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CORRELATION OF INDONESIAN ACTIVE VOLCANIC GEOCHEMISTRY WITH BENIOFF ZONE DEPTH

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SUMMARY

The active volcanic arc of Indonesia extends almost continuously over 6000 km from north Sumatra to the Molucca Sea. Chemical analyses of 196 rocks from 33 volcanoes have been processed to give molecular norms and multiple linear correlation analyses between various chemical parameters and silicon content or differentiation index (D.I.) and vertical depth of the underlying Benioff Zone, which ranges from 140 to 300 km.

The great majority of the volcanic products is of augite-hypersthene andesite or basalt, sometimes with olivine and hornblende, and occasionally with biotite, quartz and tridymite. Leucite occurs in volcanoes overlying the deepest seismic contours. Most rocks are quartz-normative, but many are olivine- and even nepheline-normative where the volcanoes overlie the greatest seismic depths.

Significant relationships exist between each of potassium %, alkalis % and the ratio of potassium to alkalis and both silicon content (or D.I.) and depth to the underlying Benioff Zone. The relationship with silicon or D.I. is petrologically controlled and the relationship with Benioff Zone depth may suggest that the magmas are produced at and rise from the Benioff Zone and that some of the chemical variation is controlled by the depth of magma production. However the best correlation obtained cannot explain more than 50 to 60% of the chemical variation in terms of depth of magma production. Future refinement of the measurement of the seismic contours and improvement of the chemical analyses may lead to a closer correlation, but on the basis of the present data it is necessary to conclude that, in addition to seismic depth, other unknown factors play an important role in controlling the chemical variation of the volcanic rocks.

INTRODUCTION

The Indonesian volcanic arc, extending over more than 6000 km from north Sumatra through Java and the Banda Arc to the Moluccas (fig. 1), is the most spectacular element of a consuming plate juncture. The systematic compilation of chemical analyses of all the active volcanoes of this region (Neumann van Padang, 1951) has prompted several studies of certain aspects of the nature of the volcanism. The first was by Rittman (1953) who generally concluded that "In any given cross-section through the Indonesian orogenic belt the calc-alkaline character of the magmas of the active volcanoes decreases regularly in the direction from the foredeep to the hinterland, becoming alkaline in the hinterland itself." He also made the important additional observation that "At single volcanoes the calc-alkaline character decreases with time."

Some time later, Kuno (1966) restated the same observations after plotting the same analyses on a $Na_2O + K_2O$ versus SiO_2 weight percent diagram. He noted that most volcanic products from the main parts of Sumatra, Java, Bali, Flores and Halmahera are of the high alumina series, whereas those of the hinterland along the northern coasts of Java, Flores and the Celebes are of the alkali series. This difference he proposed is related to an increasing depth of magma generation with increasing distance from the ocean inward into the continent.

Hatherton and Dickinson (1969) related the potassium content of a volcano, at a specific value of silica on a variation diagram, with depth to the inclined underlying Benioff Seismic Zone. From this significant paper arose the "correlation" of increasing potassium content of andesites with depth to the Benioff Zone. Numerous authors have accepted this "correlation" and have been brave enough to apply it to paleo-tectonic situations. The most notable of these attempts is perhaps that of Lipman et al. (1971) who inferred a complex geometry for the paleo Benioff Zone under western North America solely on the chemistry of the igneous rocks. Clearly this is jumping too far. It is implying a law of actualism before one has actually fully studied and agreed upon the model of a presently active volcanic arc. Hence it is not surprising that some authors have called for caution; notably Nielson and Stoiber (1973), who after a detailed statistical analysis of the Indonesian and other regions, concluded as follows: "if the potassium content is determined by the depth at which melting occurs, then some other factor or group of factors sufficiently alters the potassium content to render it of doubtful use as a quantitative indicator of the depth of origin of the lava."

Since there is controversy as to how closely the depth to the Benioff Zone controls the composition of a magma, and whether this magma is significantly altered on its upward migration, it is important to look very carefully at the data on all active volcanic arcs before applying "laws", which may

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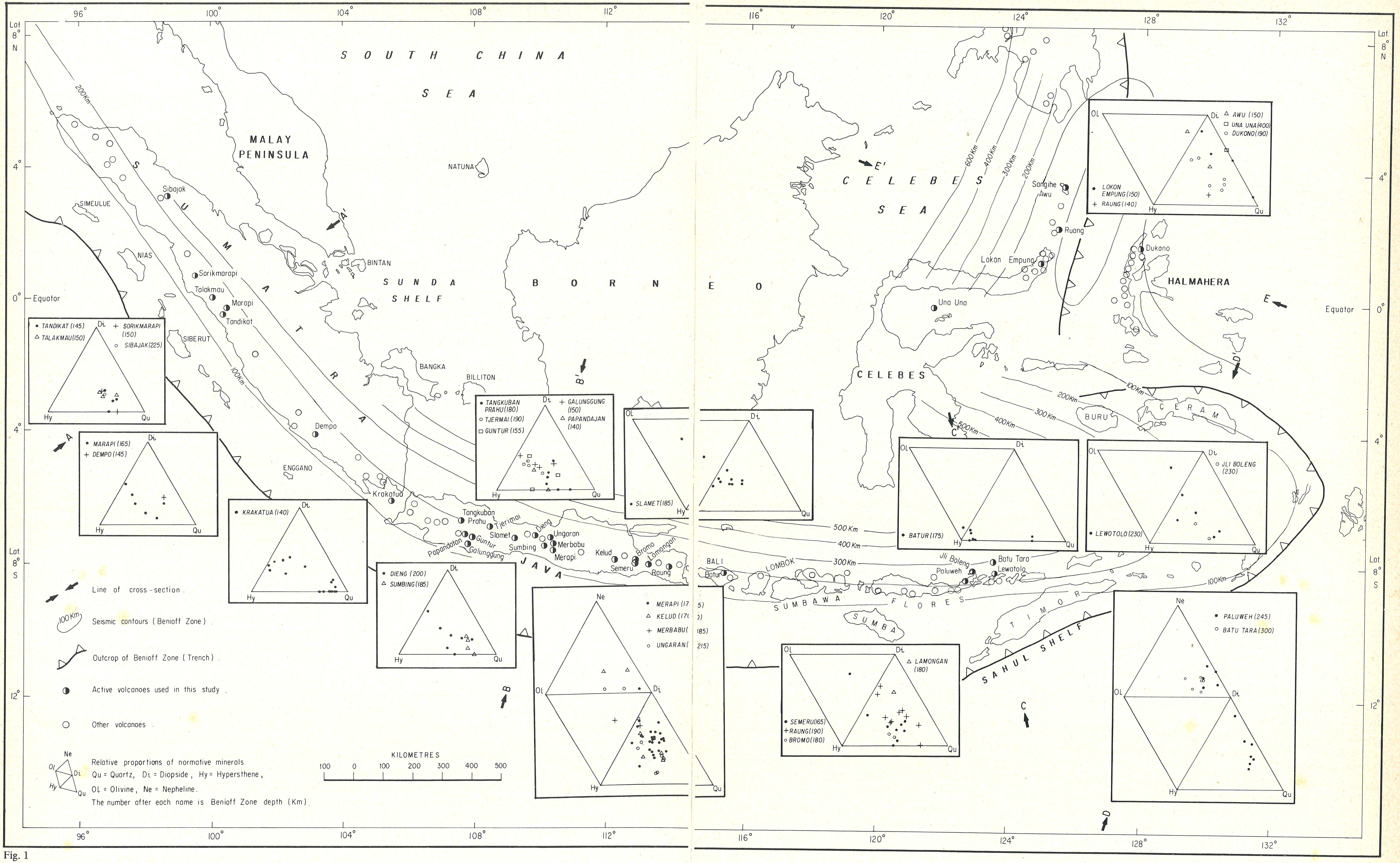

