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A Petrographic Distinction between Cenozoic Volcanics in and around the Open Oceans

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Abstract. Geographic and petrographic definitions of 'circumoceanic' and 'intraoceanic' Cenozoic lavas are proposed and tested. The association between geography and petrography proves remarkably strong; a classification based on TiO_2 content and the degree of alkali concentration relative to SiO_2 and Al_2O_3 is more than 90 per cent accurate. Failures of the classification are frequently associated with unusual enrichment in H_2O. The remarkable consistency of lava types in and around the oceans contrasts strongly with the complex mixtures of types characteristic of shallow-sea and continental areas of the globe.

STATEMENT OF PURPOSE

The Cenozoic period has been characterized by violent and prolonged volcanism on a global scale. Our knowledge of the petrography and chemical composition of materials extruded or ejected in local episodes of this volcanism is rarely more than fragmentary. For the period and the earth as a whole, however, we already possess far more information of this sort than, by conventional methods, we can effectively assimilate and use. There are certainly more than 6000 published analyses of Cenozoic volcanics sufficiently complete to permit meaningful normative computation, and there is reason to suppose [*Chayes*, 1963*b*] that an exhaustive census would raise the figure at least to something between 7000 and 9000.

There is also a considerable body of doctrine concerning relations between the petrographic nature and the geographical situation of the products of this global paroxysm. Most of us, however, have no way of summarizing or reducing the data in such fashion that they will provide a satisfactory test of the generalizations; unless we are prepared to duplicate the researches of those who have formulated them, we must either accept or reject these proposals on an essentially ad hominem basis. This is an undesirable predicament for a science which is basically empirical, and the fact that until recently it has been nearly unavoidable may partly account for the curious lack of heat and conviction with which nonspecialists usually greet discussions of the real or supposed relations between petrography and geography in Cenozoic volcanism. If we are able to tolerate the degree of abstraction and simplification they require, modern data storage and retrieval procedures at last make possible some general evaluation and utilization of the vast body of data to whose accumulation petrologists have for so long been helpless witnesses and occasional contributors.

In an earlier study [*Chayes*, 1963*a*] machine data techniques provided a summary geochemical description of the basalt-trachyte association characteristic of the ocean basins. In the present paper the Cenozoic lavas of this environment are compared with those on the shoreward sides of the great deeps which form such a large part of the boundary between ocean basin and shallow-sea or continental regions.

THE GEOGRAPHIC ENVIRONMENTS OF CENOZOIC VOLCANISM

Avoiding, for the present, the myriad complications introduced by tectonics and stratigraphy, we may differentiate four fairly distinct geographic settings in which Cenozoic volcanics occur: on islands in the open ocean, along the discontinuous trench-like rims or margins of the open oceans, in mediterranean or shallow-sea areas, and on the continents proper remote from ocean and sea.

Ocean basins and the rims of the oceans. Over a large part of its perimeter the Pacific Ocean is separated from adjacent shallow-sea or continental areas by deep troughs. The Aleutian trough extends westward from Alaska, intersecting a similar feature, the Kamchatka-Kurile trench, which trends southwestward along Kamchatka and the Kurile Islands, terminating off Hokkaido. A few miles to the south is the northern end of the great Japan trench. This, in turn, is succeeded, after a short break south of the Bonin Islands, by the Bonin–Mariana–West Caroline trench. There are several similar but much smaller features in the equatorial region northeast of Australia, but the next major trench is the Kermadec-Tonga, which extends from Samoa southward almost to New Zealand. Trenches have not been found in the antarctic region of the Pacific, but along the western coast of South America there are two, the long Chile trench and a similar but shorter one along the coast of central Peru. Still another parallels the coastline of Central America, off Salvador, Guatemala, and southern Mexico. In the Atlantic only two such features are known, and both are rather small in relation to those of the Pacific: the South Sandwich trench northeast of the Weddell Sea in the South Atlantic, and the Puerto Rico trench, which forms part of the boundary between the North Atlantic and the Caribbean Sea. In a somewhat analogous position, the Java trench, the only major trench in the Indian Ocean, lies between the northeastern margin of that ocean and the complex shallow-sea area of the China, Banda, and Celebes seas.

Indeed, with the possible exception of the Tonga deep, all the troughs so far mentioned separate stretches of the open ocean from continents, continental islands, or shallow-sea areas. We describe as geographically *circumoceanic* any island, island chain, peninsula, or continental area lying immediately on the shoreward side, and as geographically *oceanic* any island lying in deep water and either isolated from or on the ocean side of one of these troughs. From the oceanic group we omit certain islands whose lavas or geology suggest close relation with continental phenomena. The lavas of Jan Mayen and, in fact, of the whole Thulean province, are omitted on the ground that they are continental flood basalts, for instance, while the lavas of the Fernando Po group in the Gulf of Guinea are omitted because their geology suggests that they are outliers of the Cameroun chain, which extends far into the African mainland. From the circumoceanic group we omit the Cenozoic lavas of California, southern Oregon, New Britain, New Guinea, and New Zealand because none of these areas is now separated from the open ocean by a deep trench. We also omit the lavas of the Ryukyus and Philippines because, although both lie immediately shoreward from deep trenches, the trenches themselves are well within a shallow-sea area rather than between such an area and the open ocean. Finally, because of their distance from the Puerto Rico trench we classify the lavas of the Lesser Antilles as mediterranean (see below) rather than circumoceanic. We are thus left with data whose geographic distribution is summarized in Tables 1 and 2.

