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UNIQUENESS VERSUS CONFORMITY TO PATTERN IN PETROGENESIS¹

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During the fifty years since the Mineralogical Society of America was founded much of petrological effort has been concentrated on attempts to discern, define and interpret regularly recurring patterns of igneous and metamorphic petrogenesis. The value of this approach is obvious to the teacher and writer of text books. It permits formalization, exposition and retention in the mind of large masses of information relevant to larger problems of geology—continental drift, orogeny, physical gradients in the crust, and so on. Moreover against the background of regularity—real or supposed—in petrogenesis, petrological information accumulates and new ideas are generated. Old models become more surely established, or modified, or completely discarded in the light of new data or broadening geologic background.

Conformity of rock associations to pattern not only facilitates teaching and learning in the field of petrology but it gives a sound basis for prediction in both pure and applied geology. To many geologists, too, conformity affords a mental satisfaction that comes with the illusion of safety, order, and predictability in that part of the universe in which our principal interests lie. I do not wish to deny the existence of discernible order in petrological phenomena—indeed much of my own writing has been directed toward expounding such order. But today I would simply raise a question frequently discussed in recent years with my colleague J. Verhoogen: Every geological event, like every event in human history, is unique. If we concentrate too heavily on discernment of order and pattern, may we perhaps overlook or underrate the unique quality of each igneous or metamorphic episode? Possibly uniqueness may have as great significance as conformity to pattern when we attempt to fit the phenomena of petrology into the broad framework of geology. In this address I shall touch on this question in relation to three major petro-

¹ Presidential address to the Mineralogical Society of America, 11 November, 1969.

genic problems in each of which conformity to pattern has dominated geologic thought: the nature and relations of basaltic magma types; the existence of metamorphic facies series; correlation of lunar with terrestrial rocks.

THE BASALTIC MAGMA-TYPE PROBLEM

A universally accepted fact of igneous petrology is the world-wide predominance, among volcanic rocks of all ages, of lavas of basaltic composition. The compositional range, compared with that of igneous rocks in general, is narrow— SiO_2 of the great majority of these rocks, for example, is within the range 48 to 52 percent by weight. So narrow, indeed, is the gross chemical variation in common basalts that many geologists in the first three decades of this Society's existence envisaged primitive basalt of uniform composition as the parent of all or most other volcanic rocks. R. A. Daly in particular was a champion of the world-wide basalt concept; and he derived his basaltic magma from a world-encircling lower crustal shell.

In Britain another picture was developing during the infancy of our Society. The authors of the Mull Memoir invoked the existence of two basaltic "magma-types," each giving rise to its own line of differentiation, in the Tertiary volcanic province of western Scotland. W. Q. Kennedy (1933) sought and found their analogues outside Britain. By 1933 he had defined on a mineralogical and chemical basis his *olivine basalt* (later called alkali basalt) and *tholeiitic* magma types—the first giving rise to a trachyte-phonolite the second to an andesite-rhyolite line of descent. Today no one attempts to derive all volcanic magmas from these two parental stems. But the concept, albeit modified and elaborated, remains; and through much of the literature on basaltic provinces, especially perhaps those of Hawaii and Japan, appears a recurrent question. Which of the two magma-types is the parent, which the derivative type? The question itself implies an assumption—to me unwarranted—that order in petrogenesis is so general that only one kind of basaltic magma has a truly primitive status.

With passage of time ideas on basaltic magma-types have changed:

(1) With attention focussed on Hawaii and Japan where, it is generally thought, both types have been erupted in regular time sequences, criteria for mutual distinction have been modified. Abundant normative olivine and in many cases some nepheline are typical of the alkali basalt group; hallmarks of the tholeiitic magmas are the presence of minor quartz and much hypersthene in the norm. Tilley (1950) found that the two magma types occupied widely separate fields on a plot (weight percent) of $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ against SiO_2 . Analysis of Hawaiian basalts, as

plotted by Macdonald and Katsura (1964) show no such obvious bimodal distribution. These authors, however, on the basis of observed small-scale differentiation trends, mineralogy, and normative composition can still separate the two fields by a straight line; whose equation in the silica range 43–54 percent is

$$\text{SiO}_2 = 39 + 2.7(\text{Na}_2\text{O} + \text{K}_2\text{O})$$

Here is simplicity of pattern indeed. It provokes some questions that are not easy to answer. While most of us would place the common Hawaiian oversaturated olivine basalt of the Kilauean type as tholeiitic in character, is it genetically equivalent to other tholeiitic magmas as we know them for example in the Jurassic diabase sills of Tasmania and Antarctica or the Tertiary nonporphyritic central type of Mull? Some real chemical differences between two types of magma have been demonstrated in Hawaii. Have these any fundamental genetic significance? Or have we been concentrating on chemical criteria that can be correlated only with relatively trivial but obvious near-surface differentiation trends?

