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MAJOR-ELEMENT CHEMICAL DISCRIMINATION OF MAGMA-BATCHES IN LAVAS FROM KILAUEA VOLCANO, HAWAII, 1954 – 1971 ERUPTIONS

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ABSTRACT

Chemical distinction of magma-batches requires methods that account for the stoichiometry of all differentiation processes contributing to the chemical diversity. Intercepts on Pearce element-ratio diagrams that account for the stoichiometry of differentiation processes and ratios of conserved elements discriminate magma-batches within suites of lavas from Kilauea Volcano, Hawaii. These methods can effectively distinguish magma-batches if these are chemical systems closed to some constituents during their evolution. Compositions of material from thirteen historic eruption sequences of Kilauea Volcano between 1954 and 1971 are tested for within-suite and between-suite differences with Pearce element ratios. The within-suite variation, compared to analytical precision, measures whether the samples are from more than one magma-batch. Between-suite differences distinguish magma-batches in a set of eruptive sequences. The 1954–1971 Kilauea eruption sequences comprise a minimum of four magma-batches. The lavas from the Mauna Ulu sequence (erupted 1969–1971) can be shown to comprise more than one magma-batch. The lavas erupted in 1969 along the East Rift Zone (Aloi and Alae Craters) and the Mauna Ulu lavas have the same chemical characteristics, but differ from the lavas of the other eruptive sequences. The Kilauea Iki (1959) lava sequence represents a magma-batch that is chemically different from batches inferred for all the 1954–1971 lava sequences. One magma-batch can account for all other sequences in the period 1954–1968. The temporal and spatial relations of the delineated batches suggest that more than one batch can be in the volcanic edifice at one time and that one batch can simultaneously occupy more than one transport path.

Keywords: basalt, magma-batch, Pearce element ratio, Hawaii, Kilauea.

SOMMAIRE

La distinction chimique de plusieurs venues magmatiques demande l'utilisation de méthodes qui rendent compte de la stoechiométrie de tous les processus de différenciation contribuant à leur diversité chimique. Les diagrammes de Pearce entre éléments et rapports d'éléments rendent compte de la stoechiométrie des processus de différenciation et des rapports d'éléments conservés, et les intersections obtenues sur ces diagrammes permettent la distinction des différentes venues magmatiques dans les suites de laves du volcan Kilauéa (Hawaï). Ces méthodes permettent effectivement la distinction des venues magmatiques si elles constituent des systèmes fermés par rapport à certains constituants durant leur évolution. Les compositions de matériaux provenant de treize séquences éruptives historiques du volcan Kilauéa comprises entre 1954 et 1971 ont été utilisées pour mettre en évidence, grâce aux rapports d'éléments selon la méthode de Pearce, des différences à l'intérieur des suites et entre les suites. Comparées à la précision analytique, les variations internes aux suites indiquent si les échantillons proviennent de plus d'une venue magmatique. Les différences entre suites permettent la distinction des venues magmatiques dans un groupe de séquences éruptives. Les séquences éruptives entre 1954 et 1971 du Kilauéa correspondent à au moins quatre venues magmatiques. Il est possible de montrer que les laves de la séquence du Mauna Ulu (éruptions de 1969 à 1971) proviennent de plus d'une venue magmatique. Les laves émises en 1969 le long de la Zone du Rift Oriental (cratères d'Aloi et d'Alae) et les laves de Mauna Ulu possèdent les mêmes caractères chimiques, mais diffèrent des laves des autres séquences éruptives. La séquence lavique du Kilauéa Iki (1959) représente une venue magmatique chimiquement différente des venues déduites de toutes les séquences laviques de 1954 à 1971. Une seule venue magmatique suffit à expliquer les autres séquences de la période 1954–1968. Les relations spatio-temporelles des venues magmatiques ainsi définies suggèrent qu'il peut y avoir au même moment plus d'une venue magmatique à l'intérieur de l'édifice volcanique, et qu'une même venue magmatique peut utiliser en même temps plusieurs conduits.

(Traduit par la Rédaction)

Mots-clés: basalte, venue magmatique, rapport d'éléments selon Pearce, Kilauéa, Hawaï.

INTRODUCTION

The distinction of magma-batches whose products are erupted at different times from a single volcano constrains rates of melting processes and interpretations about chemical variations in the source regions. The Hawaiian chain in general, and Kilauea Volcano in particular, have provided data used to test hypotheses concerning magma generation, intrusion and eruption. For example, Shaw (1973), Shaw & Jackson (1973), and Shaw (1987) postulated periodic or episodic variations in rates of processes of magma generation beneath Kilauea. These types of studies can be better constrained if the number of melting events can be determined from the eruptive products of volcanos. The purpose of this paper is to distinguish magma-batches within the products of the Kilauea eruptions between 1954 and 1971 with Pearce element ratios (Pearce 1968). These constraints can then be used in models of magma generation and transport in Kilauea.

THE CONCEPT OF MAGMA-BATCH

Powers (1955) introduced the concept of *magma-batch* to explain the similarities and differences between lava compositions erupted at Kilauea and Mauna Loa volcanos. In essence, Power's contribution was to recognize that much of the chemical diversity in Kilauean lavas was due to sorting (fractionation or accumulation) of olivine. Wright *et al.* (1975) used weight percent oxides of average lava compositions from separate sequences of eruption to distinguish magma-batches, after correcting for sorting of olivine of fixed composition. Much of the remaining diversity was and continues to be attributed to chemical differences in the source regions for the different magma-batches (*e.g.*, Wright *et al.* 1975, Wright & Tilling 1980).

Central to the concept of magma-batch is the idea that a set of igneous rocks formed from magmas that were, themselves, derived from a common precursor. Magma-batches can be discriminated by the methods described in this paper if they are chemical systems that have been modified only by processes that leave the system closed to at least one constituent during its evolution. Like all chemical systems, a magma-batch is finite in extent, has a fixed size but need not be connected nor regular in shape. Like thermodynamic systems, the concept of a magma-batch is a theoretical construct or model because it is unlikely that a natural chemical system can be completely closed to any constituent. If the real system is closed to the extent that changes in some constituents are too small to be detected, the construct is still useful because it has predictable, testable consequences (Greenwood 1989).

Processes of magma mixing can be classified as external and internal (Nicholls & Russell 1990). External processes would involve mixing of parts of more than one magma-batch, whereas internal processes would involve parts of the same batch, with the parts being products of different paths of differentiation or reaching different stages of differentiation. Magmas derived from a mixture formed by external processes would constitute one magma-batch if completely mixed prior to subsequent differentiation, but would presumably show variations from analytical uncertainty greater than expected if incompletely mixed. On the other hand, there should be no chemical indication of multiple batches in lavas formed by internal mixing if the chemical criteria for distinguishing magma-batches account for the stoichiometry of the full range of differentiation processes.