The shallow-sea or mediterranean environment. The principal shallow-sea areas are four in number: the land-locked Mediterranean itself, the Caribbean, the Japan Sea, and the large area bounded on the east by the Mariana trench and on the west by Java and Sumatra, along whose southwestern margin, as we have noted, runs the Java deep. We may include here also the vast region between Australia and the Tonga trench, and perhaps also the straits between Africa and northern Madagascar, in which lies the Comores archipelago. With the exception of the last, all are known to be areas of complex topography, stratigraphy, and recent tectonic history. The Cenozoic volcanism of these areas is also complex, and in this paper we shall content ourselves with a very general résumé of it.

The continental environment. This includes all areas of the earth's surface not clearly falling in any of the other three classes. The lavas of southern Mexico and central Peru, for instance, are classified here as geographically 'circumoceanic' because of their proximity to the Guatemala and Peru trenches, but the lavas of Colombia, remote from these trenches, are considered 'continental.' Similarly, although for petrographic and geographic reasons we might be inclined to overlook the absence of a deep trench off the California coast and regard the Cenozoic lavas of western California and Oregon as circumoceanic, the Cenozoic lavas of Montana are separated from the coast by the Idaho batholith and can only be regarded as continental.

Most oceanic and much circumoceanic volcanism is very young, and active volcanoes are not rare in either environment. Except along the

TABLE 1. Distribution of Geographically Oceanic Analyses and Check List of Source References

Ocean	Island or Island Group	No. of Analyses	References
Atlantic (293)	Canaries	90	*Fúster et al.* [1954]
	Madeira	27	*Gagel* [1912, 1914]
	Azores	34	*Berthois* [1953]; *Jeremine* [1957]
	Cape Verde	44	*Part* [1950]; *Torre de Assunçao* [1954]
	Ascension	14	*Daly* [1925]
	St. Helena	11	*Daly* [1927]
	Fernando Noronha	6	*Campbell-Smith and Burri* [1933]
	Bouvet	6	*Broch* [1946]
	Tristan da Cunha	23	*Campbell-Smith* [1930]; *Dunne* [1941]
	Gough	38	*Barth* [1942]; *Campbell-Smith* [1930]; *Le Maitre* [1962]
Indian (128)	Heard	10	*Tyrrell* [1937*a*]
	Crozet	18	*Lacroix* [1940]; *Tyrrell* [1937*b*]
	Christmas	7	*Campbell-Smith* [1926]
	Mauritius	31	*Walker and Nicolaysen* [1954]
	Reunion	62	*Lacroix* [1936, 1939*b*]
Pacific (412)	Easter	18	*Bandy* [1937]
	Galapagos	8	*Richardson* [1933]
	Juan Fernandez	8	*Lacroix* [1928]; *Quensel* [1912, 1952]
	San Ambrosio and San Felix	5	*Willis and Washington* [1924]
	Pitcairn	6	*Lacroix* [1928]
	Marquesas	32	*Chubb* [1930]
	Society	38	*Lacroix* [1923]
	Tubuai	18	*Campbell-Smith and Chubb* [1927]; *Lacroix* [1928]; *Jeremine* [1959]
	Samoa	22	*Daly* [1924]; *Lacroix* [1928]
	Ponape	15	*Yagi* [1960]; *Stark and Hay* [1963]
	Truk	16	*Stark and Hay* [1963]
	Hawaiian Islands	226	*Macdonald* [1949]; *Macdonald and Eaton* [1963]; *Macdonald et al.* [1960]; *Macdonald and Katsura* [1961, 1962]; *Muir and Tilley* [1961, 1963]; *Stearns* [1940]; *Stearns and Macdonald* [1942]; *Tilley and Scoon* [1961]; *Washington* [1923]; *Washington and Keyes* [1926]; *Wentworth and Winchell* [1947]; *Winchell* [1947]

TABLE 2. Distribution of Geographically Circumoceanic Analyses and Check List of Source References

Location	No. of Analyses	References
Japan (265)		
Daisetsu and Tokachi	11	*Katsui* [1961]
Tarumai	16	*Ishikawa* [1952]
Kutcharo, Mashu	17	*Katsui* [1961]
Nyoho, Akanagi	9	*Yamasaki* [1954]
Omuro-yama	18	*Kuno* [1954]
Nasu	10	*Kawano et al.* [1961]
Hakkoda, Towada	10	*Kawano et al.* [1961]
Azuma, Adatara, Bandai, Nekoma	18	*Kawano et al.* [1961]
Takahara	7	*Kawano et al.* [1961]
Taga	11	*Tsuya* [1937]
Usami	8	*Tsuya* [1937]
Amagi	8	*Tsuya* [1937]

TABLE 2. (Continued)

