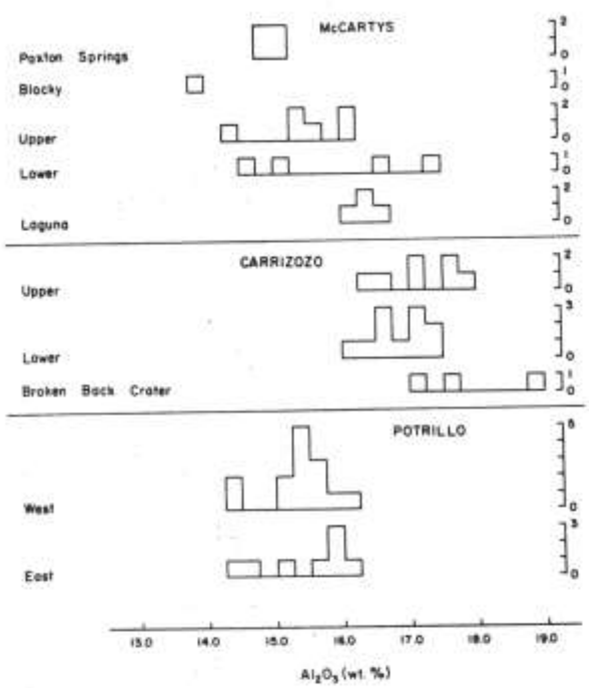

Figure 6. Distribution of alumina content.

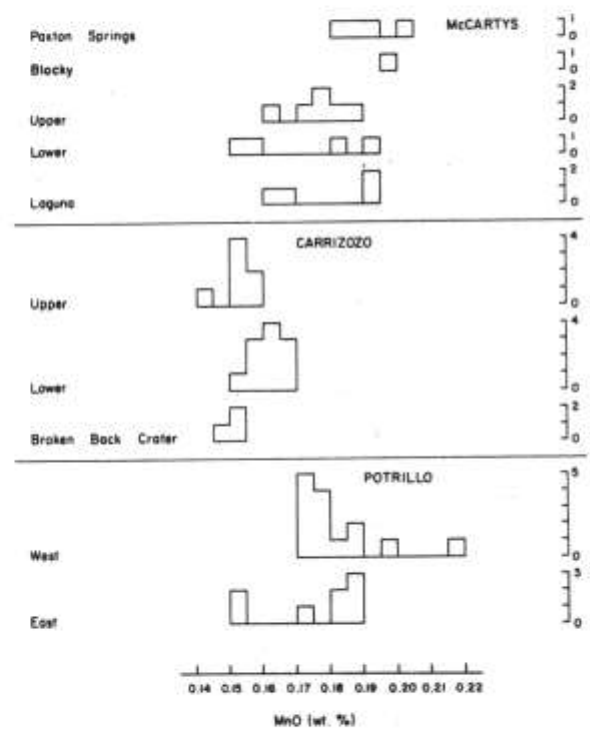

Figure 8. Distribution of manganese content.

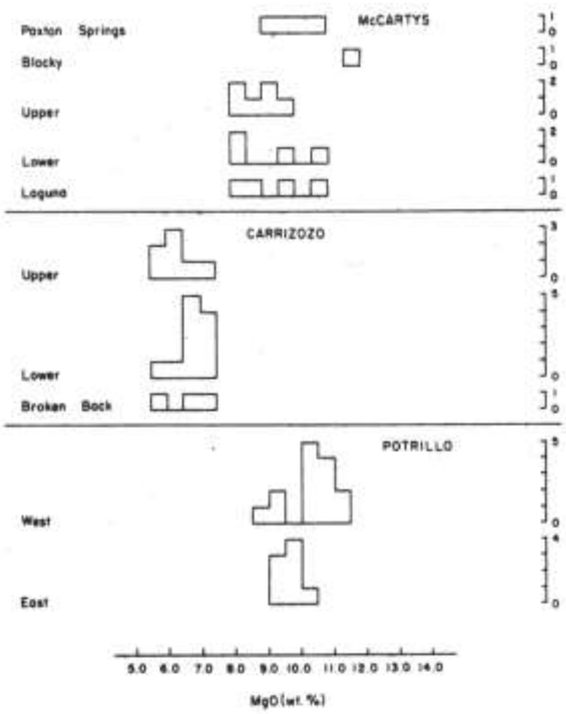

Figure 9. Distribution of magnesia content.