Methods for distinguishing magma-batches should have the following attributes: 1) They must account for changes due to the fractionation of multiple phases. Kilauean magmas, for example, have a chemical diversity that can be due to crystal sorting of Cr–Al-bearing spinel (picrite stage), olivine, plagioclase, augite (basalt stage), Fe–Ti oxides, and enstatite (later basalt stage). 2) They must account for changes due to varying mineral compositions during differentiation. For example, olivine compositions can range from Fo_{87} to Fo_{71} in related picrites and basalts (Nicholls & Stout 1988).

SOURCES AND NATURE OF THE DATA

This paper investigates the presence of distinct magma-batches in the products of the historic Kilauea eruptions that occurred between 1954 and 1971. A specific sequence of eruptions in Kilauea volcano is represented by a suite of rock compositions. The data were previously published, and all are from U.S. Geological Survey laboratories. The data are summarized and their sources are listed in Table A1 of the Appendix. The compositions have been grouped on the basis of when and where the lavas were erupted, following designations in the original publications. The data were collected on rocks erupted from the summit region of Kilauea volcano (Halemaumau and Kilauea Iki craters) and from flank eruptions along the East Rift zone. Included in the summary are notes on analytical methods: wet-chemical analyses of rocks or glasses, X-ray-fluorescence analyses of rocks.

The Distinction of Magma-Batches with Element Ratios

Magma-batches are discriminated in this study with major- and minor-element data because of their availability for the rocks erupted by Kilauea during the period 1954–1971. Other criteria that could be used to discriminate magma-batches are: petrographic data such as modes, mineral compositions and compositions of coexisting solid-solutions (Nicholls & Stout 1988, Fig. 8), compositions of residual glasses and glass inclusions (Nicholls & Stout 1988, Russell & Stanley 1990), or trace-element ratios (Hammond 1989, Halleran & Russell 1990). In the future, magma-batches also may be distinguished using geophysical techniques or physical modeling.

Pearce element ratios (Pearce 1968) are used to distinguish magma-batches because they are more sensitive to differentiation than the original oxide percentages. Element-ratio methods are easier to evaluate because they can be manipulated to compensate for the effects of magmatic differentiation. Limitations placed on the distinction of magma-batches by the precision of the analytical methods can be taken directly into account on element-ratio diagrams. Magma-batches are distinguished with Pearce element ratios using: 1) The intercepts of trends on Pearce element-ratio plots. An element-ratio diagram that completely describes the stoichiometry of the processes causing chemical diversity can be used to distinguish magma-batches because it has an intercept that is a function of the original composition of the system and remains invariant during differentiation. The stoichiometry can be determined from the mineralogy and petrography of the rocks. Diagrams can be drawn that guarantee that the intercept is a function of the initial composition of the system (Stanley & Russell 1989). Compositions of samples from the same magma-batch will have the same intercept within analytical uncertainty (Pearce 1968, Nicholls 1990). 2) The ratios of conserved elements (Nicholls 1988, Russell & Nicholls 1988). These ratios remain constant in a magma-batch undergoing differentiation. Two possible ratios that can be of use in basaltic systems are P/K and Ti/K if apatite and Fe–Ti oxides are not involved in the differentiation processes.

Intercepts on a Pearce element-ratio diagram can show variations greater than expected from analytical uncertainty for two reasons. The scatter could be due to the fact that the rocks are not derived from one magma-batch, or the rocks are comagmatic but have been affected by different processes, such that the stoichiometry of the processes affecting the two rock suites is not adequately accounted for on one diagram.

The three silicate phases that crystallize early in Kilauean lavas are olivine, augite and plagioclase. A ratio pair that accounts for chemical variations due to sorting of these three phases, in any combination, is: $Y = [0.25\ \mathrm{Al} + 0.5\ (\mathrm{Fe} + \mathrm{Mg}) + 1.5\ \mathrm{Ca} + 2.75\ \mathrm{Na}]/\mathrm{K}$ and $X = \mathrm{Si}/\mathrm{K}$. A plot with these ratios as coordinates will be referred to as a T diagram (for three-phase cotectic crystallization of olivine, plagioclase and augite). T then specifically represents the numerator of the Y-axis ratio: $[0.25\ \mathrm{Al} + 0.5\ (\mathrm{Fe} + \mathrm{Mg}) + 1.5\ \mathrm{Ca} + 2.75\ \mathrm{Na}]$.

The effect of not accounting fully for the stoichiometry is shown on Figure 1 for the 1968 picritic and basaltic lavas from Halemaumau and Hiiaka craters (Wright *et al.* 1975, Jackson *et al.* 1975, Nicholls & Stout 1988). The plot of the T/K index is near the top of the diagram. The bottom curve is based on the ratio pair: 0.5(Fe + Mg)/K *versus* Si/K, a plot that could distinguish samples

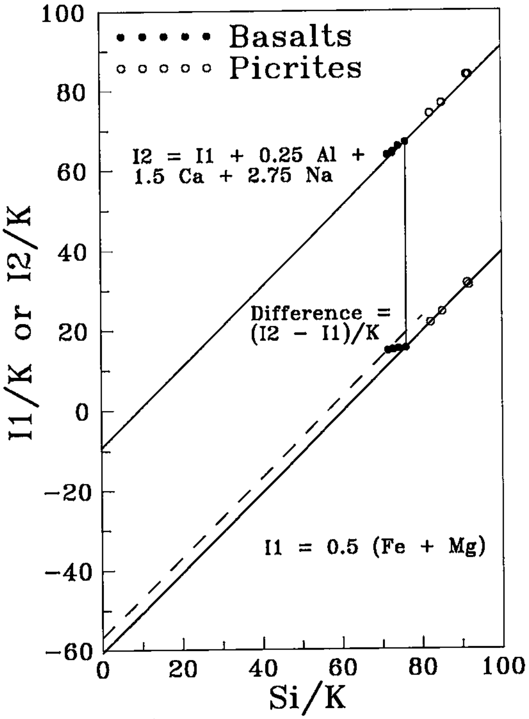

FIG. 1. Pearce element-ratio diagram illustrating relations between two indices that represent processes with different stoichiometry. Consequences of using a diagram that does not completely account for the stoichiometry of the phase assemblage responsible for the chemical variations are discussed in the text. Data from the 1968 Kilauea eruptions (Jackson *et al.* 1975, Wright 1971).

from a magma-batch that differentiated by olivine sorting alone. The vertical line joins the basalt data having the most mafic cotectic composition. The difference between the *Y*-axis coordinates in the two plots represents (0.25 Al + 1.5 Ca + 2.75 Na)/K, a conserved ratio in the picrites but a variable ratio in the basalts. The data more nearly describe a single trend with a slope of one on the T diagram (upper curve, Fig. 1). Consequently, the dispersion in the set of intercepts derived by drawing a line with a slope of one through each point of the T/K *versus* Si/K data (upper curve) will not be due to sorting of the silicate phases. The dispersion in this set of intercepts can be accounted for by analytical uncertainty (see below). If there is any dispersion due to sorting of other phases, such as oxides, it is smaller than can be detected with current analytical techniques (Fig. 2). In contrast, for the lower curve, lines with a slope of one drawn through each data point generate a range of intercepts with a variation greater than can be attributed to analytical uncertainty. It is attributable to sorting of phases other than olivine.

