Andesitic Volcanism and Seismicity around the Pacific

Abstract. *Circum-Pacific andesites, with associated basalts and dacites, are erupted from linear island arcs and marginal continental ranges whose ocean-side borders coincide approximately with the continent-side boundaries of belts of shallow seismicity that parallel adjacent trenches. The lines of active volcanoes stand above elongate subcrustal regions delineated by the intersection of inclined Benioff seismic zones and the subhorizontal Gutenberg low-velocity zone. Close correlation between content of potash in erupted lavas and vertical depth to the Benioff zone suggests that andesitic volcanism has its origins in the mantle where magmas are generated by events associated with earthquakes of intermediate focal depth.*

Andesites are the dominant volcanic rocks of the active island arcs and continental volcanic ranges around the periphery of the Pacific basin; they and their cogenetic associates are known variously as the calcalkaline (*1*), orogenic (*2*), or high-alumina (*3*) suite, which displays a broad spectrum of petrologic variation. The central field of the intermediate andesites merges on the mafic side with aluminous saturated basalts high in silica; on the felsic side, with dacites. The central field spans the boundary between saturated and oversaturated felsic rocks as defined by classical petrology. Most andesites contain quartz in their norms and are chemically equivalent to quartz-bearing diorites, tonalites, or granodiorites of orogenic plutons (*4*).

Because many andesitic chains stand in regions where the crust is thin and sial nearly absent, it is likely that andesites are erupted from the mantle (*5*). It may be that andesitic eruptions are the principal means of continental accretion, for the composition of andesites approximates the crustal average (*2*). The andesitic character of many ancient eugeosynclinal volcanic rocks of the circum-Pacific orogenic belt (*3*, *6*) is consistent with that view, and in any case underscores the significance of andesitic volcanism for petrotectonic theory.

The areal distribution of linear and arcuate chains of andesitic volcanoes defines a narrow "andesite zone" (*7*) that nearly encircles the Pacific Ocean despite a few notable gaps and bifurcations along some segments of the circum-Pacific belt. The deep structure of most of the volcanic chains displays a characteristic transverse asymmetry revealed most clearly by the incidence of earthquake foci whose array defines inclined planar zones, here called Benioff zones, dipping beneath the volcanic belts from the vicinity of the near-margins of adjacent bathymetric trenches. Benioff (*8*) suggested that these seismic zones delineate tectonic dislocations that serve as preferred loci for the production of volcanic magmas with the heat generated by strain.

Figure 1 shows typical vertical sections of hypocenters perpendicular to the Kermadec-Tonga and Kurile-Kamchatka arcs (*9*). A belt of shallow seismicity (depth, 0 to 80 km) commonly separates a deep trench from a volcanic island arc. A zone of intermediate and, in some instances, deep earthquakes dips away from the arc side of the belt of shallow seismicity at an angle varying from 15° to 60° in individual cases. Examination of all published asymmetric sections reveals that the andesitic volcanoes never occur within the region of shallow seismicity. Typically, the first line of active volcanoes marks the arc-side boundary of the shallow seismicity (Fig. 1). This boundary coincides approximately with the "volcanic front" defined by Sugimura (*10*) as the ocean-side border of the volcanic arc. In some arcs (for example, Fig. 1d), additional lines of active volcanoes occur farther from the trench.

The active volcanoes in Japan are restricted to regions directly above the loci of clusters of earthquake foci at intermediate depths in the Benioff zone (*11*). Volcanoes of the Aleutian Range also stand above the zone of epicenters of intermediate-depth events in Alaska (*12*). Kuno (*13*) indicates that significant petrologic variations among basaltic lavas of Japan can be related to inferred depth of magma generation along the Benioff zone.