Fig. 1
Outline map of the Indonesian region showing the positions of the active volcanoes. The seismic contours are taken from Fitch and Molnar (1970) and Hatherton and Dickinson (1969). The relative proportions of normative minerals are from computer norms of all rocks included in Neumann van Padang (1951) and Hadikusumo (1961).

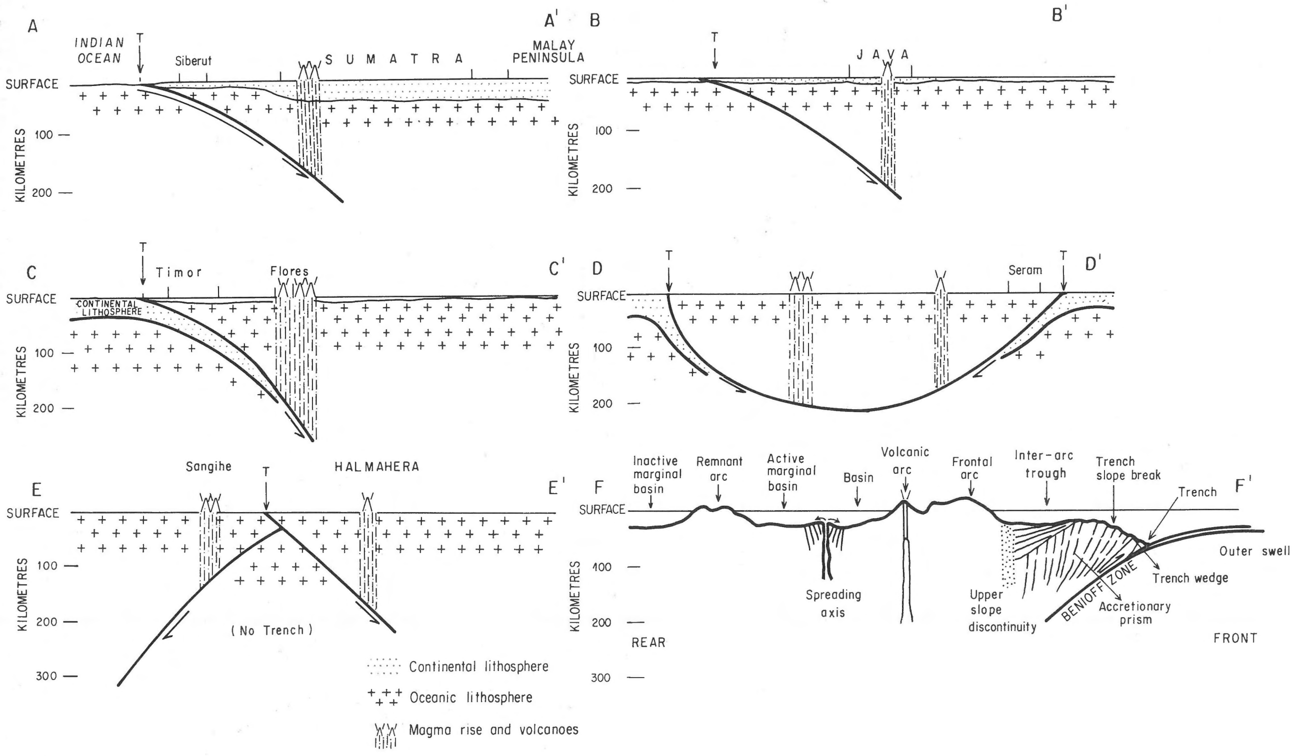

Fig. 2
Diagrammatic cross sections through the destructive plate juncture of the Indonesian region, showing the position of the volcanic arc in relation to the plate juncture and the geometry of the Benioff Zone.

have been carelessly formulated, to paleo-tectonic situations. This paper is an attempt to analyse statistically, without the eye of faith, the available data on the Indonesian region, and to ascertain the level of significance and degree of correlation which might exist between chemical variability and seismic depths, so that we might obtain a glimpse of the actualistic volcanic arc model.

PETROLOGY OF THE VOLCANOES

An initial subdivision of the region was made on the basis of fundamental differences in the nature of the plate junctures. The following sub-regions are considered separately for the reasons given:

1. Sumatra: Oceanic crust of the Indian Ocean is subducting under a well established continental crust of Paleozoic and Mesozoic age.
2. Java (from Krakatau to Bali): Oceanic crust of the Indian Ocean is subducting under predominantly oceanic crust which is overlain by only a thin veneer of continental clastic sediments of predominantly Cenozoic age.
3. Flores (Lesser Sunda Islands): Continental Australia is subducting underneath, or at least pressing against predominantly oceanic crust. This pattern continues also to include the Banda Arc.
4. Moluccas: A complicated region with oceanic crust subducting in two opposing directions under oceanic crust with two parallel active volcanic arcs on both Sangihe and Halmahera.