WITHIN-SUITE VARIATIONS

The data comprise compositions of glasses and lavas erupted on 13 different occasions or at different localities on Kilauea volcano and one prehistoric intrusive body, the Uwekahuna laccolith. The first point to decide is whether the samples in each suite are from a single magma-batch. This premise can be evaluated by examining, for each suite, the variation in the intercepts on a T diagram and the variation in the ratios, Ti/K and P/K. If any of these criteria are more variable than expected from analytical uncertainty, then either the lavas are from different batches, or the T diagram does not adequately account for the stoichiometry of the processes causing the variability.

The "comagmatic" hypothesis can be tested for each suite by comparing the dispersion in the intercept arising from variability in the original data *versus* the expected variation due to analytical uncertainty. Standard statistical techniques can be used to make the comparison. Thus the null hypothesis:

H_0: $\sigma^2(\beta,d) \leq \sigma^2(\beta,a)$ where $\sigma^2(\beta,d)$ is the variance in the intercept, β, due to variance in the data, d, and $\sigma^2(\beta,a)$ is the expected variance in the intercept, β, that would arise from analytical uncertainty, a. Rejection of the null hypothesis implies that the suite of compositions are representative of more than one magma-batch or that the diagram does not account for the stoichiometry of the chemical variations.

We adopted the following procedures: 1) From the cited values of one σ in the analytical uncertainties in the oxide concentrations (Wright & Fiske 1971), we calculate the uncertainty associated with the intercept derived by forcing a line with the model slope through a data point on the diagram. A mean value for the propagated uncertainties in

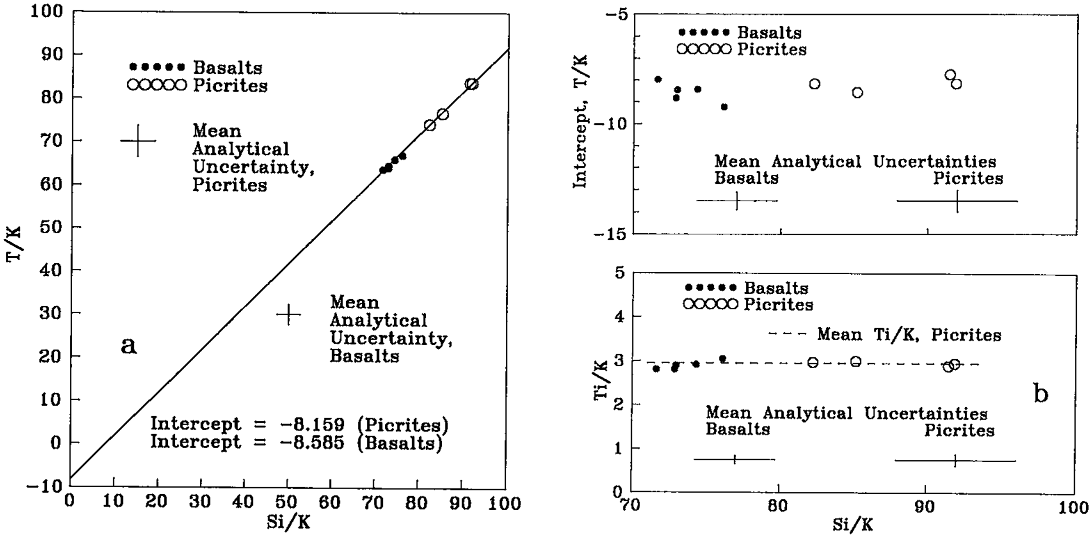

FIG. 2. a. Pearce element-ratio diagram [T diagram, T = 0.25 Al + 0.5 (Fe + Mg) + 1.5 Ca + 2.75 Na] for the 1968 Kilauea data that accounts for sorting of olivine, plagioclase and augite. The model line has a slope of one and is drawn through the mean intercept for the picrite data. b. T intercept and Ti/K plotted against Si/K for the 1968 Kilauea lava data. Both *Y*-axis variables can be criteria for distinguishing magma-batches.

the intercepts is computed (Nicholls 1990). 2) The square of the mean analytical uncertainty calculated in (1) is compared with the variance in the calculated values of the intercepts with an F-test. 3) The null hypothesis is accepted at the 95% confidence level.

T-DIAGRAMS AND INTERPRETATIONS

T/K diagrams

The results of the F-test applied to the T/K diagram intercepts for each suite of Kilauean lavas are listed in Table 1.

The chemical variations in the prehistoric Uwekahuna laccolith have been attributed to sorting of olivine alone (Murata & Richter 1961, Russell & Nicholls 1988). We expect the rocks of this small intrusive body to be part of a single magma-batch and do not expect it to be part of any magma-batch erupted between 1954 and 1971 because it is so much older. The data on the laccolith must be consistent with the "comagmatic" hypothesis and provide a standard of comparison for interpretion of the data from the historic suites. Our analysis is consistent with these statements because the null hypothesis is not rejected (Table 1). In addition, the mean intercept, -15.249, is different from any intercept derived from the data on the historic Kilauea suites (-6.868 to -9.490, Table 1), a clear chemical indicator that the Uwekahuna laccolith formed from a distinct magma-batch.

The compositions of rocks and glass separates from lavas of both the 1959 and 1960 eruptions were independently tested. The tests for consanguinity were performed on each of the four subsets (1959 rocks, 1959 glasses, 1960 rocks, 1960 glasses) and on the two combined sets of rock and glass data. In every instance, the tests failed to reveal differences greater than could be expected from analytical error (Table 1). Because the glasses and the rocks from which they were separated are unlikely to be from different magma-batches, these tests provide additional confidence that the procedures used are not prone to the spurious selection of multiple batches.

