

The Possibility of Geochemical Provinces in the Ocean Basins

Earl *Ingerson**

Abstract

From early chemical analyses of igneous rocks of ocean basins, particularly those near the margins of the basins, it was postulated that there are two different types of oceanic igneous rocks. The "Pacific series" was characterized as of tholeiitic type and the "Atlantic series" as alkalic with a low alkali-lime index.

As analyses accumulated, particularly from midocean ridges, it became apparent that the postulated sharp division was not valid. Moreover, analyses of rocks from sequences in large volcanic piles like the Hawaiian Islands indicated that the alkalic volcanics are probably derived by differentiation of a tholeiitic magma, which appears to be the fundamental one in *all* ocean basins. This impression is strengthened by studying analyses of basal basalts from mid-ocean ridges in the Indian and Atlantic oceans, from the Hawaiian Islands, the East Pacific Rise, etc. The percentages of major elements overlap completely and it is not possible to select any element or combination of elements that would characterize any particular area.

The same thing, by and large, is true of trace elements, although some authors have postulated geochemical provinces in oceanic areas on the basis of the rather scanty data available. There are larger percentage variations than those of major elements, but these may be due to the use of different analytical techniques by the various laboratories, inadequate or improper sampling methods, submarine alteration, mild metamorphism, etc. Differentiation produces much larger variations, so the only really valid comparison is of analyses of flows of primitive undifferentiated tholeiitic magma.

* Prof. Dr. Earl *Ingerson*, Dept. of Geology, University of Texas, Austin, Texas 78 712, USA.

Most of the analyses available are of samples dredged from ocean margins and ridges, sea mounts, etc. What is needed now is to fill in some of the gaps by analyzing cores of igneous rocks brought up from underneath the cover of sediments on the broad ocean floors and eventually from some of the deeps. Analyses for major and trace elements should be done on the same samples and, particularly for trace elements, the determinations should be done in the same laboratory, or if in different laboratories by the same methods and closely co-ordinated so that the results will be as closely comparable as possible.

Zusammenfassung

„Geochemische Provinzen auf den Ozeanböden“

Aus früheren chemischen Analysen magmatischer Gesteine von den Ozeanböden und hier vor allem solcher, die nahe der Ränder der Ozeanbecken genommen wurden, wurde die Forderung nach zwei verschiedenen Typen ozeanischer magmatischer Gesteine erhoben. Die „Pazifische Reihe“ war durch den tholeiitischen Magmentyp, die „atlantische Reihe“ als alkalisch mit niedrigem Kalk-Alkali-Index gekennzeichnet.

Sobald mehr Analysen vor allem von den mittelozeanischen Rücken vorlagen, wurde klar, daß diese scharfe Zweiteilung keine Gültigkeit hat. Vielmehr ergaben die Analysen ganzer Gesteinsserien in großen Vulkanbauten wie z. B. den Hawaiischen Inseln, daß die alkalibetonten Effusiva wahrscheinlich durch Differenziation aus tholeiitischem Magma entstanden sind, welches das ursprüngliche Magma in allen Ozeanbecken zu sein scheint. Dieser Eindruck wird durch das Studium der Analysen von Basalten der mittelozeanischen Rücken des Indischen und Atlantischen Ozeans, von den Hawaiischen Inseln, dem Ostpazifischen Rücken und anderen bestärkt. Die Prozentanteile der Hauptelemente decken sich weitgehend und man kann kein Element oder keine Elementgruppe erkennen, die ein bestimmtes Gebiet charakterisieren würde.

Dasselbe gilt im großen und ganzen auch für die Spurenelemente, obwohl einige Autoren trotz der geringen Zahl verfügbarer Daten geochemische Provinzen in ozeanischen Bereichen unterschieden haben. Es gibt hier größere Schwankungen der Anteile als bei den Hauptelementen, was aber auch von den verschiedenen angewandten Bestimmungsmethoden in verschiedenen Laboratorien, unzulänglicher oder ungeeigneter Probenahme, untermeerischen Veränderungen, schwacher Metamorphose etc. herrühren mag. Die Differenziation erzeugt viel größere Unterschiede, sodaß der einzig zulässige Vergleich auf Analysen von Lavaströmen ursprünglichen, undifferenzierten tholeiitischen Magmas beruht.