The active volcanoes are shown on figure 1 and the essential tectonic differences, as outlined above for the different sub-regions, are illustrated diagrammatically on figure 2.

Summary descriptions of the petrology and depths to the Benioff Zone of the active volcanoes for which chemical data exist are given in table 1. Unless otherwise specified, most data are from Neumann van Padang (1951). Many of these analyses are old and probably not of great accuracy. This is the biggest source of uncertainty in the present correlation analysis. Nine newer analyses from Hadikusumo (1961) have been added (table 1). The depth of the Benioff Zone is estimated from seismic contours given by Hatherton and Dickinson (1969) and Fitch and Molnar (1970) as shown in figure 1, and these are also a source of uncertainty, for significant differences exist between the two references. It is seen that the volcanism is predominantly andesitic to basaltic. The most common rock type is an augite-hypersthene andesite. Some rocks contain biotite, quartz or tridymite, and more contain olivine. A few are alkaline and contain leucite.

At the beginning of this study it was decided not to set any arbitrarily chosen and artificial limits on the chemical definition of the rocks because a plot of the complete chemical data of the whole region (fig. 3) does not appear to depart from a normal distribution with mode in the andesitic composition. The artificial restrictions of Neilson and Stoiber (1973) of rocks between SiO_2 52 and 63 weight percent were therefore not followed, and all published analyses have been included in this study. Likewise the procedure of Hatherton and Dickinson (1969) of excluding all ashes and rocks with more than 2% water was discarded as being too arbitrary. It is known that hydrated glasses tend to undergo alkali exchange, but most of the Indonesian andesites have a glassy matrix, so that possible alkali exchange of unknown amount is another important element of uncertainty.

Procedure

All rock analyses were recalculated to water-free cationic percentages and the Niggli molecular norms computed by the programme of Hutchison and Jeacocke (1971). From the computed norms the differentiation index (D.I.) was calculated as the total of the salic minerals less anorthite after the method of Thornton and Tuttle (1960). This allowed the subsequent comparison of chemical variation of the rock suites not only with the silica content but also with D.I., which is considered to be a more useful petrological parameter than silica alone. The relative proportions of normative quartz, diopside, hypersthene, olivine and nepheline were calculated.

Results

The 196 rock analyses of the region show an approximately normal frequency distribution when plotted on the silicon cationic percent scale, with a well defined mode at Si_{51}. Differentiation index also shows a similar type frequency distribution, with mode at D.I.$_{51}$, but with a much greater spread reflecting the range of alkali content in the rocks over and above the silicon range (fig. 3).

The volcanoes of Sumatra (fig. 1) are all quartz-normative, ranging from 0.4 to 22.9% normative quartz. In the Java sector the majority are quartz-normative, but in the east an increasing number of volcanoes is olivine-normative, and some volcanoes are even nepheline-normative. Batur, on Bali, is unusual in that it is very low in normative diopside.

In the Flores sector, where the depths to the Benioff Zone are greater, nepheline is of considerable importance in the norm, and leucite-bearing rocks occur on the volcano of deepest seismic depth. The Moluccas are from shallower depths and, like Sumatra, are mainly quartz-normative.

CHEMISTRY OF THE VOLCANOES

Several authors have either suggested or demonstrated some systematic relationship between certain chemical parameters of the Indonesian volcanoes and their horizontal distance from the trench (Rittman, 1953; Kuno, 1966) and their respective depth to the underlying Benioff Zone (Hatherton and Dickinson, 1969). Only the latter attempted some kind of statistical analysis of the data, and others simply noted that a relationship exists without any attempt to discover how good is the relationship and its level of significance. There can hardly be any doubt that some kind of relationship of magma type with depth must exist. This can be shown simply by looking at the rock types (table 1): the deepest seismic depth is under Batu Tara, and its volcanism is unlike the region as a whole in being leucite-rich. However a systematic relationship with depth is by no means clear from table 1 or even from a tabulation of the chemical analyses (Neumann van Padang, 1951).

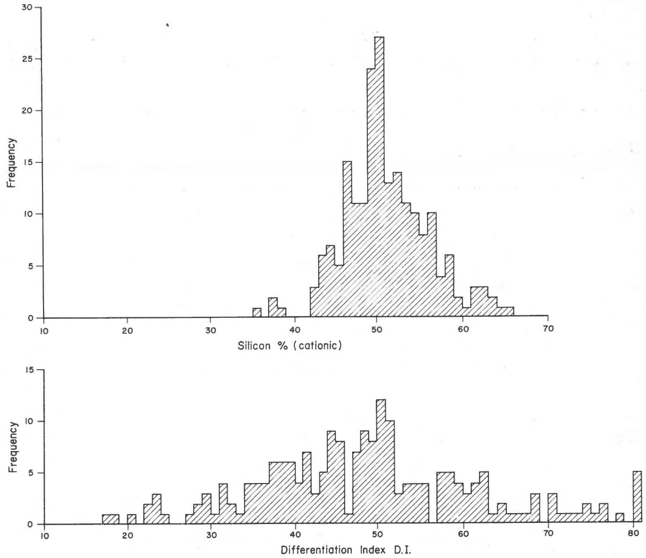

Fig. 3
Frequency distribution diagram of all the active volcanic analyses in Neumann van Padang (1951) and Hadikusumo (1961) on the scale of cationic % silicon and differentiation index.

Method of illustration

If we assume that the content of an element in a rock can be correlated with the depth of magma generation beneath the volcano, generally assumed to be the vertical depth to the underlying Benioff Zone, we must simultaneously of necessity take into account the dependence of this element on the silicon content (or differentiation index). Variation diagrams for rocks of a single volcano, on which each element (or its oxide) is plotted against the silicon content of the rock (or its differentiation index) clearly show the correlation of each element in turn with the silicon content or D.I. Over the restricted range of silicon content (or D.I.) for a predominantly andesitic suite of rocks (fig. 3) most

Table 1
List of all the active volcanoes of Indonesia and its sub-regions for which chemical analyses are available, giving the seismic depth and the distance to the trench, number of rock analyses, and summary rock descriptions of each volcano.