Location	No. of Analyses	References
Hakone	36	*Kuno* [1950, 1962]
Osima	19	*Iwasaki et al.* [1958]
Izu Islands	67	*Iwasaki et al.* [1958]; *Kuno* [1962]; *Tsuya* [1937]
South Pacific (103)		
Saipan, Guam, Marianas	22	*Schmidt* [1957]
Iwo-Jima	10	*Macdonald* [1948]
New Hebrides	51	*Lacroix* [1939*a*]
Tonga Islands	7	*Richard* [1962]
South Shetland Islands	13	*Tyrrell* [1945]
South America (49)		
South Sandwich Islands	4	*Tyrrell* [1945]
Cerro Tronador, Patagonia	8	*Larsson* [1941]
Chile	16	*Friedlaender* [1933]; *Hausen* [1938]; *Larsson* [1936]
Ecuador	13	*Washington* [1917]
Peru	8	*Bearth* [1938]; *Jenks and Goldich* [1956]
Central America (49)		
El Salvador	21	*Meyer-Abich* [1958]; *Williams and Meyer-Abich* [1955]; *Weyl* [1961*b*]
Guatemala	2	*Weyl* [1961*a*]
Nicaraugua	26	*Burri and Sonder* [1932]; *McBirney* [1958]
Mexico (68)		
Paricutin and vicinity	40	*Wilcox* [1954]; *Williams* [1950]
Tequila, Orizaba, Colima	10	*Burri* [1930]
Miscellaneous (active)	18	*Mooser* [1958]
Alaska and Aleutian chain (136)		
Katmai	39	*Bordet et al.* [1963]; *Fenner* [1926, 1950]
Unalaska	7	*Drewes et al.* [1961]
Umnak	18	*Byers* [1961]
Adak and Kanaga	16	*Coats* [1952]
Delarof and Andreanov	7	*Fraser and Barnett* [1959]
Semisopochnoi	15	*Coats* [1959]
Amchitka, Rat, etc.	7	*Lewis et al.* [1960]; *Nelson* [1959]; *Powers et al.* [1960]; *Simons and Mathewson* [1955]
Kiska and Little Kiska	9	*Coats et al.* [1961]
Little Sitkin	13	*Snyder* [1959]
Buldir	5	*Coats* [1951]
Kamchatka and Kurile chain (154)		
Ichinsky	10	*Vlodavetz and Piip* [1959]
Sheveluch	26	*Vlodavetz and Piip* [1959]
Kliuchevsky	52	*Vlodavetz and Piip* [1959]
East central Kamchatka	15	*Vlodavetz and Piip* [1959]
Avachinsky Bay	19	*Vlodavetz and Piip* [1959]
Southern Kamchatka	3	*Vlodavetz and Piip* [1959]
Kurile Islands	29	*Gorshkov* [1958]
Indonesia (179)		
Java	82	*van Padang* [1951]
Sumatra	91	*Westerveld* [1952]
Barren and Narcondam Islands	6	*Washington* [1924]

Great rift in Africa, however, the Cenozoic volcanoes of the continents are mostly extinct. The geological situation of Cenozoic volcanism on the continents often seems either completely uninformative or capriciously variable, but it is possible that this was not so during the time of active volcanism. A proper understanding of the environmental relationships of continental Cenozoic volcanism requires a thorough knowledge of broad regional tectonics and detailed local stratigraphy. In this paper we are not concerned with continental Cenozoic volcanism.

Distribution of Two Summary Normative Parameters in the Oceanic and Circumoceanic Volcanic Assemblages

At the time of this writing our reference file includes 1003 geographically circumoceanic analyses and 834 analyses of oceanic volcanic rocks. The sample distributions of the Thornton-Tuttle index (the sum of normative Ne, Lc, Or, Ab, and Q) and of the sum of normative salic minerals are listed in Table 3 and shown in Figure 1. It is evident from a glance at the figure that there are indeed important collective or group differences in these distributions. For the Thornton-Tuttle index the oceanic volcanics peak sharply at 25 and 90 while the circumoceanic volcanics show a broad but well-defined region of high density centered between 45 and 50, near the lower boundary of the conspicuous region of low density in the oceanic suite. The principal difference between the Thornton-Tuttle index and the sum of normative molecules (Σ(sal), the major taxonomic parameter of the CIPW classification) is that the latter includes An. The difference in sample distributions of the two statistics is striking. The oceanic peak at 25 in the Thornton-Tuttle index is raised to 55 by the addition of An; the circumoceanic peak between 45 and 50 moves up to between 75 and 80.

TABLE 3. Distribution of Thornton-Tuttle Index and Σ (sal) in Geographically Oceanic and Circumoceanic Cenozoic Volcanics

Upper Class Mark	Thornton-Tuttle Index		Σ (sal)	
	Oceanic	Circum-oceanic	Oceanic	Circum-oceanic
5	1	0	0	0
10	4	0	0	0
15	30	8	1	0
20	72	17	2	0
25	149	50	7	0
30	124	98	29	0
35	79	81	42	0
40	61	125	33	1
45	31	114	70	4
50	31	103	93	8
55	20	100	118	19
60	23	69	91	49
65	19	48	57	110
70	17	49	39	134
75	12	30	39	179
80	26	32	37	177
85	43	27	34	151
90	66	24	73	80
95	26	26	66	69
100	0	2	3	22
Σ	834	1003	834	1003

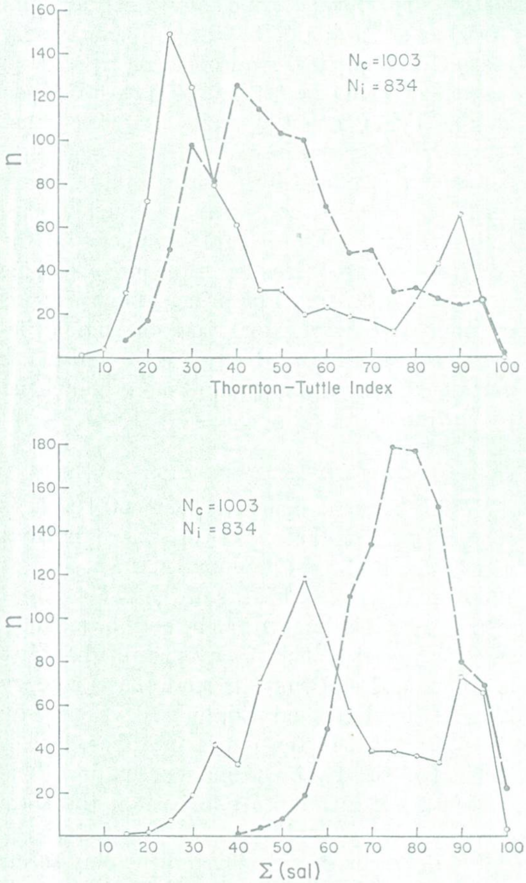

Fig. 1. Sample distributions of Thornton-Tuttle index and Σ(sal) in oceanic and circumoceanic Cenozoic volcanics. (Oceanic, solid line and open circles; circumoceanic, dashed line and solid circles.)