Die meisten der verfügbaren Analysen stammen von Proben, die von den Rändern der Ozeanbecken, ozeanischen Rücken oder von Guyots gedredgt wurden. Was wir heute anstreben ist, die bestehenden Lücken durch Bohrkernanalysen

magmatischer Gesteine, die vom Untergrund der Sedimentbedeckung der breiten Ozeanböden und eventuell auch von den Tiefseegräben stammen, zu füllen. Die Analysen der Haupt- und der Spurenelemente sollte an denselben Gesteinsproben vorgenommen, und die Bestimmungen — dies gilt vor allem für die Spurenelemente — im selben Laboratorium durchgeführt werden, oder wenn dies nicht möglich ist, zumindest mit denselben Methoden und in enger Zusammenarbeit erfolgen, um so gut als möglich vergleichbare Ergebnisse zu erhalten.

Introduction

The idea of chemical inhomogeneities in the upper mantle that may extend into or beneath ocean basins as recognizable geochemical provinces is not new. The nomenclature was different, but the concept goes back at least to the publication of Volume II of J. E. *Spurrs Ore Magmas* in 1923. He used the notion that there are areas in the "stable under-earth" enriched in certain metallic elements to explain both "metallographic" (metallogenic) provinces and metallogenic epochs.

Spurr describes the immense distribution of late Tertiary lavas all around the Pacific, but points out that only in certain restricted areas, such as in parts of Arizona and New Mexico, are there significant copper deposits associated with the lavas. He attributes this to heterogeneities in the material underneath the crust, — the "permanent storehouse of the metals", from which the magmas are generated, or at least where they acquire their abnormal load of ore metals.

Spurr pictures this as the lowermost of three zones that „have to do with ore deposits". The intermediate zone is in the lower part of the crust and is "stable neither as to form nor as to position". In a lower sub-zone of the intermediate zone the magma moves but does not differentiate; the upper sub-zone is one of differentiation.

Differentiation produces concentrations of ore metals, in metallographic provinces, which give rise to ore deposits in the top part of the intermediate zone and the lower parts of the uppermost zone, which is a superficial crust of consolidated rocks, and is stable in form but unstable in position.

Spurr postulates that the heterogeneities in the lowermost layer (our upper mantle) "originated at least far prior to the beginning of our geological record". This picture readily explains the existence of a metallogenic province at a given time, but in order to explain repeated metallogenic epochs that supplied the same element(s) to the same area of the crust at widely separated times it is necessary to assume that the heterogeneities in the upper mantle were not only in fixed positions with respect to each other, but also that they had a fixed relation to the overlying crustal rocks.

For example, there have been four periods of copper mineralization in Arizona, ranging in age from Precambrian to late Tertiary and separated by spans of time from about 50 m. y. to some 500 m. y. *Spurr* pictures only localized

movement of magma picking up copper from the copper-rich areas and moving upward into the crust in response to imbalance produced by erosion, telluric pressures, etc.

Large scale, deep acting convection currents in the mantle would destroy the inhomogeneities at the top of the mantle, or at least would remove them from their respective positions subjacent to "metallogenic provinces" in the crust. Likewise, large scale movements of continental masses over, or through the upper part of, the mantle would destroy these relationships.

It appears to be necessary to assume, therefore, either 1) that there have been no large scale relative movements between mantle and crust, at least since very early geologic time or 2) that the "permanent storehouses of the metals" are not in the mantle at all, but in a zone low in the crust where they can maintain more or less constant spatial relations to the overlying units even if the whole system is in motion with relation to the underlying mantle.

It is not difficult to imagine a model of this kind, — heterogeneities near the base of the crust that are enriched in ore-forming metals. They could be in a zone of magma generation and/or in the path of a more primitive magma ascending from the mantle, which could pick up metal from the "storehouse" and on subsequent differentiation yield up at least part of it to form ore deposits.