Sub-region	Volcano name	Depth (km) Benioff zone	Distance trench (km)	Number of analyses	K% at Si_{51}	Alkali% at Si_{51}	Rock types
Sumatra	Sibajak	225	330	1	(2.55)[1]	(7.53)[1]	hblde-bio-and
	Sorikmarapi	150	275	2	1.84	8.27	aug-hblde-and; aug-hyp-and
	Talakmau	150	290	3	1.47	8.09	aug-hyp-and; aug-hyp-hblde-ol-and.
	Marapi	165	305	6	2.50	8.40	aug-hyp-and; aug-hyp-ol-and; aug-and-pitchstone. qu and trid may occasionally be present.
	Tandikat	145	285	5	1.48	6.38	aug-hyp-and; aug-hyp-ol-and.
	Dempo	145	285	1	(3.14)[2]	(9.10)[2]	py-and
Java	Krakatau	140	232	18	1.62	7.75	trid-and; bas; scoriae; hyp-and; aug-hyp-and; pumice; bas ash; aug-hyp-ol-and.
	Tangkuban	180	305	5	0.98	6.13	py-and; py-ol-and.
	Papandajan	140	252	2	0.24	6.15	aug-hyp-ol-and; aug-hyp-and.
	Guntur	155	275	3	1.08	6.51	labradorite bas; aug-hyp-ol-and.
	Galunggung	150	275	4	0.71	7.36	labradorite bas; aug-labradorite-ol-and; aug-hyp-and.
	Tjerimai	190	325	4	1.37	7.23	aug-hyp-ol-and.
	Slamet	185	330	11	1.74	8.10	aug-hyp-and; hyp-and; bas-and; and scoriae.
	Dieng	200	345	7	2.39	8.49	bas; aug-hyp-and; aug-hyp-hblde-and; aug-hyp-bio-and; bytownite-ol-and
	Sumbing	185	320	4	0.86	12.68	aug-ol-and; aug-hyp-hblde-and; hblde-and.
	Ungaran	215	347	9	3.27	9.50	aug-ol-bas; aug-ol-and; aug-hblde-and; aug-hblde-bio-and.
	Merbabu	185	315	2	1.95	9.61	aug-ol-bas; aug-and.
	Merapi	175	305	27	2.29	8.85	aug-ol-bas; aug-ol-and; aug-hyp-and; pumice; aug-hyp-hblde-and; leucite phonolite.
		(includes 7 from Hadikusumo, 1961)					
	Kelud	170	282	8	1.23	6.85	hyp-and; hyp-hblde-and; gabbro inclusions.
	Semeru	165	280	9	1.38	7.28	aug-ol-bas; aug-hyp-and.
	Bromo	180	300	5	2.15	8.36	aug-hyp-and; shoshonite; ash; ol-hyp-bas.
	Lamongan	180	310	1	(0.67)[3]	(5.88)[3]	ol-bas.
	Raung	190	310	11	2.18	6.89	hblde-aug-bas; hyp-and; bas; ash.
		(includes 2 from Hadikusumo, 1961)					
	Batur	195	307	8	1.65	7.44	aug-hyp-and; hblde-aug-and; ol-bas; hyp-bas.
Flores	Paluweh	245	355	12	2.34	9.37	hblde-aug-hyp-bas; aug-hyp-and; pitchstone; ash; pumice; hblde-anorthite-gabbro; hblde-plagioclase-aug-rock; hblde-hyp-pitchstone
	Ili Boleng	230	290	2	1.93	8.63	ob-bas; py-and.
	Lewtolo	230	270	6	3.32	8.86	ol-bas; py-and; amphibole-py-and; trachy-and.
	Batu Tara	300	315	6	6.52	13.64	leucite basanite; leucite bas; bio-leucite-tephrite.
Moluccas	Una Una	?400?	?400?	1	(3.82)[4]	(14.03)[4]	hblde-bio-and.
		(excluded from analysis because of uncertain depth)					
	Lokon Empung	150	130	5	1.20	8.20	aug-ol-bas; aug-hyp-and.
	Raung	140	100	1	(1.40)[5]	(8.28)[5]	hblde-hyp-aug-and.
	Awu	150	125	2	2.45	7.48	hblde-py-and; aug-hyp-and; diorite.
	Dukono	190	200	6	1.62	7.03	py-and; pumice; ol-aug-hyp-and; ol-bas; pitchstone.

and = andesite; bas = basalt; aug = augite; bio = biotite; hblde = hornblende; hyp = hypersthene; ol = olivine; trid = tridymite; qu = quartz;
1 = value of K and alkali % at Si 53.9; 2 = at Si 57.1; 3 = at Si 44.3; 4 = at Si 57.7; 5 = at Si 53.1.

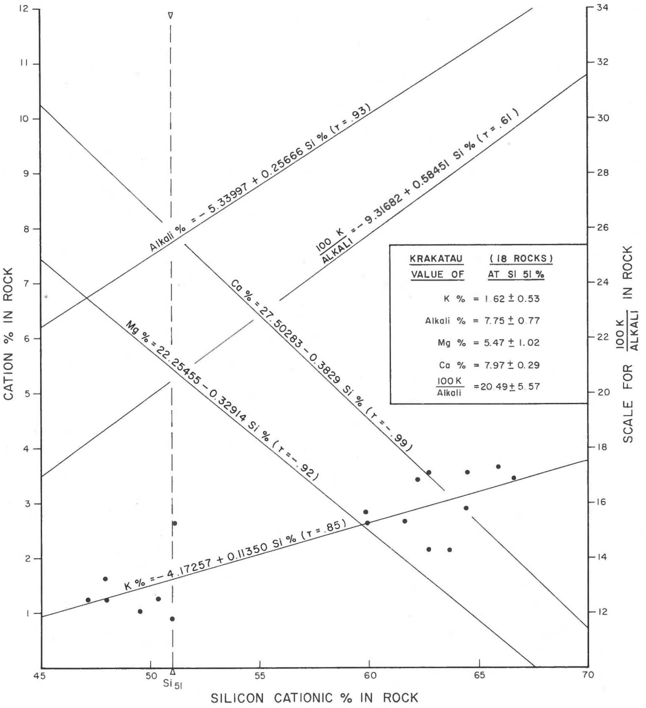

Fig. 4
Variation diagram for Krakatau, plotting various chemical elements against cationic % silicon to illustrate how the Si_{51} value is obtained for this volcano. The actual points are plotted only for potassium %. All lines are drawn from the computed regression equations. Similar diagrams are also constructed against differentiation index.

petrologists would visually construct a straight line variation correlation between each element and silicon (or D.I.) as shown for potassium versus silicon in figure 4. Although the line may not be theoretically straight, there is no apparent reason for trying to fit any other type of curve to the plotted points, which are frequently few in number.