Although group differences emerge as clearly with one statistic as with the other, neither provides a useful criterion for classifying individual specimens. For the Thornton-Tuttle index the overlap is so complete that this is self-evident, but low values of Σ(sal) are very rare in circumoceanic analyses. If we classify as oceanic any analysis in the collection in which Σ(sal) is less than 55, for instance, more than 90 per cent of these decisions will be correct. But if we classify as circumoceanic any analysis with Σ(sal) over 55 our probability of error is very nearly 1 in 3 whereas we would not expect it to be greater than 1 in 2 if we based each decision on the flip of a coin. Results based on other previously suggested normative or chemical parameters are equally unsatisfactory.

Although feldspathoidal salic and highly magnesian femic volcanics are common in the oceanic and rare or lacking in the circumoceanic environment, in terms of principal constituents or normative parameters the distinction between other lavas of the two environments is much more a matter of group than of individual properties.

Circum- and Intraoceanic Basalts

In the circumoceanic environment basalt is common and in the oceanic islands it is by a large margin the most abundant lava. It was long considered that basalts of the two environments differed in important chemical or mineralogical properties. This view fell into disrepute in the second and third decades of the century but was revived and skillfully developed by *Kennedy* [1933]. Its renaissance has led to much fruitful research and speculation. The present concensus appears to be that there are indeed two principal types of basalt, but the notion of a sharp geographical dichotomy seems once more to be losing favor. Following a suggestion first made by *Tilley* [1950], for instance, contemporary students of Hawaiian petrography are in agreement that tholeiite, Kennedy's name for the basalt type specifically characteristic of continental areas, is abundant in this island group. Lavas very like the tholeiites of Hawaii are known from other oceanic islands, and their recognition appears to require either abandonment or drastic modification of the Kennedy model, according to which there are two principal basalt types, an alkaline one which may occur anywhere on the earth and a tholeiitic one confined to the continental areas of the globe. The old argument thus continues in a new form.

We have already noted that despite marked differences in group properties no compositional parameter so far suggested for the purpose will permit us to distinguish efficiently between individual lavas of the oceanic and circumoceanic environments. Salic lavas of the oceanic islands, unlike those of the circumoceanic environment, are usually feldspathoidal, but such lavas are only a minor member of the oceanic assemblage and are far from abundant in the circumoceanic environment. The critical problem is thus whether the basalts of the two environments can be distinguished from each other on the basis of composition. Machine sorting makes it possible to examine this matter with a thoroughness and detail not previously possible.

Our first requirement is a definition of basalt relying only on the raw chemical analysis or parameters which can be computed from it. For present purposes a very simple one proves satisfactory. Rocks with SiO_2 greater than 53 per cent or Thornton-Tuttle index over 40 rarely satisfy any petrographic definition of basalt. Making appropriate allowance to assure inclusion of doubtful specimens, if we reject every analysis with SiO_2 greater than 54 per cent or Thornton-Tuttle index over 50 we shall retain almost every specimen called basalt as well as an occasional one called andesite and a few exceedingly mafic phonolites and trachyandesites. In the remainder of this paper the term 'basalt' is used neither in its traditional sense nor in the sense assigned it in any petrographic classification, but merely to denote a lava whose analysis shows less than 54 per cent SiO_2 and whose norm yields a Thornton-Tuttle index of less than 50.

Distribution of essential oxides in oceanic and circumoceanic analyses meeting these specifications are listed in Tables 4 and 5 and shown in Figures 2 to 5. Comparisons between the basalts of the two environments show drastic differences from oxide to oxide. From the traditional distinction between 'alkaline' and 'calc-alkaline' suites we might anticipate that differences in contents of CaO, Na_2O, and K_2O would prove critical, but in fact these three oxides are of no help at all. High Na_2O and K_2O values are somewhat commoner in oceanic than in circumoceanic basalt, but overlap is so extensive that the content of neither alkali provides a reliable indicator of the geographic origin of the specimen in which it occurs, and even the group differences are not pronounced. The virtual identity of the two CaO distributions is both striking and unexpected.

The distributions of the remaining principal oxides other than Fe_2O_3 clearly suggest signifi-

TABLE 4. Distribution of Essential Oxides, Weight Per Cent, in 579 Analyses of Geographically Oceanic 'Machine' Basalt

Oxide	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
Origin	39.0	0	7.0	0	0	0	0	0	0
Class Width	0.75	0.35	0.75	0.50	0.60	1.00	1.00	0.35	0.35
Class No.									
1	30	0	14	2	0	0	0	0	49
2	12	2	9	10	1	2	0	1	154
3	9	5	21	37	1	5	0	7	120
4	17	7	18	65	1	35	0	20	110
5	20	17	24	60	4	57	1	35	59
6	36	54	31	68	2	57	4	55	41
7	40	75	45	66	4	71	14	121	18
8	33	96	40	60	8	83	45	87	16
9	50	78	75	46	10	44	61	75	5
10	60	74	73	35	17	33	115	49	3
11	48	59	63	35	39	29	154	49	4
12	49	45	51	31	44	30	98	28	0
13	47	23	41	18	55	31	44	17	0
14	31	20	31	9	79	27	22	14	0
15	30	10	20	10	76	18	9	7	0
16	33	6	13	14	95	8	9	6	0
17	13	3	4	4	77	6	0	5	0
18	20	3	1	1	47	10	2	1	0
19	1	1	2	3	13	4	1	1	0
20	0	1	1	1	2	5	0	0	0
>20	0	0	2	4	4	24	0	1	0