The situation is quite different in ocean basins. If the present widely accepted hypotheses about sea floor spreading, plate tectonics and continental drift are correct, then vigorous subduction zones at continental margins would preclude extension of the heterogeneities that may serve as the basis of geochemical and metallogenetic provinces into or beneath the ocean basins.

If it were established that the geochemical and/or metallogenetic provinces do extend from continental masses into adjacent ocean basins the reality of the supposed subduction zones could be questioned and a model involving permanent chemical heterogeneities in the upper mantle that transcend continental boundaries would again become a theoretical possibility.

On the other hand, if no such extensions can be demonstrated the question of the existence of geochemical provinces in the ocean basins is a problem that is not directly related to that of similar provinces on the continents and must be approached independently.

If the current popular theory of up-welling-translation-subduction has any validity it will certainly not be possible to identify any "permanent" inhomogeneities in the oceanic crust or the underlying upper mantle, which have existed since early geologic times.

Because there are so many uncertainties about the rate, direction, and depth of circulation of possible convection currents in the mantle, it would be very difficult to set up a model that would enable one to predict the types, locations, extent, duration, etc., of geochemical provinces that might exist in ocean basins.

Suggested Studies

A more realistic approach would be to demonstrate empirically whether such provinces do exist. If their existence can be proved, then a model constructed to explain their properties might also help in the critical study of some of the hypothetical and controversial mechanisms that have been proposed to explain other features of ocean basins. Since large numbers of samples from many places in the ocean basins are becoming available for study, a logical approach would be to study the question of geochemical provinces in oceanic materials first. Then, if such provinces can be identified and outlined, the problem of their possible correlation with similar provinces on the continental masses can be pursued subsequently.

The suggested empirical study of the geochemistry of ocean basins might consist of three stages for the present and near future:

1. Compile, study, and plot all usable analyses, both for major and trace elements, that have been made of igneous rocks from all of the principal ocean basins.

2. Analyze all available appropriate samples from the current deep drilling programs. When preliminary results are available perhaps the scientific staffs could be prevailed upon to modify plans as to depth of drilling and/or details of location of holes in the interest of contributing more significantly to the geochemical studies.

3. The currently planned drilling "legs" will provide only a very loose network of sample locations. Many of the drill holes do not penetrate to the igneous rocks, or they provide only a little weathered material. If steps 1 and 2 appear to warrant it, funds might be obtained to mount a special drilling program to fill in the critical areas, re-enter holes to get deeper and better samples, etc.

In considering step 1, compilation and interpretation of existing data, the problem of defining "usable analyses" immediately arises. There is no point to plotting all available analyses of igneous rocks, or even all extrusive rocks, because differentiation has proceeded to different extents and possibly in different directions, in different parts of the ocean basins. Even in a relatively compact "province" like the Hawaiian Islands (*Macdonald* 1949), the volcanic centers, even on a single island, show marked differences in degree of differentiation, with attendant large differences in amounts and ratios of both major and trace elements.

The problem is further complicated by the probability that the primary tholeiitic magma can differentiate either in the direction andesite-trachyte-rhyolite, or to produce alkalic end products such as nepheline basalt (*Bowen*, 1928; *Engel & Engel*, 1964a). Therefore, in comparing analyses of rocks for the purpose at hand we should, ideally, select samples from different areas that represent differentiation in the same sequences (calcalkalic or alkalic) and to the same degree. Moreover, other factors such as submarine alteration and mild metamor-

phism may change the composition, especially with respect to trace elements.

Since it is not possible to match degrees of differentiation accurately, or to evaluate trace element loss, or gain, during submarine alteration the logical samples to use would be fresh, unmetamorphosed ones of primary ("primitive", undifferentiated) tholeiitic basalt. It is easy to recognize, either in the samples themselves or in most published descriptions, the cumulates like oceanite or picrite-basalt and differentiates to which names other than "basalt" are given. There is still the problem of which "basalt" analyses to use for comparison; how much olivine does a "primitive" tholeiitic basalt contain? Tröger (1935) has given 7% for the type tholeiite; and the A. G. I. Glossary says a tholeiitic magma is one that "contains little or no olivine".