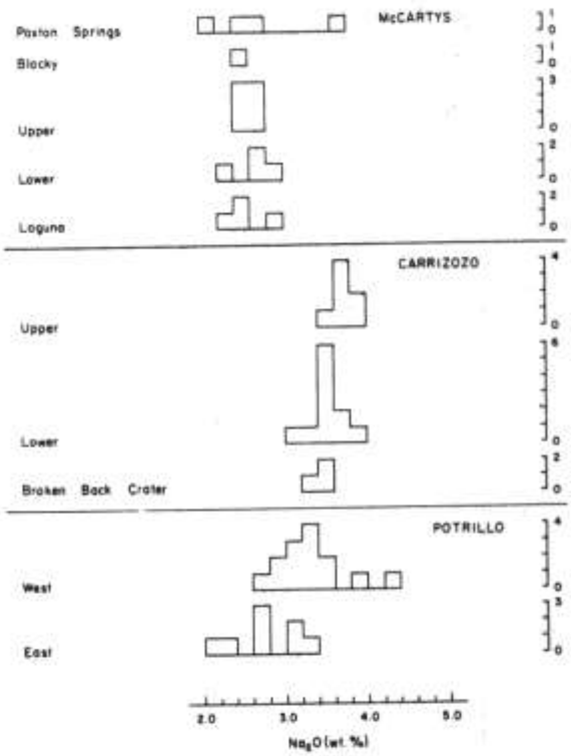

Figure 11. Distribution of soda content.

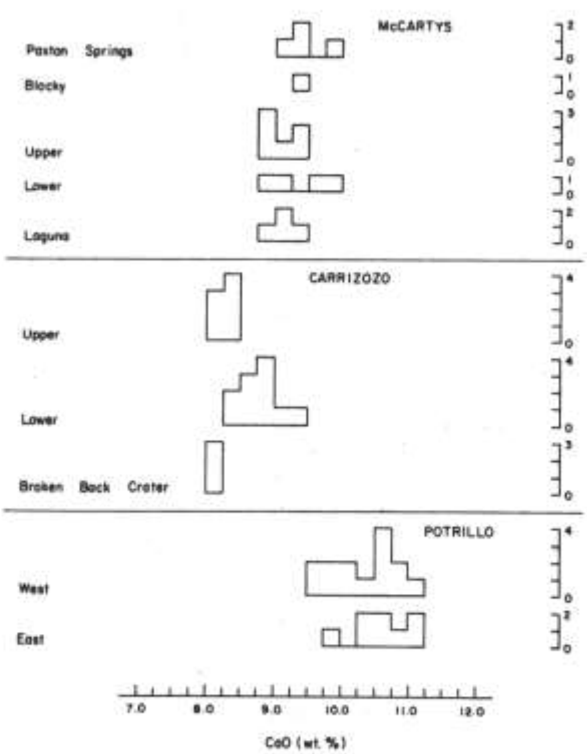

Figure 10. Distribution of lime content.