TABLE 5. Distribution of Essential Oxides (weight per cent) in 360 Analyses of Geographically Circumoceanic 'Machine' Basalt

Oxide	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
Origin	39.0	0	7.0	0	0	0	0	0	0
Class Width	0.75	0.35	0.75	0.50	0.60	1.00	1.00	0.35	0.35
Class No.									
1	0	10	0	2	0	0	0	0	75
2	0	31	0	3	3	0	0	0	97
3	0	154	0	4	1	18	0	3	73
4	1	84	0	15	2	48	0	9	62
5	0	49	0	52	5	123	0	27	26
6	0	15	1	53	4	76	2	60	16
7	1	4	5	61	9	40	5	54	6
8	1	8	2	50	24	21	15	66	4
9	4	2	5	49	29	14	70	66	1
10	3	0	9	26	46	12	106	46	0
11	8	1	30	14	68	3	86	19	0
12	7	1	41	10	50	2	51	6	0
13	18	0	35	4	29	1	18	1	0
14	17	0	40	4	25	0	5	0	0
15	27	1	57	5	17	1	1	2	0
16	51	0	50	3	8	0	1	0	0
17	55	0	39	4	16	0	0	0	0
18	56	0	32	0	14	0	0	1	0
19	59	0	6	0	4	1	0	0	0
20	52	0	5	0	3	0	0	0	0
>20	0	0	3	1	3	0	0	0	0

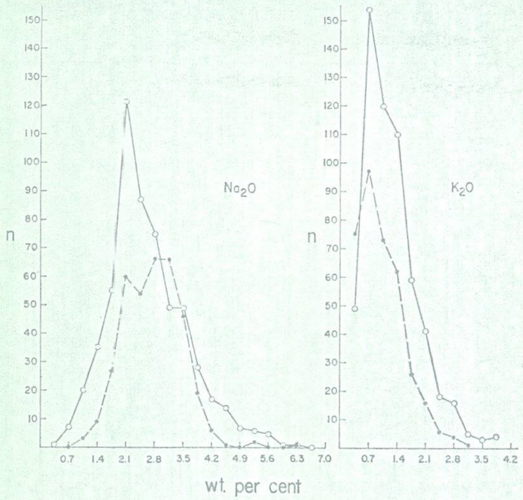

Fig. 2. Sample distributions of alkalis in 360 circumoceanic and 579 oceanic Cenozoic basalts. Symbols as in Figure 1.

cant group differences, oceanic basalts being on the whole richer in FeO and MgO and poorer in Al_2O_3 and SiO_2. Persuasive as these group differences are, however, the sample distributions are such that no one, and probably no unweighted combination, of the oxides so far discussed may be expected to provide an effective discriminant for individual specimens.

In discussions of this problem TiO_2 rarely receives more than incidental notice and is frequently ignored. From time to time it is pointed out—for instance, by *Kushiro* [1961]—that of two lava types otherwise similar in bulk composition, the oceanic one will usually be richer in TiO_2. So far as I know, however, no one has suggested that the actual amount of TiO_2 in a specific basalt analysis might provide a reliable basis for deciding whether the basalt is geographically oceanic or circumoceanic in origin. Yet this is precisely what the data show. As a discriminant, TiO_2 is superior to any other oxide or commonly used combination of oxides; it is also rather efficient in an absolute sense. Of the 360 circumoceanic basalts in the tally, only 32 contain more than 1.75 per cent TiO_2; of the 579 oceanic basalts only 31 contain less than 1.75 per cent TiO_2. Classifying each of a series of analyses chosen at random from among the basalts of the present collection as geographically oceanic or circumoceanic, depending on whether it contained more or less than 1.75 per cent TiO_2, we would expect to be wrong less than once in 14 trials.

A Digression on Petrographic Terminology

Oceanic and circumoceanic mafic lavas evidently differ sharply in TiO_2 content, but useful

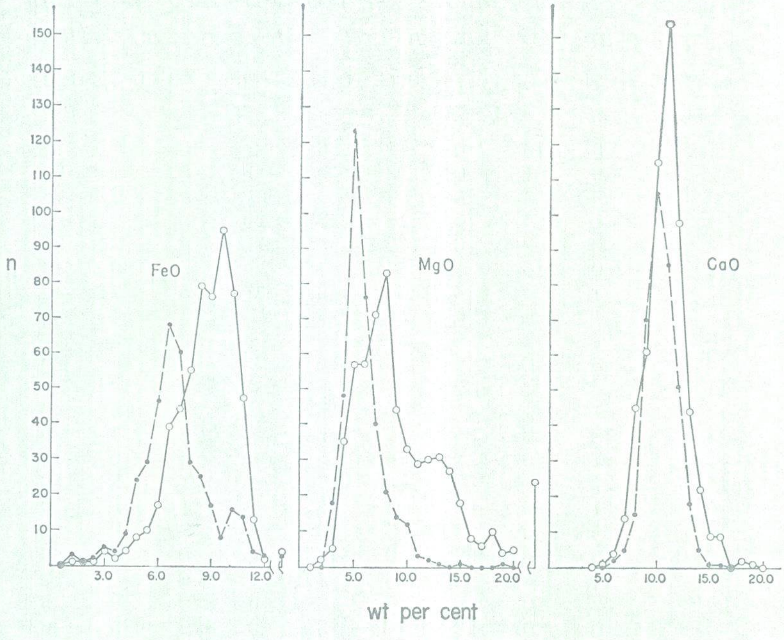

Fig. 3. Sample distributions of FeO, MgO and CaO. Data and symbols as in Figure 2.