TABLE 1. COMPARATIVE STATISTICS ON INTERCEPTS ON T/K *vs* Si/K DIAGRAMS FOR THE ANALYSIS OF WITHIN-SUITE VARIANCE

YEAR	N	$F^{(N-1,\infty)}$	X	σ_D	σ_A	F_c	Result
UWE	5	2.37	-15.249	0.9912	1.2986	0.583	--
1954	2	3.84	- 7.679	0.0928	0.3787	0.060	--
1955	22	1.56	- 8.173	0.4632	0.2993	2.395	H_a
1959*	27	1.50	- 6.975	0.4117	0.4160	0.979	--
1959G	7	2.10	- 7.282	0.1527	0.3928	0.151	--
1959R	20	1.59	- 6.868	0.4125	0.4240	0.988	--
1960*	20	1.59	- 7.694	0.3114	0.3657	0.725	--
1960G	4	2.60	- 7.937	0.4159	0.3365	1.528	--
1960R	16	1.67	- 7.633	0.2617	0.3730	0.492	--
1961	8	2.01	- 8.009	0.2346	0.3792	0.383	--
1962	2	3.84	- 8.058	0.0453	0.3253	0.019	--
1963	8	2.01	- 8.000	0.4368	0.3682	1.407	--
1965A	3	3.00	- 8.055	0.2788	0.3884	0.515	--
1965M	10	1.88	- 8.331	0.6376	0.4017	2.519	H_a
1968*	9	1.94	- 8.391	0.4837	0.4551	1.130	--
1968P	4	2.37	- 8.159	0.3360	0.4961	0.459	--
1968B	5	2.37	- 8.585	0.4738	0.4140	1.310	--
1968O	4	2.60	- 8.569	0.5743	0.4102	1.960	--
1969	6	2.21	- 9.277	0.3918	0.4772	0.674	--
1970	39	1.40	- 9.490	1.336	0.5670	3.997	H_a

N = number of analyses; X, σ_D, σ_A are mean intercept, standard deviation of the data, and the estimated analytical uncertainty of the mean value, respectively. (*) indicates both rock and glass analyses included; G glass analyses only; R rock analyses only. (--) indicates failure to reject null hypothesis; H_a indicates rejection of null hypothesis because σ_D is significantly larger than σ_A.

The 1968 data are shown on Figure 2. On Figure 2a, the intercepts calculated for the picrites and the basalts are the same within analytical uncertainty. The F-test (Table 1) was applied to the picrite (1968P) and basalt (1968B) data separately, as well as to the whole data-set (1968*). In each case, the null hypothesis could not be rejected. In addition, the model line with a slope of one drawn through the mean intercept is consistent with each data point to within analytical uncertainty (For a discussion of error representations on Pearce element-ratio diagrams, see Nicholls 1990, p. 81–97, and Stanley 1990). Figure 2b compares the behavior of the T/K diagram intercepts and the ratio of conserved elements, Ti/K. The intercept shows no obvious systematic variation, whereas there may be some systematic variation in Ti/K because the ratios decrease with Si/K. The variation is, however, too small to be significant. We conclude that the T/K diagram represents the stoichiometry of the mass-transfer process and that both the intercept and Ti/K ratio are consistent with the presence of a single magma-batch.

Only three suites did not pass the T/K diagram test for consanguinity. These are the 1955, 1965M and 1970 eruptive products. The computed intercepts for the 1965M data (Makaopuhi crater) vary more than can be accounted for by sorting of olivine, plagioclase, and augite (Table 1). The largest contributor to the dispersion is one composition of a glassy skin (M1–1G) that has an anomalous value for K_2O (0.49) compared to the range (0.53–0.60) in the associated rocks.

The variability in the 1955 suite is illustrated on Figure 3. The straight-line model through the mean intercept is consistent with the data. However, the mean analytical uncertainty for the intercept (Fig. 3b) is significantly smaller than the actual range of calculated intercepts. Hence the null hypothesis is rejected, which implies the presence of more than one magma-batch or factors in the stoichiometry unexplained by a T diagram. In addition, the variability in Ti/K is greater than can be accounted for by analytical uncertainty (Fig. 3b), which suggests that one or both of Ti and K are not conserved in this suite. If true, the ratios for the

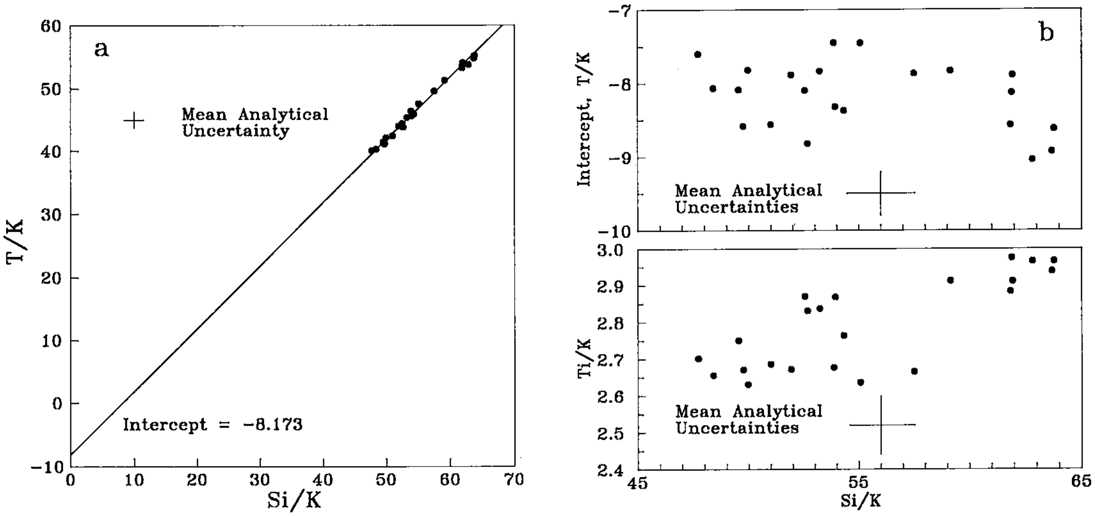

FIG. 3. a. T diagram for the 1955 Kilauea lavas [T = 0.25 Al + 0.5 (Fe + Mg) + 1.5 Ca + 2.75 Na]. Model line with a slope of one is drawn through the mean intercept value. b. T intercept and Ti/K for the 1955 Kilauea data plotted against Si/K.

T/K diagram do not adequately describe the stoichiometry of the processes that affected this suite. Microphenocrysts of Fe–Ti oxides are reported in these lavas (Murata & Richter 1966, Anderson & Wright 1972, Ho & Garcia 1988) and may explain the variability in Ti/K and in the intercepts on the T/K diagram. Consequently, the 1955 lavas may not be samples from multiple magma-batches. This conclusion requires further testing and consideration of sorting of Fe–Ti oxides (see below).

The 1970 suite comprises samples erupted from Mauna Ulu between 1969 and 1971 (Wright *et al.* 1975). The Mauna Ulu products have previously been interpreted as the result of magma-mixing processes (Wright *et al.* 1975, Wright & Tilling 1980, Halleran & Russell 1990) or fractionation of olivine and chromiferous spinel within a single magma-batch or series of identical magmas (Hofmann *et al.* 1984). Our results suggest that this suite consists of more than one magma-batch even after an account of possible sorting of oxides (see below p. xx). The effects of mixing magma-batches on the dispersion of the data are revealed by comparing the T/K diagrams for the 1955 (Fig. 2a) or 1968 (Fig. 3a) sequences of eruption against the equivalent T/K diagram for the Mauna Ulu lavas in Russell & Stanley (1990, Fig. 11).