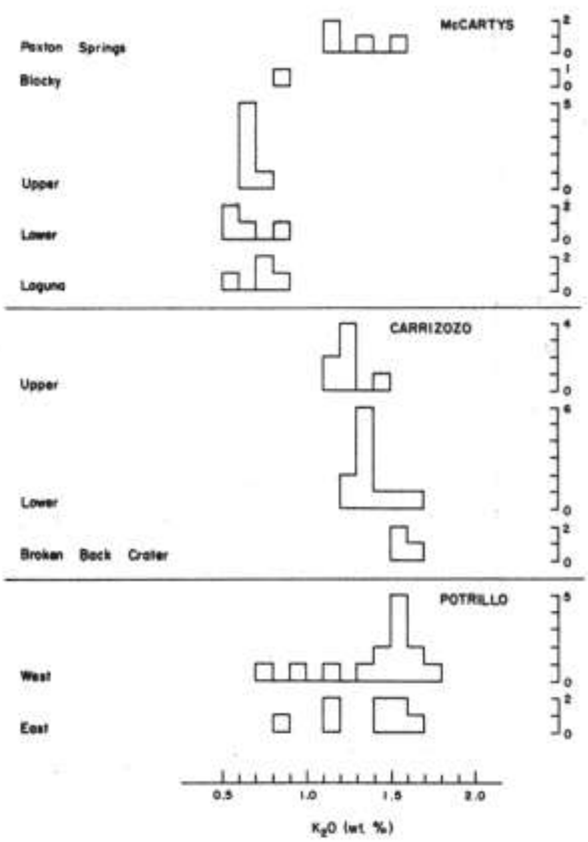

Figure 12. Distribution of potash content.

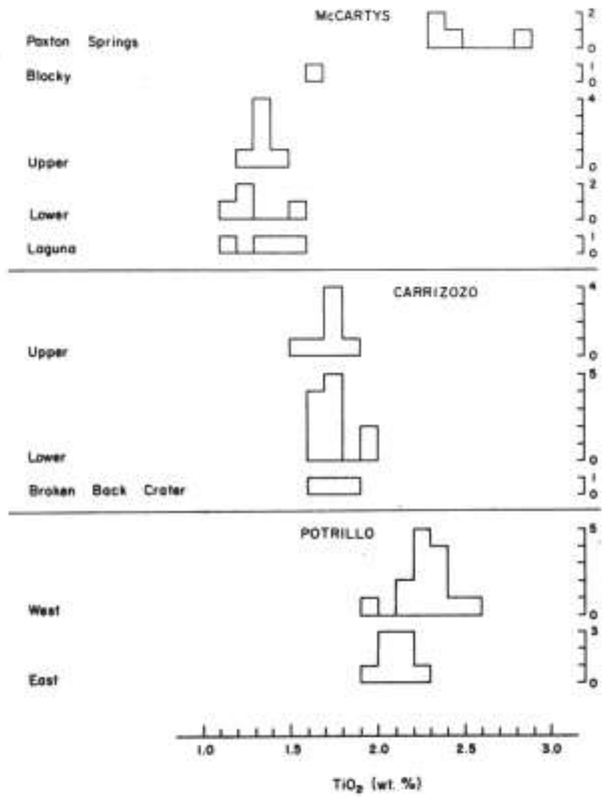

Figure 13. Distribution of titania content.

LIME

The dispersion of CaO is small for all the volcanic fields. The lower Carrizozo flow is significantly higher in lime content than is the upper flow, which is consistent with a normal differentiation trend. No such differences are detectable in the Potrillo and McCartys fields.

SODA AND POTASH

All the Carrizozo flows and all the McCartys flows, except for the Paxton Springs flow, show close family resemblances with respect to both alkalies. The Paxton Springs flow resembles the other lavas of the McCartys field in Na_2O content, but it is significantly higher in K_2O content. On the other hand, the east and west Potrillo flows resemble each other in potash, but differ in soda.

TITANIA

The TiO_2 distributions for all the lavas, except Paxton Springs, have small dispersions, and the large dispersion of the Paxton Springs is due to only one sample. There are close family resemblances among the sampling units of the various fields, with the exceptions of the Paxton Springs flows. In the analyses reported here, the greatest similarity in titanium concentration occurs among the basalts of the Carrizozo field and among the Laguna, lower and upper McCartys, and Blocky flows. The west Potrillo lavas are significantly higher in TiO_2 content than the east Potrillo lavas, and the Paxton Springs lavas are significantly higher than the rest of the McCartys lavas.

Origin of the Basalts

The extent of differentiation of basaltic magmas can be estimated from the solidification index, SI, of Kuno et al. (1957):

$$SI = (MgO \times 100)/(MgO + FeO + Na_2O + K_2O)$$

where FeO is total iron calculated as Fe^{2+}.

In general, SI decreases with decrease in proportion of liquid remaining from differentiation. Values of SI greater than 40 suggest accumulation of olivine crystals, values from 35 to 40 imply little or no differentiation, and values of SI less than 35 are thought to result from differentiation of basaltic magma within the crust.