Perhaps the best we can do on the initial attempt is to use analyses of rocks called "tholeiitic basalts" or simple basalts, unless there is evidence in the descriptions that they contain excessive cumulate olivine or other irregularities that make them suspect. Presumably the authors and analysts will have selected the most representative and freshest material available.

There is another possible difficulty and there appears to be no way to evaluate it at the moment. The magma appears to be generated by differential melting of mantle material and the *degree of melting* at different places and at different times may produce magmas with somewhat different compositions, even without inhomogeneities in the mantle, or any differentiation subsequent to generation.

Most of the analyses made thus far are from lavas of volcanic islands and samples that have been dredged from seamounts and other relatively thick sequences. These are the places where differentiation has been most active, so the analyses must be selected with care. On the great oceanic plains the flows are undoubtedly fewer and thinner and it is probable that they are more nearly representative of the primitive tholeiitic magma. For that reason the samples obtained by drilling these areas should be interesting and important.

For the purpose at hand no attempt has been made to glean from the literature *all* of the acceptable analyses of oceanic tholeiitic basalts, but to select representative analyses and averages for widely separated areas in the three principal oceans where enough samples have been collected to give comparisons of the over-all compositions of the primary (primitive) tholeiitic rocks in the different areas.

The following were selected:

1. Mid-Atlantic Ridge
2. East Pacific Rise
3. Hawaiian Islands
4. Indian Ocean Ridges

Rocks from island arcs were not considered because they resemble continental rocks more than oceanic ones in type, association, etc. Two hundred new analyses of Canary Island "basaltic rocks" (Ibarrola, 1969) were neglected, because they are the result, in part, of alkalic differentiation, which produced some feldspath-

oid-bearing varieties; many others are high-olivine basalts, alkalic olivine basalts, etc.

The localities chosen span some 240° of longitude and at least 70° of latitude. As to petrographic type the rocks are described as basalt, tholeiite, tholeiitic basalt, olivine-bearing basalt, etc. An attempt was made to choose analyses of rocks with less olivine than the 7% mentioned for tholeiite by Tröger and most of them have less than 5% olivine. The assumption is that more olivine indicates a cumulate rather than a primary igneous rock. No analyses were selected where the presence of a feldspathoid was indicated or where the alkali-lime index suggested alkalic affinities.* However, in many cases it was not possible to be sure of mineral composition, because descriptions gave only norms, or no mineralogical composition at all, — only rock names.

Analyses showing more than 2.5—3% water were rejected. Larger amounts change the dry weight percentages of the other constituents significantly. Moreover, high water content indicates weathering or some other type of alteration, which may have an effect on concentration of some elements.

Major Elements

Table 1 gives the ranges of major element composition for tholeiitic basalts from the four selected areas mentioned above. A glance at the table shows that there are very considerable overlaps for most of the components and that many of them overlap almost completely. The Hawaiian basalts appear to be consistently high in TiO_2 and low in Al_2O_3 . This is due in part to the fact that the figures for Hawaii are from averages for the various centers, whereas the other columns represent ranges for all the individual analyses. If we take the individual analyses for Hawaii the overlaps for TiO_2 and Al_2O_3 , as well as for some of the other components, are larger.

Table 2 gives some averages that have been suggested for the tholeiitic basalts in the areas under consideration and two more general averages. It should be emphasized that these averages are not comparable in numbers or selection of samples, areas covered, volumes represented, etc.; they are just the averages of the analyses available. Nevertheless, the averages are remarkably consistent for values obtained in the way they were. The larger deviation for the Hawaiian samples (eight of eleven components outside the range of the other averages) is due to the fact that a great many of the samples were olivine-bearing tholeiites, which explains the low values for silica, alumina, and Na_2O , and the high ones for FeO , MgO and TiO_2 .

* Except trace element contents of some rocks from Polynesia (Table 3), which are included for comparison. These results on alkalic rocks are not included in any of the averages and are not used to determine total spread for the rock types under consideration.