T/P diagrams

The "comagmatic" hypothesis can be further tested with a different conserved element in the denominator of a T diagram (*e.g.*, P or Ti). If the element in the denominator is not conserved, then the intercepts tend toward zero, and we gain information about sorting of additional phases (*e.g.*, apatite or oxides).

Table 2 summarizes the statistics used to evaluate the cogenetic hypothesis using the intercepts on a T/P diagram. If each denominator constituent (K, P, or Ti) were conserved throughout differentiation and could be measured with the same relative precision, then the results of each set of tests for multiple magma-batches would be identical. The

TABLE 2. COMPARATIVE STATISTICS ON INTERCEPTS ON T/P *vs* Si/P DIAGRAMS FOR THE ANALYSIS OF WITHIN-SUITE VARIANCE

YEAR	N	$F^{(N-1,\infty)}$	X	σ_D	σ_A	F_c	Result
UWE	5	2.37	-40.61	2.610	8.540	0.093	--
1954	2	3.84	-23.574	0.307	2.739	0.013	--
1955	22	1.56	-23.981	1.698	2.047	0.688	--
1959*	27	1.50	-21.30	1.136	2.855	0.158	--
1959G	7	2.10	-21.89	0.792	2.673	0.088	--
1959R	20	1.59	-21.10	1.181	2.918	0.164	--
1960*	20	1.59	-21.62	1.449	2.232	0.649	--
1960G	4	2.60	-23.33	0.548	2.276	0.058	--
1960R	16	1.67	-21.20	1.276	2.221	0.330	--
1961	8	2.01	-24.87	1.809	2.850	0.403	--
1962	2	3.84	-23.76	0.032	2.218	0.000	--
1963	8	2.01	-24.79	2.124	2.763	0.591	--
1965A	3	3.00	-24.43	0.953	2.792	0.341	--
1965M	10	1.88	-24.80	0.854	2.814	0.092	--
1968*	9	1.94	-25.23	2.239	3.247	0.475	--
1968P	4	2.60	-23.84	2.099	3.337	0.396	--
1968B	5	2.37	-26.68	1.283	3.193	0.161	--
1968O	4	2.60	-25.88	0.842	2.981	0.080	--
1969	6	2.21	-26.39	0.728	3.172	0.230	--
1970	39	1.40	-26.81	2.732	3.743	0.730	--

N = number of analyses; X, σ_D, σ_A are mean intercept, standard deviation of the data, and the estimated analytical uncertainty of the mean value, respectively. (*) indicates both rock and glass analyses included; G glass analyses only; R rock analyses only. (--) indicates failure to reject null hypothesis; H_a indicates rejection of null hypothesis because σ_D is significantly larger than σ_A.

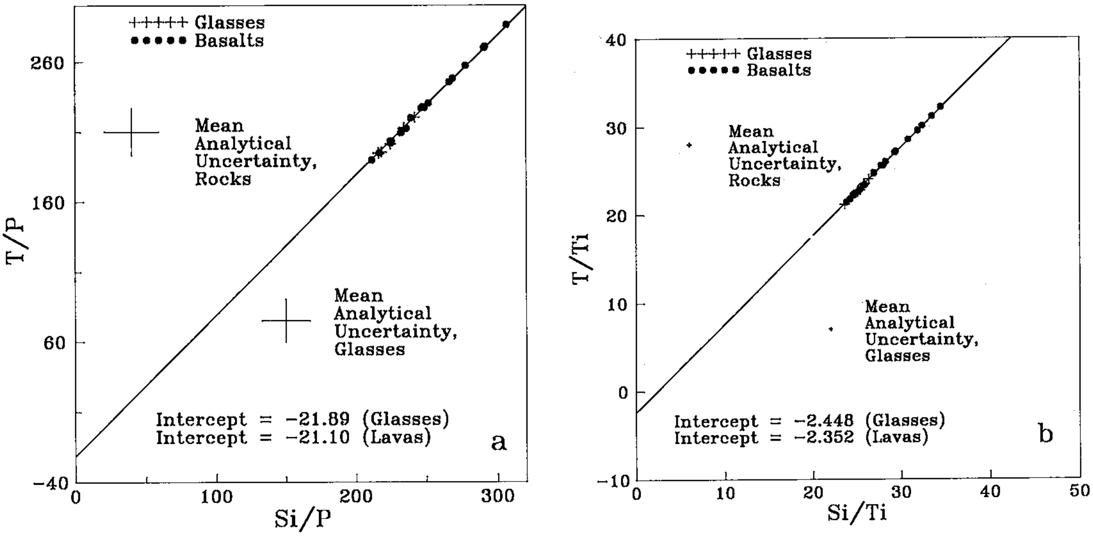

FIG. 4. a. T diagram [T = 0.25 Al + 0.5 (Fe + Mg) + 1.5 Ca + 2.75 Na] with P as denominator for the 1959 Kilauea Iki data. The model line has a slope of one and is drawn through the mean intercept. b. The same data as in Figure 4a, plotted on a T diagram with Ti as denominator. The mean analytical uncertainty associated with the data is smaller than in 4a because of the relatively greater analytical precision associated with the determination of TiO_2.

analytical precision with which Ti, K and P are measured controls the ability to discriminate.

The data, plotted on a T/P *versus* Si/P diagram, are consistent with the hypothesis that each suite represents a single magma-batch (Table 2). The differences between Table 1 and Table 2 reflect the greater analytical uncertainty associated with P compared to K. An example containing data for both rocks and glasses is shown on Figure 4a. Notice that the model line is consistent with every data point to within a very small fraction of the estimated analytical uncertainty. This suggests that the quoted uncertainty in P_2O_5 is too large. In the results of 27 wet-chemical analyses, there should be some points further from the model line if the analytical uncertainty is as large as commonly cited (Wright & Fiske 1971, Carmichael *et al.* 1968). Whereas excessive caution in estimating analytical uncertainties is considered, by conventional wisdom, to be a reasonable action, Meyer (1974, p. 294) presented a different opinion: "It is important in reporting results of an investigation to specify exactly what the results are. It is reprehensible to understate the precision of an estimate as well as to overstate it."

The direct result of *understating* the precision of a measurement is a loss in discriminatory power. Diagrams with P in the denominator have very little power for the discrimination of magma-batches within a set of analytical results, given the cited uncertainty.