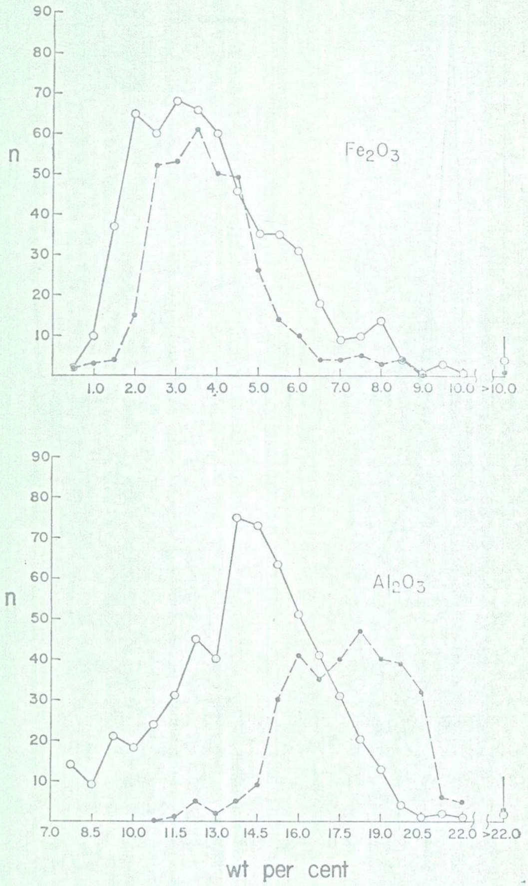

Fig. 4. Sample distributions of Al_2O_3 and Fe_2O_3. Data and symbols as in Figure 2.

comparison of salic lavas of the two environments requires characterization of the content of alkalis relative to certain other key oxides. In this section I describe and attempt to justify my own choice of terminology bearing on this matter. Confusion has so often resulted from attempts to clarify, explicate, or modify the petrographic terms 'alkaline,' 'calcalkaline,' 'tholeiitic,' 'atlantic,' 'pacific,' etc., that I shall not attempt a thorough review.

Rather, I adopt a definition of 'alkaline' which seems to have been first formalized in terms of the CIPW norm by *Holmes* [1921] but was proposed by *Iddings* [1892] long before announcement of the norm system, and which conforms closely to customary petrographic usage. In most plutonic igneous rocks, and probably in most magmatic rocks of all kinds, the molar amounts of available silica and alumina are such that if this were the only requisite condition, all the alkalis present *could* form feldspar. When this situation exists, the CIPW norm in fact does form Ab out of all soda and Or out of all K_2O, and in the Holmes nomenclature the rock (or analysis) is calcalkaline. (In most such rocks there will be some excess of Al_2O_3 over that required for (Or + Ab); if, CaO being present, the molar inequality CaO > (TiO_2 − FeO) holds, as it does in the vast majority of analyses, the norm will then contain An. But there is no requirement that An or (An + Ab) be strongly dominant over Or, so that the analogy between the modal classification of Rosenbusch and the normative one of Holmes is not exact.)

If either silica or alumina is not in sufficient supply, the alkalis must find some other normative expression, and in eucrystalline rocks they appear in other modal assemblages as well. If silica is insufficient, the norm will contain feldspathoids, and, if there is any soda in the rock, the CIPW conventions require that Ne be the first of these to appear. If alumina is insufficient, that is to say, if the molar amount of Al_2O_3 is less than that of the molar sum (Na_2O + K_2O), the CIPW conventions require formation of the soda-iron pyroxene Ac. This can occur only if both Na_2O and Fe_2O_3 are present, but it is very rare that either is entirely lacking. Thus a departure from the usual sufficiency of SiO_2 and Al_2O_3 will nearly always be indicated by the appearance of Ne or Ac (or both) in the norm. Such analyses, following Holmes, I shall call *alkaline.*

Petrographic usage of the term calcalkaline, perhaps never as simple as the definition proposed by Holmes, has become progressively more complex and is now hedged in with geographic restrictions as well as chemical considerations having nothing to do with the contents of lime, soda, or potash. No one will object if norms in which (Ne + Ac) > 0 are called alkaline, for rocks whose norms behave in this fashion are considered alkaline by all petrographers. Norms in which (Ne + Ac) = 0 I shall here designate *subalkaline,* this now seldom-used term having, in normative context, about the same significance previously assigned it on mineralogical or other chemical grounds by *Iddings* [1892, p. 183], *Daly* [1914], and *Bowen* [1922]. The subalkaline class thus includes both the

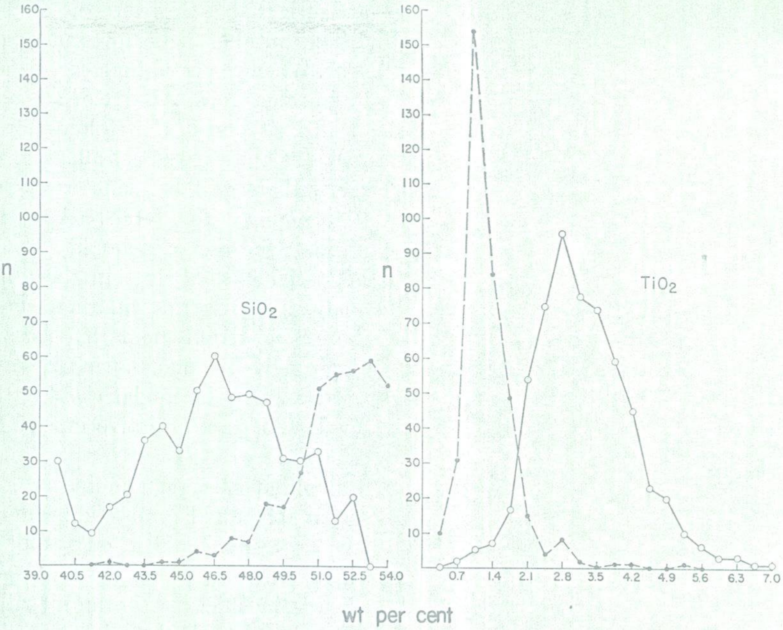

Fig. 5. Sample distributions of SiO_2 and TiO_2. Data and symbols as in Figure 2.