(2) Over the past twenty years many students of volcanic rocks have found the framework presented by the two classic magma-types too narrow to accommodate all basaltic magmas. New magma-types have been proposed; and as basaltic magma-types have proliferated, questions inevitably arise as to their genesis, evolution and possible mutual relations. As early as 1950 Tilley was inquiring as to the status of high-alumina basalts of northern California. Kuno (1960) endorsed the concept of a high-alumina basalt magma-type and explored its character and distribution in Japan and elsewhere. Is there only one high-alumina type? And what if any are its relationships to tholeiitic and alkali-basalt magmas? And what of nephelinites and basanites which, though commonly associated with more "normal" alkali olivine basalts are chemically much further from these than are alkali basalts of Hawaii from Kilauean olivine tholeiites. A recent addition is the oceanic tholeiite magma-type of Engel, Engel and Havens (1965) with its world-wide distribution across the ocean basins and distinctive chemical character—very low K_2O (<0.2 percent) Ti, Rb, Sr, U, Zr and uniquely high Na/K. At an opposite extreme are the oceanic potassic basalts of Tristan da Cunha—is this another magma-type?

(3) Over the past decade chemical patterns of quite another kind are beginning to appear in the mass of accruing data relating to the minor-element composition and isotopic ratios observed in volcanic rocks. Particular attention has been focussed on the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio as a possible clue to the site of origin and the source rocks of primitive magmas in the mantle or higher up in the deep crust. Some of these isotopic patterns

cut squarely across the accepted magma types. I shall mention but two instances. In the Hawaiian Islands the eruptive sequence olivine tholeiite →alkali basalt has occurred repeatedly over the past 3 or 4 million years. Everywhere, regardless of place, time, or magma-type, the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of basaltic rocks maintains a value of 0.703–0.705. Similar values are characteristic of other oceanic basalts and are thought to be inherited from a common primitive source in the upper mantle. By contrast the tholeiitic diabases and basalts of continental regions have significantly higher $\text{Sr}^{87}/\text{Sr}^{86}$ ratios: No igneous rocks could resemble one another more closely—chemically, mineralogically, or texturally—than diabases from these widely scattered provinces. The $\text{Sr}^{87}/\text{Sr}^{86}$ values are high compared with oceanic tholeiites, and impart to them a character generally thought of as continental. But the extreme values (0.7115) uniformly found in the Tasmanian rocks are in the range which, where found in granites, is by general consensus attributed to origin by melting of ancient crust. Unless strontium-isotope ratios have only dubious significance—and that is heresy according to the current fashion of petrological thinking—there is some fundamental difference between the tholeiitic magma-type of Hawaii and that of continental diabase-basalt provinces. Moreover the Tasmanian tholeiite magma-type has unique qualities not duplicated elsewhere even among petrographically identical rocks (not only extreme $\text{Sr}^{87}/\text{Sr}^{86}$ values but exceptionally high Th/K and Rb/Sr).

(4) The advent of radiometric dating has brought increasing appreciation of the uniqueness of every geologic event. Mid-Mesozoic regional intrusion and extrusion of tholeiitic magma in the southern continents is now seen as a number of episodes each still of great magnitude but localized in time as well as geographically: later Triassic to mid-Jurassic in the South African Karroo; mid-Jurassic in Tasmania and Antarctica; early Cretaceous in the Paraná Basin of Brazil. Hawaiian volcanism, though spanning only three or four million years, has proved to be restricted to a million years or so on each major island. The life span of each individual volcano is even shorter. It embraces repeated eruptions in intermittent cycles separated by pauses of quiescence. Olivine-tholeiite magma has been repeatedly generated at different sites in the underlying upper mantle; repeatedly it has been followed by more alkaline magmas. There is no suggestion that a common magma reservoir has been maintained and intermittently tapped throughout the history of Hawaiian volcanism. Similarity of magmas erupted at different centers—*e.g.*, Kilauea and Mauna Kea on the island of Hawaii—must merely reflect similarity in source material and in conditions of magma genesis. But there are easily recognized differences between the basalts that build these two adjacent edifices. Those of Mauna Kea are undersaturated in

silica; 10 percent or so of olivine appears in the norm. These are the least tholeiitic of tholeiites—if indeed they do qualify for this title.