T/Ti diagrams

The results of the F-tests, with Ti in the denominator, are listed in Table 3. More suites have T/Ti intercepts with variations greater than expected from analytical uncertainty compared to the results for the T/P and T/K intercepts. These suites are: 1955, 1960*, 1960G, 1963, 1965M, 1968*, and 1970. If the variability is due only to sorting of

TABLE 3. COMPARATIVE STATISTICS ON INTERCEPTS ON T/Ti *vs* Si/Ti DIAGRAMS FOR THE ANALYSIS OF WITHIN-SUITE VARIANCE

YEAR	N	$F^{(N-1,\infty)}$	X	σ_D	σ_A	F_c	Result
UWE	5	2.37	-3.733	0.1829	0.1389	1.734	--
1954	2	3.84	-2.652	0.0766	0.0903	0.720	--
1955	22	1.56	-2.927	0.1489	0.0716	4.325	H_a
1959*	27	1.50	-2.377	0.1201	0.1024	1.376	--
1959G	7	2.10	-2.448	0.0968	0.0934	1.074	--
1959R	20	1.59	-2.352	0.1196	0.1056	1.283	--
1960*	20	1.59	-2.606	0.1282	0.0853	2.264	H_a
1960G	4	2.60	-2.729	0.1317	0.0787	2.800	H_a
1960R	16	1.67	-2.575	0.1107	0.0869	1.623	--
1961	8	2.01	-2.662	0.0747	0.0851	0.771	--
1962	2	3.84	-2.821	0.0449	0.0768	0.342	--
1963	8	2.01	-2.819	0.1651	0.0878	3.536	H_a
1965A	3	3.00	-2.858	0.0819	0.0931	0.774	--
1965M	10	1.88	-2.837	0.1563	0.0904	2.989	H_a
1968*	9	1.94	-2.874	0.1544	0.1029	2.251	H_a
1968P	4	2.60	-2.763	0.0725	0.1126	0.415	--
1968B	5	2.37	-2.966	0.1220	0.0932	1.714	--
1968O	4	2.60	-2.887	0.1165	0.0899	1.679	--
1969	6	2.21	-2.958	0.0484	0.0945	0.262	--
1970	39	1.40	-2.956	0.2822	0.1078	6.853	H_a

N = number of analyses; X, σ_D, σ_A are mean intercept, standard deviation of the data, and the estimated analytical uncertainty of the mean value, respectively. (*) indicates both rock and glass analyses included; G glass analyses only; R rock analyses only. (--) indicates failure to reject null hypothesis; H_a indicates rejection of null hypothesis because σ_D is significantly larger than σ_A.

olivine, plagioclase, and augite and if Ti is a conserved element, then we reject the null hypothesis. An alternative explanation is sorting of oxides in conjunction with sorting of the silicate minerals, in which case a T/Ti diagram will not fully represent the stoichiometry of the processes causing the variability. In addition, the sensitivity is further increased because analytical measurements of Ti can be made with greater relative precision (*cf.* size of analytical uncertainty on Fig. 4a with Fig. 4b). For example, the 1959 data, both rocks and glasses, are consistent with the model line to within analytical uncertainty (Fig. 4b), even though the analytical uncertainty on the T/Ti diagram is much smaller than that for the T/P diagram.

Q DIAGRAMS AND INTERPRETATION

Before the variability in the intercept can be attributed to different magma-batches, we need to determine whether oxide sorting can account for the residual variability beyond analytical uncertainty.

The function pair

$Q = [1.36(Si + Ti) - 0.09\ Al + 0.82\ Fe - 0.18\ Mg - 0.55\ Ca]/K$

and

$[Si + Ti + Fe + Na]/K$

exactly accounts for sorting of olivine, augite, plagioclase and the Fe_2TiO_4 component in the oxides, in any combination. The other Fe–Ti oxide components (Fe_2O_3, $FeTiO_3$, Fe_3O_4) would cause small deviations from the model slope of one (Stout *et al.* 1989, Nicholls 1990, Fig. 11).

Because the stoichiometry of the combined sorting of oxides and silicates is not represented by a single line with these ratios, we can expect greater dispersion of the data than if the ratios exactly represented the stoichiometry. If, in spite of the opportunity for greater dispersion in the intercepts derived from the data, the variability on a Q/K *versus* [Si+Ti+Fe+Na]/K diagram remains smaller than can be attributed to analytical uncertainty, then there is even less justification for a suggestion that the data come from more than one magma-batch.

TABLE 4. COMPARATIVE STATISTICS ON INTERCEPTS ON Q/K *vs* Si/K DIAGRAMS FOR THE ANALYSIS OF WITHIN-SUITE VARIANCE

YEAR	N	$F^{(N-1,\infty)}$	X	σ_D	σ_A	F_c	Result
1954	2	3.84	3.843	0.077	0.239	0.103	--
1955	22	1.56	3.986	0.195	0.184	1.123	--
1959*	27	1.50	3.601	0.180	0.270	0.444	--
1959G	7	2.10	3.728	0.055	0.252	0.048	--
1959R	20	1.59	3.557	0.188	0.276	0.464	--
1960*	20	1.59	3.870	0.118	0.231	0.261	--
1960G	4	2.60	3.941	0.157	0.210	0.559	--
1960R	16	1.67	3.852	0.105	0.236	0.198	--
1961	8	2.01	4.004	0.093	0.237	0.155	--
1962	2	3.84	3.967	0.006	0.202	0.001	--
1963	8	2.01	3.939	0.162	0.229	0.500	--
1965A	3	3.00	3.951	0.119	0.241	0.246	--
1965M	10	1.88	4.094	0.255	0.247	1.066	--
1968*	9	1.94	4.112	0.179	0.277	0.418	--
1968P	4	2.60	4.038	0.139	0.307	0.204	--
1968B	5	2.37	4.171	0.199	0.252	0.622	--
1968O	4	2.60	4.192	0.237	0.250	0.895	--
1969	6	2.21	4.573	0.052	0.291	0.032	--
1970	39	1.40	4.613	0.443	0.337	1.728	H_a

N = number of analyses; X, σ_D, σ_A are mean intercept, standard deviation of the data, and the estimated analytical uncertainty of the mean value, respectively. (*) indicates both rock and glass analyses included; G glass analyses only; R rock analyses only. (--) indicates failure to reject null hypothesis; H_a indicates rejection of null hypothesis because σ_D is significantly larger than σ_A.

The results of the tests with the Q index are shown in Table 4. In every instance, except for the 1970 suite, the data are consistent with the hypothesis that the within-suite variability is due to sorting of silicate and oxide phases. These tests corroborate the suggestion that the indicated suites on Table 3, which failed to pass the test for uniformity, did undergo some sorting of oxides. Therefore, the results of the most comprehensive test of suite uniformity, Q/K *versus* [Si + Ti + Fe + Na]/K, are consistent with the hypothesis that each suite is from a single magma-batch with the exception of the suite from the 1970 (1969–1971) Mauna Ulu eruptions. This suite is polygenetic (Wright *et al.* 1975, Wright & Tilling 1980, Halleran & Russell 1990).