calcalkaline and tholeiitic groups of *Tilley* [1950] and *Kuno* [1959] and any of their 'alkali-olivine-basalt' in the norms of which $(Ne + Ac) = 0$. It is to be stressed, however, that the terms alkaline and subalkaline are used here in a purely descriptive sense, with no geographic qualifications or genetic implications whatever.

On Distinguishing Oceanic from Circumoceanic Volcanics by Composition Differences

It has long been known that salic and intermediate lavas of the open oceans are usually alkaline in the sense of the preceding section. Furthermore, although Cenozoic alkaline lavas are common in the mediterranean and continental environments, they are virtually unknown in the circumoceanic environment. (Normative feldspathoids occur, for instance, in none of the 1003 circumoceanic analyses which form the basis of this report but are present in more than 325 of the 834 oceanic analyses.) Accordingly, we combine this qualitative distinction between the salic and intermediate lavas of the two environments with a quantitative index based on TiO_2 content; the result is a hybrid discriminant which, solely on the basis of bulk composition, will classify a specimen (as oceanic or circumoceanic) with more than 90 per cent accuracy. Letting $A = (Ne + Ac)_{norm}$ and $B = TiO_2$ weight per cent -1.75, we define as *petrographically oceanic* any analysis in which either $A > 0$ or $B > 0$ and as *petrographically circumoceanic* any analysis in which $A = 0$ and $B \leq 0$.

The effectiveness of this petrographic classification is shown in Table 6, in which the column headings are petrographic and the row headings geographic. If the relation were exact the leading diagonal of the 2×2 array would contain all the data and the upper right and lower left boxes would be empty. The accuracy of our discriminant is accordingly given by the pro-

TABLE 6. Two-Way Classification, Data of Tables 1 and 2

	c	*i*	Σ
C	948	55	1003
I	92	742	834
Σ	1040	797	1837

C, geographically circumoceanic; *I*, geographically intraoceanic; *c*, petrographically circumoceanic; *i*. petrographically intraoceanic.

portion of the data in the leading diagonal, $(948 + 742)/1837 = 92$ per cent. Classifying each of a series of analyses chosen at random from the collection as circumoceanic if $A = 0$ and $B \leq 0$, and oceanic if either A or B exceeds zero, we would expect to be wrong, on the average, less than once in every twelve trials.

The rather arbitrary nature of the classification, which makes use of a qualitative normative parameter widely considered to be of critical importance and a quantitative chemical one almost universally ignored, requires no apology. One of the leading questions posed by the distribution of Cenozoic volcanism is whether oceanic and circumoceanic lavas are petrographically distinguishable. The answer is that they are, and with an accuracy which, in view of the long history of fluctuating opinion on the subject, is as gratifying as it is surprising.

It is appropriate, however, to examine both the failures of the classification and the extent to which sampling biases may be contributing to its apparent success. The failures are readily summarized. Nearly all instances of class Ci—that is, geographically circumoceanic lavas which are, in our terms, petrographically oceanic (Table 6)—are titaniferous basalts. It is perhaps worth noting that although basalts of the circumoceanic environment are ordinarily very poor in H_2O, many of those in class Ci are exceedingly hydrous.

In contrast, more than two-thirds of the geographically oceanic specimens which appear to be petrographically circumoceanic—class Ic of Table 6—are salic or intermediate lavas whose norms show neither Ne nor Ac. Subalkaline salic lavas have been reported from a number of island groups (e.g., the Marquesas, the Society Islands, Ascension, St. Helena) and those of Easter Island are well known. Except possibly at Easter Island, however, they appear to be very scarce and far subordinate in volume to the normal alkaline salic lavas of this environment, despite occasional suggestions to the contrary. It has recently been asserted, for instance, that the Azores are 'andesitic' (see Gaskell in *Runcorn* [1962, p. 305]) but of the 34 complete analyses from the group so far found in the literature, only 8 fail to pass muster as oceanic and several of these are very old analyses made on extensively altered material. Sixteen of the 34 Azores analyses are of basalts very rich in titania and 10 are of alkaline type, salic or intermediate.

As with class Ci, the members of class Ic are often exceedingly hydrous, though of course a high content of H_2O is not nearly as unusual in the oceanic as in the circumoceanic environment. Whatever the explanation, water content seems closely associated with failures of the proposed relation between petrography and geography. For samples with less than 1 per cent of H_2O the accuracy of the cross classification is 93.5 per cent, as compared with 92 per cent for the entire collection, and the number of misclassifications is 74 as compared with 147.

For a first broad summary of the kind attempted here, the failures of the classification scarcely warrant a more extended discussion. The extent to which biases in the sampling of the literature may be contributing to the success of the classification is much more difficult to appraise. It is discussed in the next section.

Possible Sampling Biases

Sampling bias may be introduced by the way in which the geographic environments are defined and, given the definitions, either by arbitrary assignment of 'doubtful' suites to one or other environment or by omission of analyses, either intentional or accidental.