Data presented below indicate, for selected andesitic volcanoes and vol-

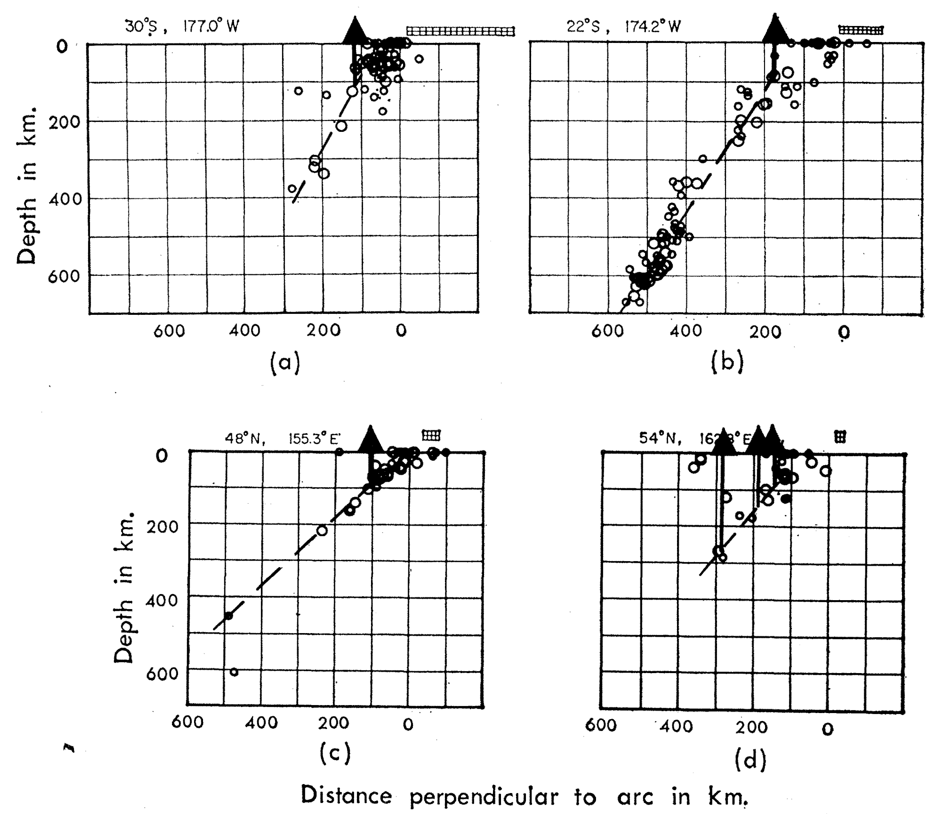

Fig. 1. Vertical hypocenter sections oriented perpendicular to arcs [after Sykes (*9*)]: (a) Kermadec, (b) Tonga (Table 1, line 6), (c) Kurile Islands (Table 1, line 3), and (d) Kamchatka (Table 1, lines 4, 15, 20). Positions of volcanoes from *Catalogue of Active Volcanoes of the World*. The geographic position (top left of each subfigure) corresponds to zero distance on abcissa. The horizontal distance *d* (Table 1) is equivalent to the abcissa distance (from each subfigure) corrected by the distance from point of origin to trench axis. Cross-hatching indicates water depths exceeding 6 km. Hypocenters are projected from distances within 150 km of each section. Larger symbols represented more accurate determinations of hypocenters.

canic chains, close correlation between significant petrochemical variation and the vertical depth from volcano to Benioff zone. The correlation suggests that andesitic magmas are initially generated well within the mantle by events with which earthquakes of intermediate focal depth are associated, and that these magmas rise to the surface without undergoing contamination sufficient to erase the petrochemical stamp imposed at the Benioff zone.

Although andesites and their close associates form a distinctive suite of rocks, their petrochemistry is not uniform from arc to arc. Systematic variations reflecting the asymmetry of arc structure have long been apparent: for example, the relative alkali content of Indonesian lavas increases regularly from foredeep (trench) to hinterland across the Sunda Orogen (*14*). To register the nature of such gradual changes, a means for serial characterization of transitional andesitic types is required.

The simplest graphic means of depicting magmatic variation by use of raw analytical data is the variation diagram of Harker (*15*): the percentage by weight of each major oxide constituent is plotted directly against percentage by weight of silica. Each rock analysis thus generates an array of points perpendicular to the silica axis. When all the analyses for a given suite of rocks have been plotted thus, the points representing given oxides can be joined to form an array of curves, one for each major rock-forming oxide. The silica percentage corresponding to the point of intersection of the lime-variation line of negative slope with the total-alkali ($Na_2O + K_2O$) variation line of positive slope is the alkali-lime index of Peacock (*16*). The alkali-lime index decreases inward from about 65 in the outer zones of northwest-Pacific arcs to about 55 in parts of the arcs farthest from trenches (*17*). Sugimura (*10*) demonstrated an analogous variation in the parameter

$$\theta = (\text{wt \% } SiO_2) - [47 \times \text{molar } (Na_2O + K_2O)/Al_2O_3]$$