The basalts studied here are plotted in Figure 14 on an MFA diagram, where MgO = SI. Also plotted in Figure 14 are the average compositions of the Servilletta, Hinsdale, and Union County basalts of northern New Mexico and southern Colorado as reported by Lipman (1969), and the compositions of the Cienega basalts of north-central New Mexico as reported by Sun and Baldwin (1958).

In terms of their solidification indices, the basalts of the Potrillo and McCartys fields are distinctly different from the basalts of the Carrizozo field. The basalts of the Carrizozo field appear to be slightly more differentiated than the Servilletta and Cienega basalts of the Rio Grande trough and slightly less differentiated than the Hinsdale and Union County basalts.

Broken Back Crater, lower Carrizozo, and upper Carrizozo basalts have mean SI's of 32.3, 32.8, and 30. 0, respectively. The differences in SiO_2, Al_2O_3, MgO, CaO, and Na_2O in the lower and upper Carrizozo flows are consistent with the change in SI, but the same is not true for Broken Back Crater flows. Although the extent of differentiation for the older Broken Back Crater basalts is less than for the younger Carrizozo flows, the character of differentiation is somewhat different, suggesting origin from different magma chambers.

The Potrillo and McCartys basalts all have SI's greater than 38, indicating little differentiation of primary basalt magma. The basalts of the Potrillo field show, in fact, the influence of olivine accumulation. In these two fields, the upper McCartys shows a slightly higher degree of differentiation than the older lower McCartys, which is consistent with the 'changes in SiO_2, Al_2O_3, and K2O; however, the differences in oxide concentration are not as conspicuous as they are in the Carrizozo basalts.

The lack of differentiation in the Potrillo and McCartys basalts implies that basaltic magma was imported from the mantle to the surface during a relatively short-lived and profound tectonic event; whereas, the other basalts mentioned probably resided in a holding chamber long enough for conspicuous differentiation to take place.

Chayes (1964) and Chayes and Velde (1965) have demonstrated statistically that TiO_2 is the best single oxide discriminator between oceanic and circumoceanic basalts. They suggested that there may be significant compositional differences between mantle material beneath the oceans and that beneath the continent which are responsible for the higher titanium concentrations in oceanic basalts.

Green (1968), in discussing the origin of basalt by partial melting of peridotitic mantle material, cited the mineralogical variability of peridotite nodules and high-temperature peridotite intrusions as evidence of heterogeneity of the mantle. Green noted that the K_2O, TiO_2, P_2O_5, and Na_2O are inadequate in peridotite to account for their concentrations in basalt by partial melting and, furthermore, that these oxides are rather randomly distributed in basalts.

Recently, MacGregor (1969) demonstrated that, in the model mafic system MgO-SiO_2-TiO_2, titanium is increasingly concentrated in the melt phase with increasing pressure up to 50 kb. MacGregor cited field evidence supporting this behavior of titanium in real basalts and suggested that TiO2 concentration in alkaline and subalkaline basalts may be more an indicator of depth of origin than compositional heterogeneity in parent mantle material.

If compositional heterogeneity is invoked to explain the differences in titania in the basalts of the Potrillo, Carrizozo, and McCartys fields, significant differences in magma composition would have to exist within a lateral distance of less than 30 km, the distance between the eruptive centers of the Paxton Springs and upper McCartys flows. The distance be-