Hatherton and Dickinson (1969) standardized the dependence of an element in a rock on the silicon content by the following method: for each volcano they constructed a variation diagram of K_2O weight % versus SiO_2% using every analysis, which had first been recast to 100% anhydrous. They then visually drew the line showing the variation between K_2O and SiO_2 and selected two arbitrary values of 55% and 60% SiO_2 at which to read off the corresponding K_2O % values which would characterise this particular volcano. In this way the correlation of K_2O % and SiO_2 % was standardized between volcanoes and they therefore then took the values of K_2O % at SiO_2 55 and 60% as being independent of silicon variation from volcano to volcano. Any variability amongst these values might then be tested for correlation with depth of the volcano to the underlying Benioff Zone.

If this method is to be applied, it should be performed without any arbitrary artificial constraints. Accordingly, in order to improve on the method so that its validity can be statistically tested, I have proceeded as follows: For each volcano, each rock analysis is recast as an anhydrous cationic percentage by the computer programme of Hutchison and Jeacocke (1971) as the preliminary part of the norm calculation. Instead of using K_2O from the reported chemical analysis recalculated to 100% anhydrous, in this study the cationic percentage of K is used and plotted against the cationic percentage of Si as shown in figure 4 for the example of Krakatau. The actual 18 rocks are plotted on figure 4 for K versus Si. However, unlike Hatherton and Dickinson (1969), the variation line is not drawn in visually, but computer calculated as a linear regression line using the least squares method. The restricted data do not warrant the use of anything but a simple linear correlation, for example between K% and Si% (or D.I.), which is better computed as a simple linear regression than by a visual estimate. The methods are widely documented in a variety of statistical books, for example Parl (1967).

By this procedure it was also possible to obtain correlation coefficients (r), standard errors of estimate, and t values from which the level of significance could be obtained from Student's tables (Beyer, 1966). These parameters are used to quantify the degree of correlation that exists between each of the two functions for which a straight line has been fitted on the variation diagrams.

The following chemical parameters are related to Si% by simple linear correlation: K%, alkali (K + Na)%, $\frac{100K}{alkali}$,Mg%, Ca%, Na%, total Fe%, Al% and Ti%. The intersection of each of the regression lines with silicon 51% (Si_{51}) was then calculated from each of the equations. The values of K% and alkali % for each volcano are given in table 1. To test if differentiation index (D.I.) is a better measure than silicon, similar regression lines were calculated against D.I. The choice of 51 for both Si% and D.I. was made because of the mode on the frequency distribution of all the rocks of this region (fig. 3). This is a better choice, because it is the value pertaining to the majority of rocks, than the arbitrary values of SiO_2 55 and 60% which were taken by Hatherton and Dickinson (1969).

Regression equations between each chemical parameter (e.g. K%) at Si_{51} and $D.I._{51}$ and depth to the Benioff Zone for all the volcanoes of Indonesia and for each sub-region in turn were computed. The results are given in table 2 as correlation coefficients (r) for the calculated linear regression lines, the level of significance (P) from Student's tables (Beyer, 1966), and the slope (b) of the regression line. A correlation coefficient (r) of 0 means that there is no correlation between the variables and a value of 1 means perfect linear correlation. However the scale from 0 to 1 is not arithmetic. Correlation coefficient (r) is readily converted to coefficient of determination (= r^2), whose meaning is perhaps more obvious. For example when r^2 = .50, 50% of the variation in the dependent variable (e.g. K%) can be explained by variation in the independent variable (e.g. depth to the Benioff

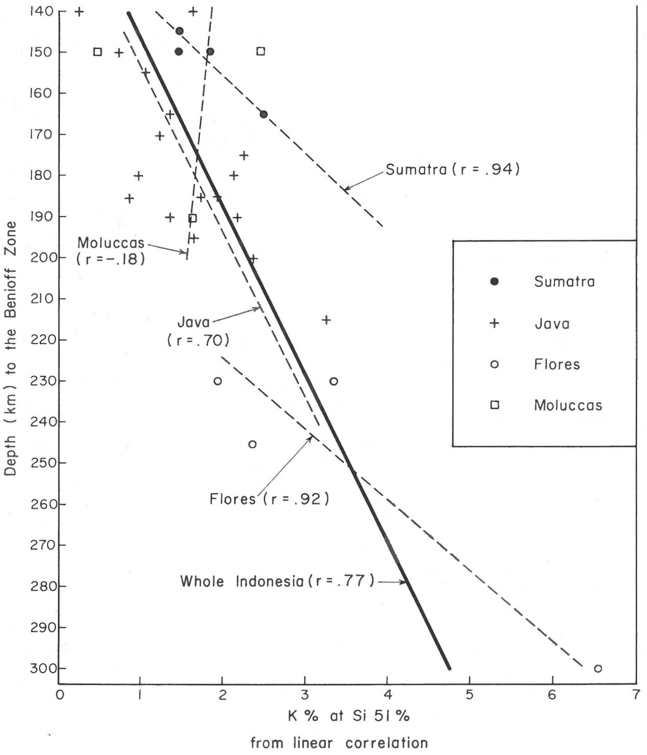

Fig. 5
Correlation of potassium % at silicon$_{51}$ with depth to the underlying Benioff Zone showing the actual data and computed regression lines and their correlation coefficients (r) for the whole Indonesian region and each of its sub-regions.

Zone). An illustration of some actual correlations of K% at silicon$_{51}$ with depth to the Benioff Zone is given in figure 5 for which the correlation coefficients (table 2) are .77 for the whole data, .94 for Sumatra, .70 for Java, .92 for Flores and −.18 for Moluccas. A correlation coefficient of .77 gives the impression of being very good, but the spread of points about the computed regression line (fig. 5) is less impressive.

D.I.$_{51}$ and Si$_{51}$ are only single values of these two parameters, both of which extend in a nearly normal distribution over a considerable range (fig. 3). Therefore a more general method over that of Dickinson and Hatherton (1969) is to relate the depth to the underlying Benioff Zone simultaneously to both Si% (or D.I.) and each of the other chemical elements in turn. Figure 6 illustrates the relationship for a multiple linear correlation surface between depth-K%-Si%, and shows clearly that Si$_{51}$ is only one of many values of silicon. The multiple correlation illustrates the continuous variation between each of the three parameters. The results of the multiple linear correlation analysis for the same chemical parameters are given in table 3. In this table r is the multiple correlation coefficient. For each entry there are two slopes, the upper is that of the slope of the regression line between the first element and the last, e.g. between K% and depth. The lower slope is that of the second element and the last, e.g. between D.I. and depth.