Because the lime-versus-silica variation line is roughly the reciprocal of the alkali-versus-silica line, the alkali line alone is capable of discriminating between the lava suites of different arcs (*18*). This total-alkali line can be used to characterize transverse petrologic variations across individual arcs in detail (*19*). We carry this manner of characterization one step further, and for three reasons propose to adopt the potash-versus-silica variation line as an indicator of serial variation in type of andesitic magma: (i) the proportional variation of potash among the range of andesitic suites is greater than of soda or of lime; (ii) our empirical experience is that the scatter of points plotted for the potash curve is less than for either the soda or lime curve, so that the position of the potash curve is least ambiguous; (iii) soda and lime are principal constituents of the plagioclase feldspars, which are common early-formed phenocrystic minerals in the andesitic suite. As a result, proportions of soda and lime in a given rock are subject to major fluctuations as crystals are either separated from residual melt or accumulated in clusters during local fractionation. Because potash is one of the least-abundant major constituents and enters no early-formed crystalline phases in important amounts, it remains dispersed through residual melt until eruption and chilling fix it within the aphanitic ground mass, which is by far the most voluminous textural component of most andesitic rocks.

Once a potash-versus-silica variation line is plotted, an approximate mean value of potash content, for any given level of silica percentage within the given suite, can be obtained. Such a value, or a serial array of such values, represents an intrinsic character of the magmatic suite. Our procedure to obtain such characters follows (Fig. 2):

1) The potash and silica contents reported in all available analyses, with less than 2 percent volatiles and summing to 100 ± 1 percent, are first recalculated to 100.0 percent on a volatile-free basis and then plotted as an array of points on a scatter diagram.

2) A straight potash variation line

Table 1. Petrology of selected circum-Pacific arc volcanoes. The number of each arc appears in parentheses. Volcano numbers are from *Catalogue of Active Volcanoes of the World* (International Association of Volcanology), from which the intercepts also are derived (Fig. 2). Values for Mount Katmai are based on data from D. Eberlein, A. Grantz, and M. Sorenson (U.S. Geological Survey; personal communication, 1967) and from Tobin and Sykes (*22*). Abbreviations: *h*, vertical depth from volcano to Benioff zone; *S*, slope of Benioff zone; *d*, distance from volcano to trench axis.

Arc, location	Volcano(s) (No.)	Intercept		h* (km)	S* (deg)	d* (km)
		K_{55}	K_{60}			
(1) Mt. Katmai, Alaska		0.6	1.1	80	16	240
(2) Kunashir I. and Iturup I., SW Kuriles	9-1 to 9-7	.6	0.7	90	41	190
(3) Matua I. *et al.*, SE side of NE Kuriles	9-24 to 9-32	.7	1.0	90	43	170
(4) Coastal range, SE Kamchatka	10-13 to 10-18	.9	1.3	90	51	170
(5) Avachinsky Volcano, Kamchatka	10-10	.6	0.8	95	45	190
(6) Tonga	4.3-1 to 4.3-5	.5	.8	100	45	200
(7) Northern Honshu	8.3-23 to 8.3-25	.5	.8	100	24	250
(8) Paramushir I., NE Kuriles	9-34 to 9-38	1.4	1.9	105	46	210
(9) NE Hokkaido	8.5-7 to 8.5-9		1.2	110	22	220
(10) El Salvador	14.3-3 to 14.3-6	1.2	1.4	115	60	170
(11) Colima Volcano, Mexico	14.1-4	1.3	2.0	115	?	225
(12) Kuzyu Volcano, Kyushu	8.2-12	1.4	1.6	120	54	
(13) Paricutin Volcano, Mexico	14.1-5	1.0	1.7	125	?	270
(14) Tokati and Daisetsu volcanoes, Hokkaido	8.5-5, 8.5-6	1.4	1.7	135	22	280
(15) Sheveluch Volcano, Kamchatka	10-27	1.2	1.3	135	51	220
(16) Tyokai Volcano, Honshu	8.3-22	1.6	2.1	145	24	360
(17) Aso Volcano, Kyushu	8.2-11	1.9	2.3	150	54	
(18) Sakurazima and Kirisima volcanoes, Kyushu	8.2-8, 8.2-9	1.4	1.8	150	52	
(19) Nicaragua	14.4-1 to 14.4-10	1.4	2.1	185	61	190
(20) Ichinsky Volcano, Kamchatka	10-28	2.6	2.7	270	51	310

* Geometric information (see Fig. 1) from data in Sykes (*9, 23*) and Wadai and Iwai (*11*).