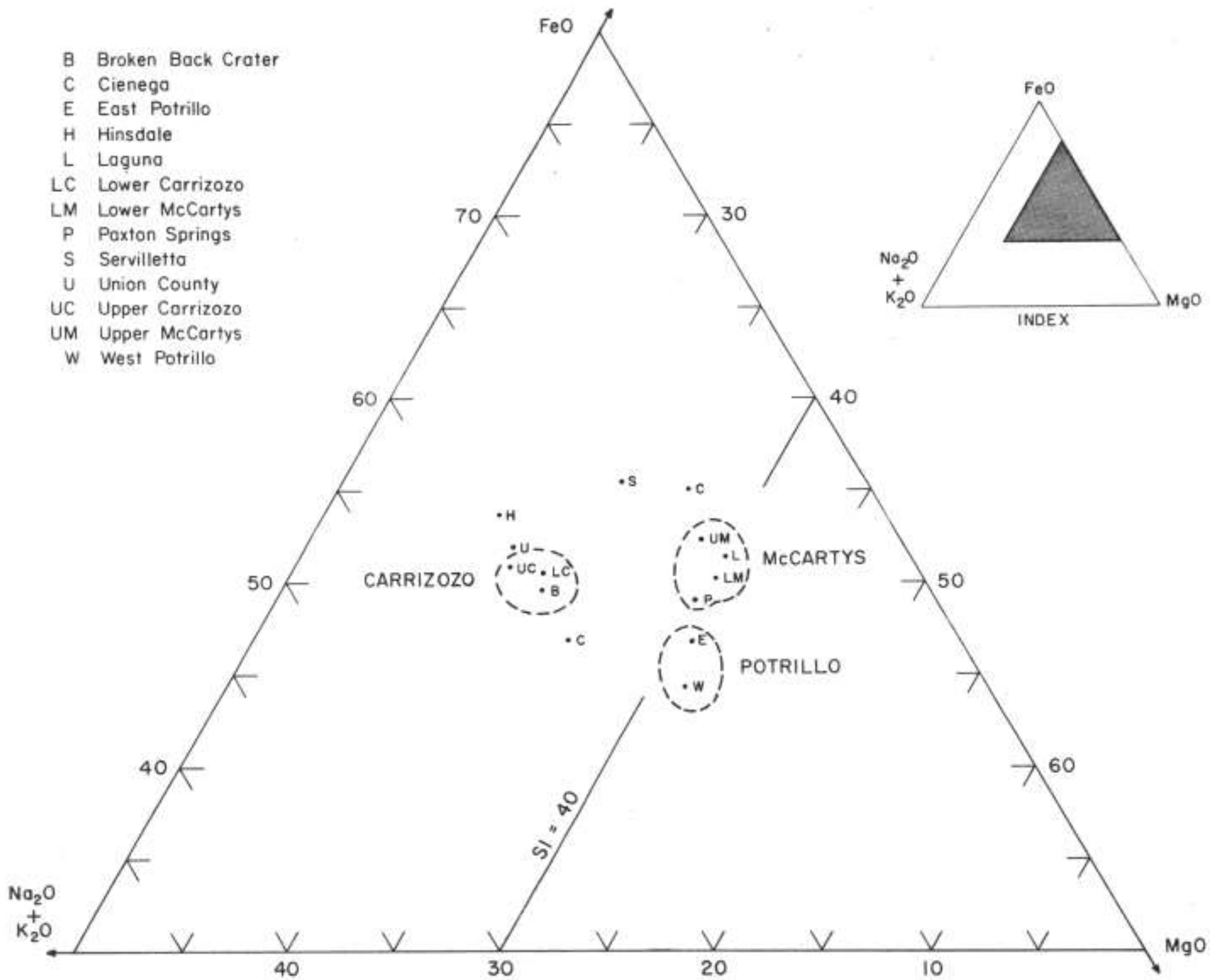

Figure 14. MFA diagram.