How much distortion have we introduced by considering as 'circumoceanic' only that portion of the ocean perimeter marked by deep trenches? After all, the oceans do have edges, whether or not they are marked by trenches. For the most part, however, the trenchless portions of the oceanic perimeter are virtually devoid of Cenozoic volcanism. The east coast of the Americas is an excellent example. Where a trench is present—the Puerto Rico trench—we have on its shoreward side petrographically circumoceanic volcanics, though, because of their distance from the trench, the Lesser Antilles have in fact been classed as mediterranean and omitted from the geographically circumoceanic group. Elsewhere along the entire Atlantic shoreline of the Americas we have only the small alkaline complex of Pocos de Caldas in Brazil, which is probably Mesozoic rather than Cenozoic; where the continent-ocean border is not marked by a Cenozoic trench, Cenozoic volcanics are not likely to be abundant and those which do occur are likely to be petrographically oceanic, whether they occur on the continent or in the ocean. As further examples, consider, for instance, Fernando Noronha, off Brazil, and the Fernando Po group in the Gulf of Guinea. The first of these has been included in the oceanic group because it is in deep water and is not known to have any connection with the South American continent. The second is classed as continental because, although it is in deep water, it is an obvious outlier of the Cameroun chain, which extends far into the African mainland. The total number of samples from the two Fernandos is so small, however, that it will scarcely matter whether all are included in either or excluded from both our groups.

It is not too difficult to decide questions of this sort when we are dealing with a portion of the ocean perimeter either marked by a modern trench or exhibiting no evidence of a trench during Cenozoic time. What shall we say of lavas strung out near or along a fossil Cenozoic trench? In this category fall the lavas of the Modoc series, Crater Lake, etc., in the far western United States, as well as those of New Guinea, New Britain, and possibly New Zealand. This would add well over 200 analyses to the present collection, and it is comforting to note that their inclusion would make little difference. The over-all accuracy of the cross classification would decrease by less than 2 per cent. Most of the new failures are contributed by New Zealand. They consist, in about equal numbers, of titaniferous basalts and alkaline salic lavas, and most members of both groups are far above average in water content. For analyses showing less than 1 per cent H_2O, in fact, the accuracy of the classification is reduced by only 0.5 per cent.

The relaxation of one restriction of course suggests the easing of others. If we are to include portions of the ocean perimeter marked only by fossil troughs, why not include modern troughs which are not—or perhaps are no longer—at the edge of the open ocean? The best example of this is the Ryukyu trench, but if we are to include the Ryukyu Islands in our circumoceanic environment, on what basis do we exclude the southern coast of western Honshu? In this way we could surely pick up enough circumoceanic analyses to counteract the effect of the unavoidable inclusion of the alkaline Eastern Otago suite in the New Zealand data. In easy steps of this sort we could soon eliminate all distinction between circumoceanic, mediterranean, and continental environments; reasons for supposing that it is desirable to maintain the distinction form the core of the next and concluding section of this paper. Here it may be of interest to point out that our literature sample is already large enough so that a few additional misclassifications outweigh many additional successful ones. In Table 6, for instance, we show 1690 successes in 1837 trials for an accuracy of 92.0 per cent, and inclusion of data from the western United States, New Guinea, New Britain, and New Zealand reduces this by about 1.5 per cent. Such a reduction would result if we added only 28 failures to our original 1837 trials, but to *increase* the over-all efficiency by a similar amount would require the addition of at least 424 new successes.

Summary and Conclusions

Even with the rather arbitrary geographic definitions of 'oceanic' and 'circumoceanic' proposed at the beginning of this paper, the Cenozoic lavas of the two environments are on the whole rather similar in composition. Feldspathoidal lavas are virtually unknown, and extreme enrichment in MgO is very rare in the circumoceanic environment. But considerably less than half the oceanic lavas of the collection are normatively feldspathoidal and, although extreme MgO enrichment is properly regarded as characteristic of the oceanic suite, it is actually found in less than 15 per cent of the oceanic analyses. Basaltic rocks are by far the commonest kind in the ocean basins, and comprise more than a third of the collected analyses of circumoceanic lavas. As a group, oceanic basalts tend to be richer in FeO and MgO, and poorer in Al_2O_3 and SiO_2, than circumoceanic ones. Despite this rather clear suggestion of group differences, however, overlap in composition is extensive; as far as content of what are ordinarily considered essential constituents is concerned, most basalts could belong as well to one group as to the other.

In view of this it is surprising that a rather simple discriminant, based on TiO_2 content and 'alkalinity' relative to SiO_2 and Al_2O_3, suggests a very strong association between petrography and geography in these two environments. Of the 1003 geographically circumoceanic analyses examined, none is normatively alkaline and 948 contain less than 1.75 per cent TiO_2. Of the 834 oceanic analyses, on the other hand, 742 are either normatively alkaline or contain more than 1.75 per cent of TiO_2. In sum, 89 per cent of the geographically oceanic analyses are petrographically oceanic and 94.5 per cent of the geographically circumoceanic analyses are petrographically circumoceanic. Geographic-petrographic associations of this strength are rare, and the relative simplicity of volcanism in and around the oceans contrasts strikingly with the situation in mediterranean or continental areas.

An earth model which 'explains' how the two lava suites may occur within short distances of each other and yet maintain their identities fairly well in the mediterranean areas is only a beginning; a satisfactory model must explain also how, despite the ready availability of both types in the shallow-sea areas, the oceanic suite may be unknown in the circumoceanic environment and the circumoceanic suite very rare in the oceanic environment.

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