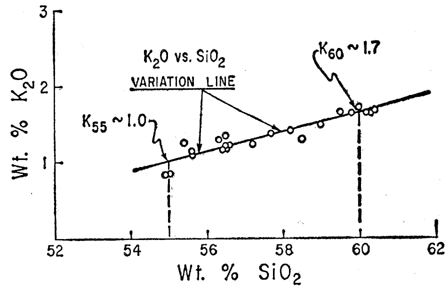

Fig. 2. Determination of the parameters K_{55} and K_{60} from a partial Harker variation plot; example illustrated is for historic lavas of Paricutin, Mexico (Table 1, line 13).

is constructed by inspection, and commonly cannot be moved more than 0.1 percent on the potash scale, for a given silica content, without introducing evident error in the positioning of the line (in no cases studied could the line be shifted more than 0.25 percent on the potash scale).

3) The potash contents at 55 and 60 percent silica are identified as K_{55} and K_{60}; these two silica levels were chosen because they lie within but near the lower and upper limits of the range of variation of the bulk of andesitic rocks. Rocks containing 50 to 55 percent silica are gradational to basalt, and those containing 60 to 65 percent silica are gradational to dacite.

Table 1 gives the potash content (K_{55} and K_{60}), depth to Benioff zone (h), distance from deepest part of trench (d), and slope of Benioff zone (S) for a number of volcanoes from the Kermadec-Tonga, Japan, Kuril-Kamchatka, and Central America arcs. The means of the potash contents of volcanoes, with depth to Benioff zones (h) in the ranges 80 to 99, 100 to 119, 120 to 139, and 140 to 159 km, are given in Fig. 3. The Benioff zone has been considered as a surface or plane for our purpose. Uncertainties in the estimate of h are possibly as great as $\pm$ 20 km (see Fig. 1), yet there appears to be real correlation between the level of potash content and the depth (h) to the Benioff zone beneath a volcano. For an individual arc this also implies that the potash content increases with distance (d) from the trench. But in the gross picture the relation of d with percentage-K_2O is not as significant as that between h and percentage-K_2O (see Table 1). The range of h above which andesitic rocks appear is 80 to 270 km, an interval corresponding approximately to the controversial "low-velocity layer" (*20*).

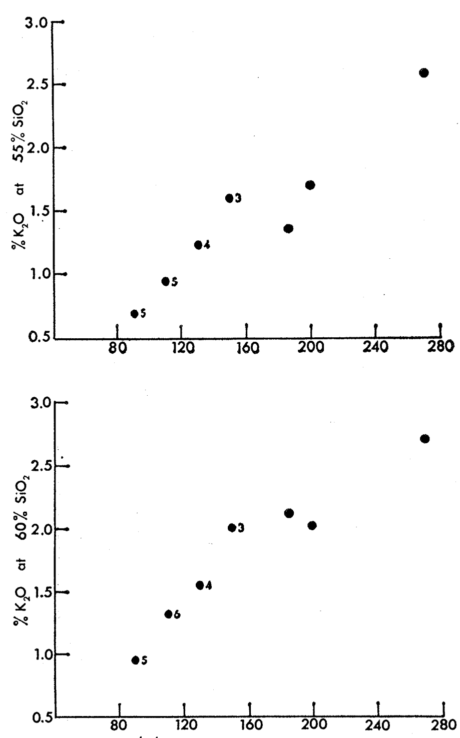

Fig. 3. Variation in K_2O content of arc andesites with depth to Benioff zone beneath volcanoes. Unnumbered points are single values and so questionable; other points show numbers of points within 20-km intervals, and represent mean values of K_{55} and K_{60} from Table 1.