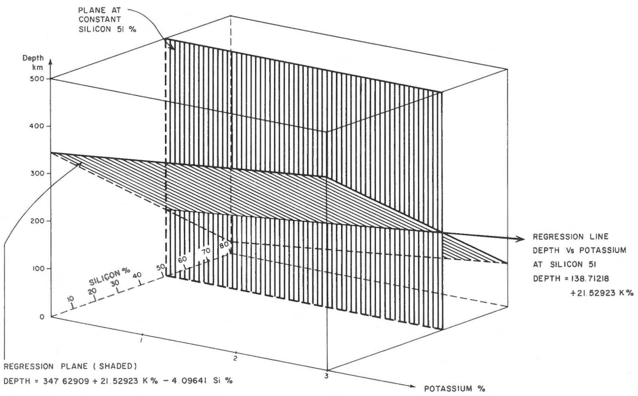

Fig. 6
Diagram showing the linear regression surface relating seismic depth (km) to potassium and silicon cationic percentages for the volcanic rocks of the whole Indonesian region, and the relationship between this surface and the regression line relating depth to silicon$_{51}$.

Discussion

To establish a useful correlation between chemical variation and depth to the Benioff Zone, the following requirements must be fulfilled: The correlation coefficient (r) should be no lower than .7 and as close to 1 as possible, and the level of significance of the data should be of the order of .001 or less. An r of .7($r^2 = .49$) means that 49% of the chemical variation can be explained by the equation relating it to the Benioff Zone depth. This leaves 51% of the variation still unexplained by the depth relationship. This, however, does not detract from the significance. The purpose of the statistical exercise is firstly, as others have done, to assume that the true hypothesis is that chemical variation is related to Benioff Zone depth. If we reject a true hypothesis on the basis of statistical testing, then a Type I error is made. The operator has control over the situation through the choice of the level of significance. For example, when a test is performed on the .05 significance level, the probability of a Type I error is .05. That is, by using the testing procedure, in the long run 5% of the true hypotheses would be rejected. The probability of a Type I error can be reduced by using a lower significance level (P), such as .01 or .001. In this particular test a significance level of .001 or lower was aimed at to minimise the chance of rejecting a true hypothesis.

Tables 2 and 3 show that for the whole Indonesian region there exists a significant correlation between potassium cationic % and depth by means of the D.I.$_{51}$ or Si$_{51}$ method (table 2) or the correlation with D.I. and Si% (table 3). Likewise a significant relationship exists between each of total alkali, and 100K/alkali, and the other parameters. However the correlation coefficients attain a highest value of .77 for

Table 2
Linear regression equation summary relating various chemical parameters determined at differentiation index and silicon cationic percent of 51 with depth to the underlying Benioff Zone.

Region (No. of volcanoes)	Indonesia (28)			Sumatra (4)			Java (17)			Flores (4)			Moluccas (3)		
	r	slope	P	r	slope	P	r	slope	P	r	slope	P	r	slope	P
K% at $D.I._{51}$ vs Depth	.70	.018	$<.001$	.95	.050	.02	.54	.019	.025	.88	.045	.07	.27	.008	.81
K% at $Silicon_{51}$ vs Depth	.77	.024	$<.001$	.94	.053	.025	.70	.025	.003	.92	.058	.04	−.18	−.005	.85
Alkali% at $D.I._{51}$ vs Depth	.65	.017	$<.001$	.81	.087	.12	.44	.019	.06	.98	.027	.003	.39	.003	.71
Alkali% at Si_{51} vs Depth	.65	.030	$<.001$	.66	.072	.30	.41	.032	.10	.99	.071	$<.001$	−.79	−.020	.32
$\frac{100K}{Alkali}$ at $D.I._{51}$ vs Depth	.57	.134	.002	.66	.297	.30	.39	.135	.12	.85	.370	.10	.09	.041	.92
$\frac{100K}{Alkali}$ at Si_{51} vs Depth	.59	.152	$<.001$	.75	.387	.20	.56	.238	.02	.81	.269	.12	−.04	−.018	.95
Mg% at $D.I._{51}$ vs Depth	.44	.011	.02	.76	.048	.19	.26	.011	.30	.93	.020	.03	.95	.020	.08
Mg% at $Silicon_{51}$ vs Depth	−.26	−.009	.20	.76	.084	.20	−.32	−.022	.21	−.90	−.023	.04	.94	.043	.11
Ca% at $D.I._{51}$ vs Depth	.23	.008	.24	−.01	−.000	.98	.12	.009	.65	.77	.017	.14	−.67	−.015	.45
Ca% at $Silicon_{51}$ vs Depth	−.53	−.014	.004	.02	.004	.03	−.47	−.019	.05	−.89	−.037	.07	.61	.006	.52
Na% at $D.I._{51}$ vs Depth	−.08	−.001	.70	.44	.036	.52	.00	.000	.99	−.66	−.018	.30	−.12	−.005	.91
Na% at $Silicon_{51}$ vs Depth	.17	.006	.40	.21	.019	.78	.09	.006	.75	.59	.013	.38	−.33	−.015	.75
ΣFe% at $D.I._{51}$ vs Depth	.11	.003	.55	.87	.048	.08	.09	.006	.75	−.34	−.006	.65	−.97	−.010	.06
ΣFe% at $Silicon_{51}$ vs Depth	−.40	−.008	.03	.51	.046	.45	−.31	−.009	.24	−.76	−.028	.19	−.36	−.001	.72
Al% at $D.I._{51}$ vs Depth	−.15	−.008	.45	−.78	−.148	.18	−.23	−.027	.35	−.06	−.001	.92	−.88	−.029	.21
Al% at $Silicon_{51}$ vs Depth	.04	.001	.82	−.53	−.180	.45	.26	.017	.30	.57	.020	.39	−.99	−.017	.015
Ti% at $D.I._{51}$ vs Depth	.07	.000	.72	.63	.006	.35	.28	.003	.29	−.28	−.001	.70	−.60	−.004	.55
Ti% at $Silicon_{51}$ vs Depth	−.33	−.002	.09	.63	.006	.35	−.25	−.002	.35	−.71	−.004	.25	−.65	−.005	.49

r = correlation coefficient   P = level of significance   Slope b as in Alkalis% at $D.I._{51} = \underset{a}{5.46709} + \underset{b}{0.01683}$ (Depth)

Table 3

Multiple linear regression analyses relating various chemical parameters with depth and either silicon % or differentiation index. The upper slope entry relates the left hand chemical parameter with depth; the lower slope relates the middle parameter with depth.