Seen in the light of these remarks the basaltic magma-types cover a broad spectrum. Probably more than one type is primitive. Others may be derivative. On a more refined but still legible scale each has its unique character: the magma-types are not just two or three but are infinite in number. The geologist who appreciates this variety among magma-types sees the mantle, wherein some basaltic magmas certainly, and most probably have their source, in a different light. The world-encircling basaltic substratum of Daly or the dual basaltic shells of Kennedy's early writing are no longer acceptable models. The upper mantle must be highly variable in composition; and within this heterogeneous mass we see magma recurrently generated at different levels covering a temperature-pressure range that adds to variety inherited from chemically variable source materials.

FACIES SERIES IN REGIONAL METAMORPHISM

When Barrow (1893) first delineated zones of progressive regional metamorphism in the Dalradian schists of the southeastern Highlands in Scotland, he set up a pattern which many of us who followed him in other lands came to regard as normal or standard. Pattern in associated metamorphic mineral assemblages is the essential foundation, too, of Eskola's concept of metamorphic facies. Both these contributions have had an enormous influence on research directed toward interpretation of metamorphic phenomena and experimental studies devised toward the same end. Some of us perhaps have placed too great an emphasis on order and pattern—especially with respect to phenomena observed on a restricted scale (*e.g.*, that of a single zone). Following preliminary steps taken by Eskola, Tilley and others, I attempted for a long time to set up a comprehensive scheme of facies and subfacies based on universally applicable criteria. In detail this has not been successful. Eskola's facies, modified and with some additions, stand up well enough. But we have come to realize that the subfacies is a unit of only local significance. The mineralogical assemblages throughout the almandine zone of southwestern New Zealand are consistent. They have much in common with those of the respective almandine zones of Barrow's Dalradian, and of New Hampshire as revealed by the work of Billings, Thompson and their co-workers. But there are discernible differences; and these, I believe, reflect differences in the temperature-pressure gradients recorded in the rocks of the three regions. Once again the unique character of the zonal assemblage (local subfacies) assumes significance that is overlooked when we seek only conformity to pattern.

The "normal" or standard status of Barrow's zones derives of course

from the fact that metamorphic zones were not mapped elsewhere for more than twenty years. And the broad pattern of zones subsequently mapped in Norway, Sweden, New Zealand, and eastern United States had much in common with those of the southern Dalradian. It was H. H. Read (1952) who first discerned another pattern, when he described regional metamorphism of what he called the "Buchan type" in a northern sector of the Dalradian in Aberdeenshire and Banffshire. Here, for example, pelitic assemblages contain andalustite and cordierite, minerals foreign to the assemblages defining the "Barrovian type" of metamorphism to the south.

When in *Memoir 73* of the Geological Society of America (Fyfe, Turner, and Verhoogen, 1958) we attempted a dozen years ago, to place some limits on pressure-temperature gradients of metamorphism, we tentatively drew a high-pressure gradient for the Barrovian zones and a gradient at lower pressure to denote the Buchan type of metamorphism. There was of course a highly speculative element in this presentation.

Japanese geologists began mapping metamorphic facies in the thirties—the pre-war work of K. Sugi (*e.g.*, 1931) being especially notable. Subsequent work by Miyashiro, Seki, Banno, and others has revealed the existence of zonal patterns very different from those of southeastern Dalradian or New England. To Miyashiro there is nothing "normal" about the Barrovian sequence. It is unfamiliar in Japan; nor can it be recognized in many another area of regional metamorphism (*e.g.*, the Californian Coast Ranges). So Miyashiro (1961) set up and developed the concept of facies series. He conceived the facies series as a mappable sequence of facies (or subfacies) as developed in some particular region; and for each facies series he inferred a temperature-pressure gradient in place. Each series so defined is unique. It was a mistake in my opinion to go further and define various standard types of facies series: andalusite-sillimanite type (Ryoke belt, Japan); low-pressure intermediate type (Read's Buchan type); kyanite-sillimanite type (Barrovian) and so on. Herein we have standardization that tends to obscure important aspects of metamorphism inherent in the uniqueness of each gradient in place and in time.