INTER-SUITE VARIABILITY

Figure 5 shows the mean values for the intercepts on both Q/K and T/K diagrams and the P/K ratio for each suite as a function of eruption date. The estimate of variability shown on this diagram is derived from the variance in the data, not the dispersion expected from analytical uncertainty. The vertical bars plotted for each suite in Figure 5 represent the standard deviations of the means of the parameters. Justification for the change comes from the fact that, within each suite, the variance in the intercepts on the Q/K diagrams was less than expected from analytical measurement, except for the Mauna Ulu data. This approach obviates the problem of whether the cited values of analytical uncertainty on the denominator constituents are too large (*e.g.*, for P) but obviously will not compensate for round-off error in the original data, an error possibly introduced because of the use of too large an estimate of analytical uncertainty.

Figure 5 provides a graphical summary of the differences within the suites in terms of parameters that test for consanguinity. For each pair of data sets (*e.g.*, 1968P and 1968B), we wish to test the null hypothesis: *The lavas of one suite could be derived from the same magma-batch as were the samples from the other suite.* The hypothesis is

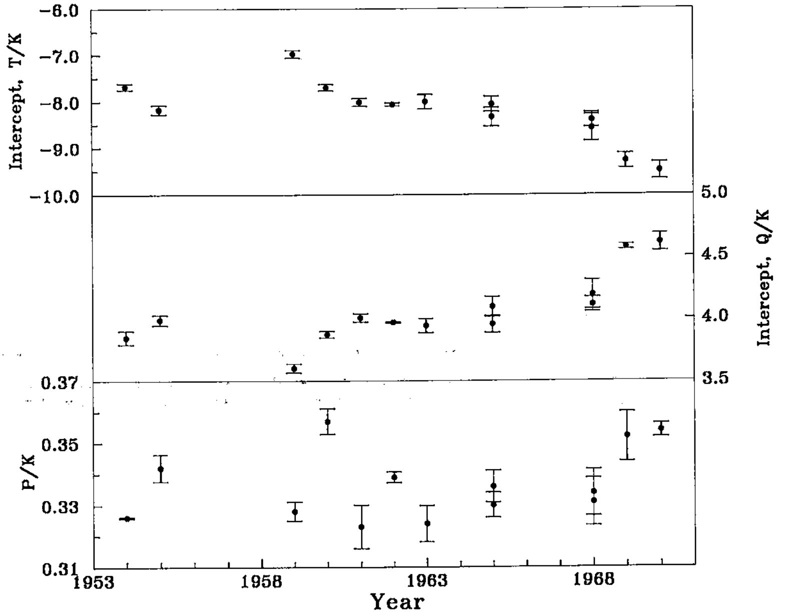

FIG. 5. Mean values of T intercept, Q intercept, and P/K values are plotted for each suite of Kilauea lavas against year of eruption. The vertical bars are ± one standard deviation of the means. Each parameter can be used as a criterion for distinguishing different magma-batches; the precision and reliability of each parameter are discussed in the text.

tested by comparing the means of the parameters using the Student's t-test to evaluate the significance of the differences. The results of the Student's t-test, applied to the T/K, Q/K, and P/K chemical parameters, are listed in Tables 5A, 5B, and 5C. These tables report the results of the Student's t-test on the means of the indicators at a tolerance level of 0.05.

The Q/K intercept is the favored discriminator because it provides the most complete description of the differentiation process, and K is more precisely measured than P and better conserved than Ti. Consequently, we rely on the results obtained for the Q/K intercept to evaluate the minimum number of magma-batches. Table 5B lists the inter-suite magmatic relations. The intersections of rows and columns contain the results of the Student's t-test. The results for the P/K index and the T/K-intercept (Tables 5A, 5C) are used to make additional inferences, but they do not discriminate magma-batches as reliably. For example, Russell & Stanley (1990) could not distinguish between the 1959 and 1954–1955 lavas with P/K ratios, and demonstrated that low analytical precision reduces discriminatory power and affects the conclusions one can draw.

CONCLUSIONS

F-tests of analytical uncertainty and chemical variability suggest that only the Mauna Ulu (1969–1971) data set contains samples that may come from more than one magma-batch. Conversely, there is no evidence, based on the major- and minor-element abundances, that any of the other data sets from Kilauea comprise samples from more than one magma-batch.

The Student's t-test of equality of means, applied to the chemical parameters, indicates a minimum of four magma-batches in the 1954–1970 Kilauea lavas. In summary, these are: the two or more batches in the 1969–1971 Mauna Ulu lavas, the 1959 Kilauea Iki lavas, and the 1954–1968 eruptive sequences, excluding Kilauea Iki.

There are the following inconsistencies in these designations: 1) Although the 1954 suite (2 samples) is not significantly different from most suites erupted in the years 1955–1968, it is distinct from the 1965M (see p. 990) and 1968* suites. The 1954 lavas are not significantly different from the 1959 lavas in Q/K intercept nor in P/K (see Table 5B, 5C). 2) The 1962 suite (2 samples) is different from the 1968* suite, but otherwise the suites erupted in

TABLE 5A. RESULTS OF STUDENT'S t-TESTS FOR EQUALITY OF MEANS OF INTERCEPTS ON T/K DIAGRAMS

Year:	1954	1955	1959*	1960G	1961	1962	1963	1965A	1965M	1968*	1968O	1969	1970
1954	--	H_a	H_a	--	H_a	--	--	--	H_a	H_a	--	H_a	H_a
1955	H_a	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1959*	H_a	H_a	--	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a
1960G	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1961	H_a	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1962	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1963	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1965A	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1965M	H_a	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1968*	H_a	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1968O	--	--	H_a	--	--	--	--	--	--	--	--	--	H_a
1969	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	--	--	--
1970	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	--	--

Each suite is compared with every other suite separately. The null hypothesis is that the means are equal. (--) indicates failure to reject the null hypothesis; H_a indicates rejection at the 95 % confidence level or above and that there is a significant difference in the mean intercepts.

TABLE 5B. RESULTS OF STUDENT'S t-TESTS FOR EQUALITY OF MEANS OF INTERCEPTS ON Q/K DIAGRAMS

Year:	1954	1955	1959*	1960G	1961	1962	1963	1965A	1965M	1968*	1968O	1969	1970
1954	--	--	--	--	--	--	--	--	H_a	H_a	--	H_a	H_a
1955	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1959*	--	H_a	--	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a
1960G	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1961	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1962	--	--	H_a	--	--	--	--	--	--	H_a	--	H_a	H_a
1963	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1965A	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1965M	H_a	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1968*	H_a	--	H_a	--	--	H_a	--	--	--	--	--	H_a	H_a
1968O	--	--	H_a	--	--	--	--	--	--	--	--	H_a	H_a
1969	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	--	--
1970	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	H_a	--	--

Each suite is compared with every other suite separately. The null hypothesis is that the means are equal. (--) indicates failure to reject the null hypothesis; H_a indicates rejection at the 95 % confidence level or above and that there is a significant difference in the mean intercepts.