Table 1
Major Elements in Tholeiitic Basalts

	Mid-Atl. Ridge ¹	Ind. Ocean Ridges ²	E. Pac. Rise ³	Hawaii ⁴
SiO ₂	47.11—50.91	49.52—51.39	49.13—50.42	48.39—50.66
TiO ₂	0.72—2.03	0.97—1.37	0.99—2.18	2.09—2.86
Al ₂ O ₃	14.03—20.07	15.88—21.09	14.85—17.42	13.25—14.95
Fe ₂ O ₃	0.85—2.76	0.94—4.14	1.35—4.30	1.88—4.83
FeO	4.35—9.89	7.09—7.88	4.54—10.24	6.83—9.75
MgO	6.00—10.29	5.47—8.65	5.82—8.37	7.70—9.17
CaO	10.44—14.10	10.86—13.22	10.45—12.83	9.48—10.60
Na ₂ O	2.10—3.15	2.64—3.51	2.37—3.24	1.84—2.50
K ₂ O	0.08—0.77	0.14—0.25	0.11—0.38	0.13—0.54
P ₂ O ₅	0.10—0.19	0.04—0.14	0.04—0.28	0.19—0.30
MnO	0.09—0.21	0.09—0.19	0.11—0.22	0.12—0.18

¹ *Aumento* (1968, 1969); *Engel & Engel* (1964a); *Muir & Tilley* (1964); *Nicholls, Nakwalk & Hays* (1964).

² *Engel & Fisher* (1969); *Engel, Fisher & Engel* (1965).

³ *Engel & Engel* (1963, 1964b).

⁴ *Macdonald & Katsura* (1964).

Table 2
Major Element Averages — Tholeiitic Basalt

	Mid-Atl. Ridge ¹	Ind. Ocean Ridge ²	Carls-berg Ridge Ind. O. ³	East Pacific Rise ⁴	Hawaii ⁵	Ocean Tholeiites ⁶	Ocean Floor Basalts ⁷
SiO ₂	49.78	50.65	51.81	50.25	49.36	49.94	49.61
TiO ₂	1.29	1.36	1.88	1.56	2.50	1.51	1.43
Al ₂ O ₃	16.92	17.09	15.56	16.09	13.94	17.25	16.01
Fe ₂ O ₃	1.94	1.66	3.56	2.72	3.03	2.01	
FeO	7.32	7.00	6.39	7.20	8.53	6.90	11.49
MgO	8.18	7.49	7.10	7.02	8.44	7.28	7.84
CaO	11.34	11.52	9.35	11.81	10.30	11.86	11.32
Na ₂ O	2.77	2.82	3.87	2.81	2.13	2.76	2.76
K ₂ O	0.16	0.18	0.11	0.20	0.38	0.16	0.22
P ₂ O ₅	0.14	0.08	0.20	0.15	0.26	0.16	0.14
MnO	0.16	0.15	0.17	0.19	0.16	0.17	0.18

¹ *Engel, Fisher & Engel* (1965).

² *Ibid.*

³ *Ibid.*

⁴ *Ibid.*

⁵ *Macdonald & Katsura* (1964).

⁶ *Engel, Engel & Havens* (1965).

⁷ *Cann* (1971).

The striking similarity in tholeiitic basalts over very large areas in ocean basins has led to the belief that they represent in composition the predominant if not the only magma generated beneath the ocean floors (e. g. *Engel & Engel*, 1964a). Even those who believe that alkalic magmas are generated independently agree that the tholeiitic one is very much more abundant and probably more "fundamental".

Bowen (1928) believed that both calc-alkalic and alkalic rocks could be formed by differentiation of this fundamental magma and developed a model, largely on experimental evidence, of how it could happen. A model like this is now widely accepted. There are compelling lines of evidence other than *Bowen's* experimental demonstration. The alkalic rocks in big oceanic piles like the Hawaiian Islands commonly occur near the tops of the piles; that is, they are very late in the sequence and they ascend through the same channels that gave rise to the earlier sub-alkalic rocks.

Also, trace elements that are not readily fractionated early in the sequence, such as Co, Ga, V, Y, Yb, etc., show almost identical concentrations in tholeiitic and alkalic basalts. It is highly improbable that this would be the case if the two kinds of rocks were produced from different kinds of magma that originated entirely independently.