Region (No. of rocks)	Indonesia (196)			Sumatra (18)			Java (138)			Flores (26)			Moluccas (14)		
Multiple regression	r	slopes	P	r	slopes	P	r	slopes	P	r	slopes	P	r	slopes	P
K% – D.I. – Depth	.68	+25.676 – 1.631	<.001	.45	+12.998 – 1.185	.19	.58	+17.188 – 1.124	<.001	.82	+13.867 – 1.074	<.001	.58	+15.312 – 0.696	.12
K% – Silicon% – Depth	.72	+21.529 – 4.096	<.001	.46	+10.077 – 3.023	.18	.57	+12.802 – 2.472	<.001	.85	+12.534 – 2.740	<.001	.55	+14.757 – 1.844	.15
Alkali% – D.I. – Depth	.52	+19.758 – 2.633	<.001	.34	+ 4.027 – 1.167	.32	.33	+ 6.796 – 1.077	.004	.58	+16.998 – 2.386	.021	.33	+16.270 – 1.863	.41
Alkali% – Si% – Depth	.56	+11.579 – 4.912	<.001	.37	+ 1.771 – 2.805	.29	.37	+ 3.477 – 2.089	.001	.62	+ 9.674 – 4.103	.015	.26	– 2.151 + 1.682	.52
$\frac{100K}{Alkali}$ – D.I. – Depth	.61	+ 2.201 – 0.930	<.001	.45	+ 1.487 – 0.834	.19	.55	+ 1.472 – 0.674	<.001	.81	+ 1.296 – 0.647	<.001	.52	+ 1.264 – 0.170	.16
$\frac{100K}{Alkali}$ – Si% – Depth	.67	+ 2.074 – 3.043	<.001	.52	+ 1.522 – 2.838	.12	.58	+ 1.353 – 1.888	<.001	.85	+ 1.239 – 1.982	<.001	.51	+ 1.234 – 0.372	.18
Mg% – D.I. – Depth	.29	+ 5.802 + 0.386	.004	.33	+ 7.022 + 0.377	.35	.21	+ 0.116 – 0.317	.08	.44	+ 7.658 + 0.931	.11	.25	+ 2.706 + 0.623	.55
Mg% – Silicon% – Depth	.36	– 0.824 – 2.771	<.001	.36	+ 2.131 – 1.798	.30	.33	– 1.831 – 1.987	.004	.43	+ 0.875 – 1.565	.12	.34	+ 2.107 + 2.908	.41
Ca% – D.I. – Depth	.38	+12.969 + 1.664	<.001	.28	– 4.046 – 1.305	.42	.21	– 0.018 – 0.336	.08	.60	+19.597 + 3.366	.018	.37	– 9.270 – 1.430	.35
Ca% – Silicon% – Depth	.39	– 6.105 – 5.111	<.001	.36	– 2.319 – 3.277	.30	.40	– 6.728 – 4.082	<.001	.43	– 4.069 – 3.921	.12	.26	+ 1.362 + 1.623	.54
Na% – D.I. – Depth	.26	– 7.991 + 0.046	.007	.27	+ 0.322 – 0.764	.45	.28	– 5.151 – 0.006	.015	.64	–12.713 + 0.399	.007	.41	– 8.852 + 0.819	.30
Na% – Silicon% – Depth	.37	– 2.344 – 2.145	<.001	.35	– 1.105 – 2.488	.31	.34	– 2.879 – 0.927	.004	.62	– 9.553 – 0.413	.01	.45	– 7.581 + 2.276	.29
ΣFe% – D.I. – Depth	.25	+ 8.007 + 0.258	.01	.44	+10.506 + 0.078	.20	.32	+ 6.656 + 0.273	.005	.28	– 3.315 – 0.809	.31	.26	+ 5.265 + 0.628	.54
ΣFe% – Si% – Depth	.38	– 5.639 – 3.811	<.001	.44	+10.282 + 0.077	.20	.32	+ 2.417 – 0.716	.006	.57	–11.867 – 4.852	.02	.49	+14.756 + 4.473	.21
Al% – D.I. – Depth	.23	– 3.159 – 0.659	.02	.28	– 1.621 – 0.811	.42	.23	+ 1.222 – 0.250	.06	.34	– 3.896 – 0.521	.22	.38	– 4.124 – 0.006	.35
Al% – Silicon% – Depth	.42	– 4.450 – 3.079	<.001	.38	– 2.248 – 2.875	.28	.31	+ 0.569 – 1.214	.007	.49	– 4.427 – 2.083	.07	.38	– 3.686 + 0.244	.35
Ti% – D.I. – Depth	.18	+ 0.592 – 0.465	.07	.27	– 9.323 – 0.777	.45	.21	+ 1.018 – 0.326	.08	.26	– 5.064 – 0.521	.35	.19	– 5.815 + 0.188	.65
Ti% – Silicon% – Depth	.37	–13.958 – 2.745	<.001	.39	–31.597 – 3.259	.26	.32	– 3.969 – 1.404	.006	.46	–39.770 – 2.675	.10	.25	+ 0.766 + 0.902	.55

r = multiple correlation coefficient   Slopes b as in $\text{Depth} = \overset{a}{176.12319} + \overset{b}{17.18799}\text{K\%} - \overset{b}{1.12434}\text{D.I.}$ P = level of significance

Table 4
Linear regression equations for the whole Indonesian region. All chemical components are cationic percentages (anhydrous) in the rocks. D.I. = differentiation index.