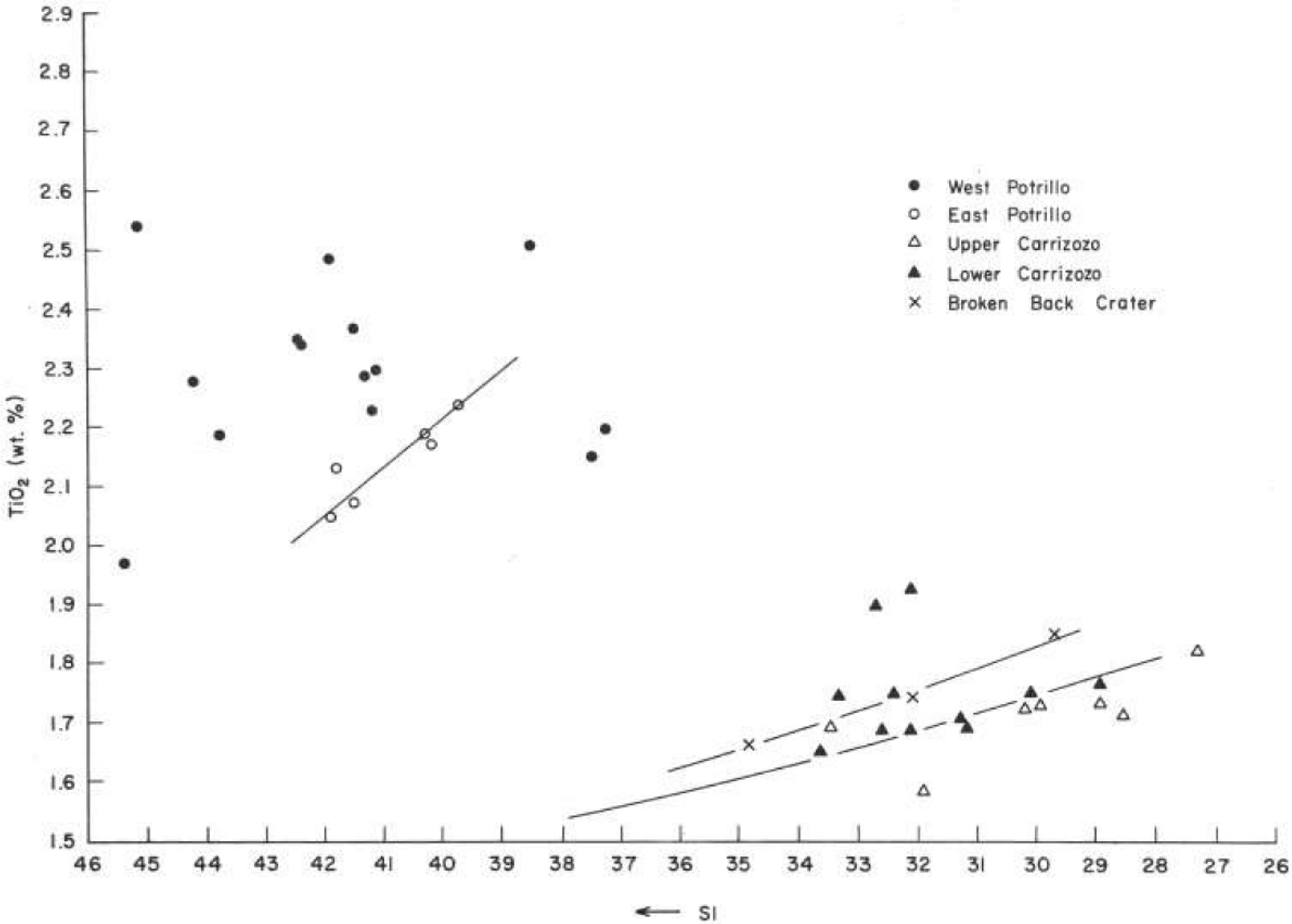

Figure 15. Variation of titania content with solidification index.

tween Aden Crater and the axis of cones in the west Potrillo lavas and the distance between the vents of the upper and lower McCartys flows are both 16 km. Between the Broken Back Crater vent and the upper Carrizozo vent, the distance is 13 km. As the Carrizozo basalts have nearly the same concentration of TiO_2, regions of homogeneity might be at least this large.

Differentiation could account for changes in TiO_2 concentration in similar basalts from the same volcanic field, and Kuno (1968) has shown that titanium tends to increase with differentiation in the range of SI characterizing the basalts studied here. This consideration could not apply to the difference in titanium between the Paxton Springs basalt and the other sampling units of the McCartys field, for its concentrations of SiO_2, $A1_2O3$, and K_2O indicate that it is genetically different.

In Figure 15, the variation of TiO2 versus SI is shown for the Potrillo and Carrizozo fields. In the Potrillo field, the east Potrillo basalts group nicely and are distinctly different from the west Potrillo lavas, indicating that they are not products of the same magma. In the Carrizozo field, titanium in the lower and upper Carrizozo flows follows differentiation trends that are similar to each other if one excludes two anomalously high TiO2 analyses in the lower flow. The titanium in the Broken Back Crater flows appears to follow a different trend, but additional analyses are necessary to establish this better; in addition, the concentrations of the other major oxides and the age relationships of the Carrizozo field basalts suggest that the Broken Back Crater basalts were derived from a different magma.