TABLE 5C. RESULTS OF STUDENT'S t-TESTS FOR EQUALITY OF MEAN P/K VALUES

Year:	1954	1955	1959*	1960G	1961	1962	1963	1965A	1965M	1968*	1968O	1969	1970
1954	--	H_a	--	--	--	--	--	--	--	--	--	H_a	H_a
1955	H_a	--	H_a	--	H_a	--	H_a	--	--	--	--	--	H_a
1959*	--	H_a	--	--	--	H_a	--	--	--	--	--	H_a	H_a
1960G	--	--	--	--	--	--	--	--	--	--	--	--	--
1961	--	H_a	--	--	--	--	--	--	--	--	--	H_a	H_a
1962	--	--	H_a	--	--	--	H_a	--	--	--	--	--	H_a
1963	--	H_a	--	--	--	H_a	--	--	--	--	--	H_a	H_a
1965A	--	--	--	--	--	--	--	--	--	--	--	H_a	H_a
1965M	--	--	--	--	--	--	--	--	--	--	--	--	H_a
1968*	--	--	--	--	--	--	--	--	--	--	--	--	H_a
1968O	--	--	--	--	--	--	--	--	--	--	--	--	--
1969	H_a	--	H_a	--	H_a	--	H_a	H_a	--	--	--	--	--
1970	H_a	H_a	H_a	--	H_a	H_a	H_a	H_a	H_a	H_a	--	--	--

Each suite is compared with every other suite separately. The null hypothesis is that the means are equal. (--) indicates failure to reject the null hypothesis; H_a indicates rejection at the 95 % confidence level or above and that there is a significant difference in the mean intercepts.

1955 and between 1960 and 1968 are indistinguishable.

These inconsistencies may be the result of the small sample-sizes or they may be clues that there are other, slightly different magma-batches in these suites. We would rather err by missing magma-batches than err by suggesting batches where there are none, a subjective decision. Consequently, these inconsistencies are not considered sufficient evidence for attributing the 1954 lavas to a separate magma-batch.

The 1969 and the Mauna Ulu lavas (1969–1971) are chemically distinguishable from all other earlier historic Kilauea lavas but are indistinguishable from each other on the Q/K-intercept diagram (Fig. 5, Table 5B), in T/K intercepts (Table 5A), and in P/K values (Table 5C). The Mauna Ulu data set, however, failed the F-test of variance, which implies that the lavas had not sampled a single magma-batch. Further work, using available trace-element data, shows the Mauna Ulu lavas to be mixtures of at least two magma-batches (Halleran & Russell 1990), an example of external processes of mixing. Helz (1990) cited textural features as evidence that mixing was a frequent and pervasive process of differentiation in the production of the 1955, 1959 and 1960 Kilauea lavas. The chemical data analyzed in this study indicate that any magma mixing, other than that between the Mauna Ulu batches, would have to be internal mixing between parts of single batches or involve amounts undetectable with current data and techniques.

The 1954 lavas may be part of a 1954–1968 magma-batch or, because of their place in the history of the eruptions, a separate magma-batch. We cannot chemically distinguish another magma-batch with the parameters used. The 1954 lavas and the 1960–1968 lavas have similar mean Q/K intercepts, T/K intercepts and P/K values, but have at least one parameter different from the mean value for the 1959 Kilauea Iki lavas. If the 1954 and the 1960–1968 lavas are from the same magma-batch, then the Kilauea Iki lavas are part of a separate batch that was in the volcanic edifice at the same time. On the other hand, the 1954, the 1959 and the 1960–1968 lavas could originate from at least three different batches. Currently available data are not sufficient to distinguish among these possibilities.

There appears to be a general and gradual increase in Q/K intercept values between 1960 and 1969 (Fig. 5), which suggests a progressive change in this index with time. The magnitude of the change, compared to the variation in the data, however, is insignificant.

Interpretations of the seismic data (Ryan *et al.* 1981, Ryan 1987a, b, Klein *et al.* 1987) suggest several paths of magma transport beneath Kilauea. If more than one transport path can be occupied at a time (see the interpretation by Ryan *et al.* 1981), then the possibility exists that the 1959 Kilauea Iki batch occupied one transport path while other paths contained the 1954–1968 batch. The eruption sequence and vent locations combined with the differentiation path inferred for the 1968 Halemaumau and Hiiaka craters suite (Nicholls & Stout 1988) require more than one transport path. If the 1954–1955 and 1960–1968 suites are all from the same magma-batch, then the plumbing system beneath Kilauea may be more complex in time and space than previously suggested. One batch may follow multiple paths (*e.g.*, 1968), and others may follow a unique path (*e.g.*, 1959).

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TABLE A1. SOURCES OF DATA FOR KILAUEA LAVAS

ERUPTION LABEL	NO.	SAMPLED (D/M/Y)	LOCATION	ANALYSIS TYPE	SOURCE
UWE	5	-----	HM	1	Murata & Richter (1961)
1954	2	31/05/54	HM	1	MacDonald & Eaton (1957) Wright (1971)
1955	22	28/02/55 25/05/55	ERZ	1	MacDonald & Eaton (1964) Wright & Fiske (1971)
1959*	27	14/11/59	KI	1 (20)	Murata & Richter (1966)
1959G	(7)	20/12/59		2 (7)	Wright (1973)
1959R	(20)			3 (3)	
1960*	20	13/01/60	ERZ	1 (16)	Murata & Richter (1966)
1960G	(4)	18/02/60	(Kapuha)	2 (4)	
1960R	(16)			3 (1)	
1961	8	24/02/61 23/09/61	HM & ERZ (Napau)	1	Richter *et al.* (1964)
1962	2	07/12/62	ERZ	1	Fiske & Koyanagi (1968) Moore & Koyanagi (1969)
1963	8	15/08/63 06/10/63	ERZ (Alae and Napau)	1	Moore & Koyanagi (1969)
1965A	3	24/12/65 25/12/65	ERZ (Aloi)	1	Fiske & Koyanagi (1968)
1965M	10	05/03/65 15/03/65	ERZ (Makaopuhi)	1	Wright *et al.* (1968)
1968*	9	05/11/67	HM & ERZ	1	Wright (1971)
1968P	(4)	25/08/68	(Hiiaka)		Jackson *et al.* (1975)
1968B	(5)				
1968O	4	07/10/68 22/10/68	ERZ	1	Jackson *et al.* (1975)
1969	6	22/02/69 26/02/69	ERZ (Aloi to Alae)	1	Swanson *et al.* (1976)
1970	39	24/05/69 19/04/71	ERZ (Mauna Ulu)	1	Wright *et al.* (1975)

HM-Halemaumau, KI-Kilauea Iki, ERZ-East Rift Zone. Analysis type: 1, 2, 3 denotes wet-chemical analysis of rocks, wet-chemical analysis of glass separates and XRF analyses, respectively.