The simplest model we can devise requiring the correlation displayed by Fig. 3 as a necessary consequence is the following: andesitic magmas are generated at Benioff zones and rise to the ground surface without ever undergoing sufficient contamination to mar the pattern of chemical variations established at the sites of partial melting in the mantle. The linearity, of volcanic chains erupting andesite, reflects lines of intersection of the Benioff zones with subhorizontal zones favorable for melting within the Gutenberg low-velocity zone. Alternative models would require correlation of each of the two parameters with some additional parameter that does not readily come to mind. If this model is approximately correct, it apparently predicts the trend of variation in distribution coefficients for potash in the *P-T* region between solidus and liquidus at varying pressures appropriate to depths of 80 to 270 km within the mantle. Specifically, the partition of potash between incipient melt and residual crystalline phases should be such that the potash content of the melt rises as confining pressure rises. The alternate interpretation, that the absolute potash content rises with depth in the mantle, appears untenable. Whether the absolute potash content of erupted lavas is established at the Benioff zone, or is developed by a complex and massive fractionation of the sort proposed by O'Hara (*21*) for basalts, is not predicted by the model. That *relative* potash contents be established at the Benioff zone would be sufficient to deny the importance of crustal assimilation for the evolution of andesitic magmas. Because the view that andesitic magmas arise from the contamination of basalts in the hydrous roots of orogens has been forcefully argued for cogent reasons (for example, *22*), denial of the concept would have broad implications. To the extent that some of the more mafic granitic rocks are plutonic equivalents of andesites, partial rejection of the concept of melting in orogen roots may also be justified.

WILLIAM R. DICKINSON

School of Earth Sciences, Stanford University, Stanford, California

TREVOR HATHERTON

Geophysics Division, Department of Scientific and Industrial Research, Wellington, New Zealand

References and Notes

1. G. S. Gorshkov, *Bull. Volcanol.* **28**, 162 (1965).
2. S. R. Taylor and A. J. R. White, *Nature* **208**, 271 (1965).
3. W. Hamilton, *Science* **146**, 635 (1964); *Can. Geol. Surv. Paper 66-15* (1966), p. 348.
4. F. Chayes, *Carnegie Inst. Paper 1455* (1965), p. 155.
5. G. S. Gorshkov, *Amer. Geophys. Union Monog.* **6**, 110 (1962).
6. W. R. Dickinson, *Geol. Soc. Amer. Bull.* **73**, 1241 (1962); *Tectonophysics*, in press.
7. T. P. Yen, *China Geol. Soc. Proc.* **3**, 117 (1960).
8. H. Benioff, *Geol. Soc. Amer. Bull.* **65**, 385 (1954).
9. L. R. Sykes, *J. Geophys. Res.* **71**, 2981 (1966).
10. H. Sugimura, *Can. Geol. Surv. Paper 66-15* (1966), p. 337.
11. K. Wadati and Y. Iwai, *Geophys. Mag.* **25**, 167 (1954); **27**, 11 (1956).
12. D. G. Tobin and L. R. Sykes, *J. Geophys. Res.* **71**, 1659 (1966).
13. H. Kuno, *Bull. Volcanol.* **20**, 37 (1959).
14. A. Rittman, *ibid.* **14**, 45 (1953).
15. A. Harker, *The Natural History of Igneous Rocks* (London, 1909).
16. M. A. Peacock, *J. Geol.* **39**, 54 (1931).
17. S. Taneda, *Bull. Volcanol.* **26**, 415 (1963).
18. S. I. Tomkeieff, *ibid.* **8**, 87 (1949).
19. H. Kuno, *Can. Geol. Surv. Paper 66-15* (1966), p. 217.
20. S. P. Clark and A. E. Ringwood, *Rev. Geophys.* **2**, 35 (1964).
21. M. J. O'Hara, *Scot. J. Geol.* **1**, 19 (1965).
22. A. C. Waters, *Geol. Soc. Amer. Spec. Paper 62* (1955), p. 703.
23. L. R. Sykes, unpublished.
24. Discussions with members of the 1967 Circum-Pacific Seminar, School of Earth Sciences, Stanford University, helped to develop these ideas. L. R. Sykes and A. Grantz called our attention to their highly pertinent unpublished data.

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