Equation number	Linear regression equation	Standard error of estimate	Correlation coefficient	Level of significance
	Depth (km) to Benioff Zone =			
1	$148.3 + 19.8\,(\text{Alkali\%}) - 2.6\,(\text{D.I.})$	29.9	.52	$<.001$
2	$342.0 + 11.6\,(\text{Alkali\%}) - 4.9\,(\text{Silicon\%})$	28.9	.56	$<.001$
3	$206.0 + 25.7\,(\text{K\%}) - 1.6\,(\text{D.I.})$	25.7	.68	$<.001$
4	$347.6 + 21.5\,(\text{K\%}) - 4.1\,(\text{Silicon\%})$	24.4	.72	$<.001$
5	$171.9 + 2.2\,(\frac{100\text{K}}{\text{Alkali}}) - 0.9\,(\text{D.I.})$	27.7	.61	$<.001$
6	$287.4 + 2.1\,(\frac{100\text{K}}{\text{Alkali}}) - 3.0\,(\text{Silicon\%})$	25.8	.67	$<.001$
7	$-33.7 + 25.3\,(\text{Alkali\% at D.I.}_{51})$	28.1	.65	$<.001$
8	$69.3 + 13.8\,(\text{Alkali\% at Silicon}_{51})$	28.3	.65	$<.001$
9	$120.1 + 26.7\,(\text{K\% at D.I.}_{51})$	26.5	.70	$<.001$
10	$135.3 + 24.5\,(\text{K\% at Silicon}_{51})$	23.7	.77	$<.001$
11	$118.8 + 2.4\,(\frac{100\text{K}}{\text{Alkali}}\text{ at D.I.}_{51})$	30.5	.57	$= .002$
12	$131.5 + 2.3\,(\frac{100\text{K}}{\text{Alkali}}\text{ at Silicon}_{51})$	30.0	.59	$<.001$

K% for the whole Indonesian region for data of significance less than the .001 level. This means that 59% of the variation in K can be explained by Benioff Zone depth. The Flores sector (tables 2 and 3) gives a nearly perfect correlation of alkali% and 100K/alkali with depth, but other sub-regions give considerably poorer correlations.

Because an increase in potassium in a rock must cause a relative decrease in some other single or group of elements, it is to be expected that some correlation of the other elements with depth may exist. Table 3 shows that Mg%, Ca%, Na%, total Fe%, Al% and Ti% each relate to silicon and depth at a significance level less than .001. However these elements give a poor correlation coefficient, which shows that their variability is largely independent of the Benioff Zone depth.

For any relationship to be useful, it is also necessary that the slope of the regression line or surface be of reasonable magnitude. Table 3 shows that K% has a greater dependence on depth than all other chemical elements (slope of +25.676). Even if a correlation is significant, but the regression slope is low, the relationship will be of no practical use because the element variation will then be largely independent of depth.

With all these considerations in mind, it is concluded that the only useful relationships of chemical elements with depth are the first three of tables 2 and 3, and their complete regression equations are given in table 4. From these equations, depth to the underlying Benioff Zone may be estimated from the chemistry of the rocks. The standard error of estimate of depth is generally between 25 and 30 km irrespective of whether the D.I._{51} (or Si_{51}) method is used or a three-way correlation is made. These equations, however, have little real value and result only from this mathematical exercise. The best correlation coefficient (table 4) is .77, which means that only 59% of the variation of potassium% at silicon_{51} can be explained by the depth to the underlying Benioff Zone by equation 10, and the other equations explain much smaller percentages of the chemical variation.

Since there is no significant difference in the correlation coefficients or the standard errors of estimate between the two techniques of D.I._{51} (or Si_{51}) and the three-way correlation, it is recommended that there is no advantage in the method of Hatherton and Dickinson (1969). Indeed there are serious disadvantages, because Si_{51} (or D.I._{51}) cannot be calculated unless one first obtains a number of rock analyses which are definitely known to come from the same volcano. A volcano with a single analysis cannot be used and a variation diagram (fig. 4) cannot be reliably constructed for a volcano unless a minimum number of three analyses is available. On the other hand, the first six equations of table 4 can be applied to even a single rock analysis for a region like Indonesia for which a regression correlation has already been established.

The Hatherton and Dickinson (1969) method cannot be applied to every extinct set of volcanoes in a folded terrane, for it will normally be impossible to know for certain that all rocks collected from a neighbourhood actually come from a single volcano unless there is very good geological control. The multiple linear regression equations (table 4, equations 1 to 6) have the advantage of being applicable to single rocks and therefore do not have this severe disadvantage. However, in applying these equations to any paleo situation, it is warned that these equations apply only to Indonesia and do not necessarily have any similarity to the situation prevailing elsewhere. Even within Indonesia itself, the slopes of the equations differ between Java and Sumatra (tables 2 and 3, fig. 5).

It will be noted that from each of the first 6 equations of table 4, an equation for $D.I._{51}$ or Si_{51} can be obtained by substituting the value of 51 where appropriate. For example, equation 4 becomes: depth at $Si_{51} = 347.6 + 21.5(K\%) - 4.1 \times 51 = 138.7 + 21.5(K\%)$. Although this equation is not exactly identical to equation 10, which has been derived by a relatively more complex procedure, it is closely similar. Likewise each of the other equations (table 4, equations 1 to 6) is closely similar to its counterpart in the lower part of the table. This is shown by the similar, though not identical, slopes. The much greater simplicity of the basis for equations 1 through 6 makes them preferable for useful applications to equations 7 through 12.

The complete procedure outlined in this paper of relating chemical element variation to depth of the underlying Benioff Zone, has been repeated using horizontal distance from the outcrop of the Benioff Zone (trench) to each volcano. This exercise was not nearly so successful as when depth was used, and the correlation coefficients so obtained are all significantly worse. The conclusion from this is that in the Indonesian region the distance of a volcano from the trench is not linearly related to the depth of the Benioff Zone under that volcano. This is because of either uncertainty of the actual outcrop position of the trench (fig. 1), or variation from place to place in the slope of the Benioff Zone, particularly in its low angle dip region close to the trench.

Conclusion

About 60% or less of the variation in K%, alkali % and K/alkali in the Indonesian volcanic rocks can be significantly explained by linear correlation with the vertical depth to the underlying Benioff Zone. The remaining unexplained variation is due to unknown causes such as inhomogeneity of the magma and contamination on its upward migration to the surface. The rather low correlation between chemical variation and Benioff Zone depth may also result from uncertainty of the depths to the Benioff Zone and inaccuracy in the chemical analyses. However it is justifiable to conclude that depth to the Benioff Zone is only one of the independent factors which control the chemistry of the Indonesian volcanic rocks.

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