The differences in TiO_2 concentration within the various volcanic fields may be correlated with their structural setting. A prediction of the stress distribution in block faulting gives upthrown blocks as being under less compressive stress than are downthrown blocks, and consequently the upthrown blocks would tend to have more deeply penetrating fractures. Brouwer (1962) showed how changes in the stress field influences the birth and extinction of volcanoes within the framework of this simple concept. In view of the pressure control on TiO2 concentrations in the MgO--SiO_2 -TiO2 system, basalts erupted through up-thrown blocks should be richer in titanium than basalts erupted through adjacent downthrown blocks, provided that differences in TiO_2 are not the result of mantle heterogeneity or diffe rentiation.

In the McCartys field, the Paxton Springs basalt erupted through a Precambrian block in the east end of the Zuni uplift (Kelley, 1967). This block is bounded on two sides by high-angle faults, and a fault is mapped in the valley occupied by the Paxton Springs basalt. The other sampling units of the McCartys field erupted through structurally and topographically lower units where Permian rocks are exposed (Dane and Bachman, 1965).

In the Carrizozo field,, the Broken Back Crater flows erupted through Permian sediments and the Carrizozo flows through Triassic sediments (Dane and Bachman, 1965) on the west flank of a north-south basin defined at the top of the Precambrian (Foster and Stipp, 1961). The vents lie on a west-northwest axis defined by the linear intrusions of Capitan Mountain and Jones dike. The vent of the upper Carrizozo flows lies near the crest of the Carrizozo anticline, defined by Kelley and Thompson (1964) at the top of Permian beds. A northnortheastward-trending normal fault crossing U. S. 380 in T. 6 S. , R. 9 E. , projects midway between the Broken Back Crater vents and the upper Carrizozo vent. It is down to the west, with the Permian San Andres Limestone in contact with the older Permian Yeso Formation. The southernmost branch of the Chupadera fault, down to the east and defined on the basis of topography by Kelley and Thompson (1964), projects north-northeastward between the two vents of the Broken Back Crater flows. The main trend of the Chupadera fault is also down to the east and passes 1 mile east of the two Broken Back Crater vents.

In the Potrillo field, a branch of the Texas lineament (Muehlberger, 1965) passes across the northern end of the East Potrillo Mountains and south of the east Potrillo basalts; however there is no geologic control for this structure in the Potrillo field. A north-northwestward-trending fault, down to the northeast passes along the northeast side of the East Potrillo Mountains (Dane and Bachman, 1965). Unpublished geophysical information of various petroleum companies indicates that the east Potrillo basalts are structurally lower than the west Potrillo basalts.

North of the east Potrillo flows, a pair of northeast-trending fault scarps (Kottlowski, 1960) indicate that the east Potrillo basalts are down relative to the west Potrillo basalts. The east Potrillo basalts are also topographically lower. A few linear features within the lava fields indicate movement since eruption. One of these, north of the East Potrillo Mountains and trending north-northwestward, suggests movement with the east side down; another, about 6 miles west of the East Potrillo Mountains and trending northward suggests that the west side is down.

In each of the three volcanic fields, where there is evidence of faulting, basalts on structurally higher rocks have higher mean titanium concentrations than do those on structurally lower rocks. These observations are consistent with regional differences in average TiO_2 concentrations observed by Lipman (1969) in the Servilletta basalt, within the Rio Grande trough, and the Hinsdale basalts of southern Colorado and the Union County, New Mexico, basalts to the west and east of the trough, respectively.

The Carrizozo field shows little variation in TiO_2 content, but, if the Chupadera fault scarp extending northward from the Broken Back Crater flows represents the major structural break associated with the Carrizozo field, the higher mean TiO_2 concentration in the Broken Back Crater flows is consistent with the titanium variation in the other areas studied.

It should be noted that the mean TiO_2 concentration in the lower Carrizozo flow is too high by virtue of two analyses. If these are discounted, its mean concentration is 1.716 percent, which is almost identical to its mean concentration in the upper Carrizozo basalts.

Although compositional heterogeneity in the mantle cannot be discounted (nor easily tested) as an explanation for TiO_2 differences in adjacent basalt flows, it would have to be conspicuous on a relatively small geographic scale. Tectonic control of TiO_2, on the other hand, is supported by observed field relations in New Mexico, as well as by experimental studies.

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