Cann (1971) made a detailed study of major element variations in ocean-floor basalts and concluded that these can be explained by "precipitation of calcic plagioclase, forsteritic olivine and augite" and probably to a lesser extent by "crystal-liquid processes involving amphibole".

It would be possible to cite many more opinions and to give much more data supporting the essential uniformity of primary tholeiitic basalts of the great ocean basins. Two or three more examples should suffice for the present. *Kay, Hubbard & Gast* (1970) conclude that observed variations in the chemical composition of oceanic ridge volcanic rocks can be ascribed to shallow differentiation dominated by plagioclase and olivine.

Bonatti & Fisher (1971) have studied volcanic rocks on and at a distance from oceanic ridges and they conclude that "the conditions of magma generation are similar beneath ridges and away from them".

Nicholls & Islam (1971) appear to accept the essential uniformity of the major element composition of tholeiitic basalts from the ocean floor, but state that variations in trace elements are much more marked than those in major element contents. Theirs is the only positive statement encountered that "Geochemical provinces exist in oceanic areas just as they do in continental regions." See below, under *Trace Elements*, the discussion of these ideas.

Trace Elements

Trace element ranges for tholeiitic basalts from the same areas as those selected for major elements are shown in Table 3. The last two columns show values for

some Polynesian basalts with alkalic tendencies and the effects of different degrees of silica saturation, respectively. As would be expected, the undersaturated alkalic rocks (normative Ne) are high in such things as Sr, Ba, Rb and Zr, whereas the undersaturated calcalkalic rocks (normative Ol) are high in Cr and Ni. Co, Ga, Sc, V and Y do not show large or systematic variations, even in alkalic rocks or those with variable silica saturation.

Table 3
Trace Elements in Tholeiitic Basalts

T. E.	Mid-Atl. Ridge ¹	Indian Ocean Ridges ²	East Pacific Rise ³	Hawaii ⁴	Poly-nesia ⁵	Dif. Silica Satur. ⁶
Ba	20—200	6—96	6—25	50—125	200—550	14—498
Co	22—100	26—110	28—38	30—60	25—60	25—42
Cr	40—700 (3000)	65—420	160—460	300—500	125—300	67—700
Cu	45—100	62—110	64—87	100—200	—	30—100
Ga	10—25	12—38	14—20	15—30	20—25	7—22
Li	2—10	—	3—6 (21)	1—10	10—20	2—11
Ni	70—220 (1000)	85—170	58—140	70—350	120—320	51—220
Rb	5—28	4—8	10	—	5—40 (275)	1—33
Sc	10—65	20—80	30—56	10—30	—	15—61
Sr	20—320	85—240	97—120	350—600 (1000)	500—1000 (1800)	130—815
V	70—420	120—440	170—440	200—400	150—280	220—350
Y	10—60	33—39	21—60	20—30	20—25	10—54
Yb	3—6	3—4	2—7	—	—	—
Zn	51—100	—	—	—	—	35
Zr	30—160	61—165	44—150	50—200	175—230	45—333

* Alkalic tendency.

¹ *Aumento* (1968, 1969); *Engel, Engel & Havens* (1965).

² *Muir & Tilley* (1964); *Engel & Fisher* (1969); *Nicholls & Islam* (1971).

³ *Engel, Engel & Havens* (1965).

⁴ *Nockolds & Allen* (1956); *Wager & Mitchell* (1953).

⁵ *Nockolds & Allen* (1954).

⁶ *Nicholls & Islam* (1971).

If we do not consider the analyses of the Polynesian rocks of alkalic affinity then all of the trace element results from the other four areas show just as extensive overlaps as do the major element compositions of rocks from these same areas. Very many fewer trace element analyses are represented in Table 3 than the major element analyses of Table 1. If we also consider that slight contamination

or micro-inhomogeneities, differences in methods, techniques and interpretation and other vagaries of analyses of rocks for trace elements can easily result in differences of an order of magnitude in reported results, there appears to be no more reason to postulate geochemical provinces in ocean basins on the basis of trace elements than from the major element compositions.

Most of the authors of papers reporting trace element results do not concern themselves with problems of geographic differences. They are more concerned with patterns of trace element distribution in a given area, and the bearing it has on questions of magma origin, and mechanism of development of the series (singular or plural) of rocks under consideration. For example, concerning the rocks of the Mid-Atlantic Ridge *Muir & Tilley* (1964) merely say, "It is clear that a much more intensive collection and study of the rocks . . . is necessary". *Wager & Mitchell* (1953) from a study of trace elements in Hawaiian rocks conclude that "The results are in conformity with the view that the Hawaiian series are essentially the result of fractional crystallization".

Gast (1971) studied trace elements in ocean ridge basalts from three widely separated localities. He mentions no geographic differences but concludes that variations in trace element contents are explained by crystallization of plagioclase and olivine from a magma whose over-all chemistry is determined by partial melting of mantle material at depths of 15—25 km.

Nicholls & Islam (1971) discuss a number of factors that may cause apparent geographic variations in trace element contents of oceanic basaltic rocks. These probably explain most of the observed variations but Nicholls and Islam believe that after all these have been considered ". . . there remain variations in trace element contents of otherwise comparable basalts from different parts of the ocean floor, which appear to represent real variations in the trace element contents of the erupted basaltic magmas".

When we look at the discussion of individual trace elements, however, there does not seem to be a strong case for significant geographic differences. For practically all of the elements discussed specifically they say, "there are too few data", or there is "no real evidence of regional variations" or "the results are erratic", etc. Barium, to the discussion of which more than a page is devoted, appears to be the element on which Nicholls and Islam depend most heavily in postulating geochemical provinces.

On general grounds it appears that positive results on more than one element are needed to support such a fundamental postulate. And barium may be a particularly unfortunate element for such a role. Its concentration changes very rapidly and by at least an order of magnitude during differentiation in the basaltic range (*Wager & Mitchell*, 1951, Fig. 6). This is undoubtedly the explanation of some of the high Ba values of individual analyses.

Unless one could be *sure*, therefore, that basalts being compared from different localities are at almost *exactly* the same stage of differentiation, the barium concentrations would not be significant in delineating geographic differences.

Conclusion

From early chemical analyses of igneous rocks of ocean basins, particularly those near the margins of the basins, it was postulated that there are two different types of oceanic igneous rocks. The "Pacific series" was characterized as of tholeiitic type and the "Atlantic series" as alkalic with a low alkali-lime index.

As analyses accumulated, particularly from mid-ocean ridges, it became apparent that the postulated sharp division was not valid. Moreover, analyses of rocks from sequences in big volcanic piles like the Hawaiian Islands indicated that the alkalic volcanics are probably derived by differentiation of a tholeiitic magma, which appears to be the fundamental one in *all* ocean basins. This impression is strengthened by studying analyses of basal basalts from mid-ocean ridges in the Indian and Atlantic oceans, from the Hawaiian Islands, the East Pacific Rise, etc. The percentages of major elements overlap completely and it is not possible to select any element or combination of elements that would characterize any particular area.

The same thing, by and large, is true of trace elements. There are larger percentage variations, but these may be due at least in part to the use of different analytical techniques by the various laboratories.

From thoughtful consideration of these data, some of which are tabulated above, it does not appear that current available information can justify any strong stand in favor of the idea of geochemical provinces in ocean basins. I hope that I have not appeared prejudiced in favor of this point of view. I began this study fully expecting to find evidence of such provinces and thought that the principal problem would be, not the question of their existence, but rather their delineation and characterization.

Most of the analyses available now are of samples dredged from ocean margins and ridges, seamounts, etc. What is needed now is to fill in some of the gaps by analyzing cores of igneous rocks brought up from underneath the cover of sediments on the broad ocean floors and eventually from some of the deeps. This would be essentially stages two and three of *Suggested Studies*, above.

Analyses for major and trace elements should be done on the same samples and, particularly for trace elements, the determinations should be done in the same laboratory or if in different laboratories by the same methods and closely co-ordinated so that comparisons of analyses would be as meaningful as possible. It might be helpful to reanalyze (again, especially for trace elements) splits of some samples previously analyzed and reported. This could indicate the magnitude of some variations in results which are not due to geographic differences.

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