The zones of New England, the Pennine Alps, and the Otago-Alpine schist belt of New Zealand have all been identified by one or another worker with the Barrovian type. All have characteristics in common. Kyanite and sillimanite zones have been mapped in the Alps and in New England, though not in New Zealand (perhaps because pelitic schists here are rare). In all four regions there is a well defined almandine zone. But there are obvious divergences from any common pattern. Intrusion of "Older" and "Newer" granites plays a conspicuous role in Dalradian

metamorphism. Throughout the whole Otago-Alpine schist belt of New Zealand granitic rocks are conspicuously lacking. Common to all four regions is repeated deformation throughout the metamorphic cycle. However each terrane has a unique deformational history; and this may even show different relations to metamorphic crystallization at mutually distant points in the same terrane. There are divergences too as to the order of appearance of index minerals with rise in metamorphic grade. Stilpnomelane seems to be more widely developed in the chlorite zone of Otago than in that of the Dalradian. In Otago the chlorite zone is preceded by a zone of pumpellyite so far not recognized in the Alps or in Scotland. The relative order of appearance of biotite, almandine and oligoclase is not identical in all four regions. The metamorphic pattern, the facies series in each, has unique characteristics.

As divergences of this kind have become increasingly apparent there have been attempts to increase the number of standard series. Hietanen, for example, has proposed a scheme embodying eight facies series. Each is allotted a rectilinear pressure-temperature gradient radiating from surface conditions. None crosses any other! Here insistence on conformity to pattern has led to a geologically untenable conclusion namely that natural gradients plotted against temperature-pressure coordinates may never cross.

Regional metamorphism, tectonism, and orogeny are different aspects of major crustal disturbances that may span intervals of 100 million years or more. Rather than attempting to identify locally established facies series with some standard type I would suggest a procedure designed to bring out the unique character of the metamorphic history in relation to other aspects of the same disturbance. This involves two steps: (a) calibrating the temperature-pressure gradient in *place*, as recorded by the mineralogical sequence in the facies series (b) tracing, as far as this is possible, the fluctuation of conditions at any point (especially temperature) with *time* during the metamorphic cycle. Again it is radiometric dating that makes it possible to evaluate the time element in regional metamorphism.

COMPARISON OF LUNAR WITH TERRESTRIAL ROCKS

When Turkevich's analysis of α -scatter data obtained during the Surveyor 5 to 7 missions (Turkevich, *et al.*, 1967) gave us our first clear information on the chemical composition of small samples of lunar surface rock, speculation as to possible analogies between lunar and terrestrial rocks received a tremendous impetus. The high content of O, Si and Al in the lunar samples—in view of the known low melting entropy of silica and aluminosilicates—suggested that silicate melts had played a

fundamental role in their origin. To compare the lunar material with terrestrial igneous rocks was the obvious next step—and it was enthusiastically attempted by a number of geologists, but with divergent results.

The α -scatter analyses demonstrated a real difference between samples from the Sea of Tranquility and material from lunar highlands. Although limits of possible error were wide, the data seemed to exclude materials such as granite, peridotite, and most kinds of meteorite (eucrites being a notable exception at this stage). But to go further was to indulge in free speculation of the kind that is generally considered permissible in more serious types of science fiction. Some, nevertheless, were bold enough to speculate; and here are some of their published conclusions:

The analysis points to a basaltic composition. . . . It is both gratifying and significant that the chemical composition of the lunar material appears to be most like that of a common terrestrial rock. . . . Material of basaltic composition at the Surveyor V landing site implies that differentiation has occurred on the moon.

(Gault, *et al.*, 1967)

Alpha-scatter analyses of surface materials at two widely separated points on the lunar mare are interpreted as being compositionally similar to terrestrial tholeiitic flood basalts. Material analyzed by Surveyor 7 in the lunar highlands is interpreted as being compositionally similar to terrestrial high-alumina basalts.

(Jackson and Wilshire, 1968)

An opinion independently reached by optical remote sensing (Jackson and Wilshire, 1968) states

The lunar crust is probably not chondritic, but is similar in composition to terrestrial iron-rich basalts.

It is true that average compositions of basaltic rocks can be fitted to Turkevich's first analyses. I found it equally possible to fit the rarest of all terrestrial lavas—the wyomingites of Leucite Hills. When Turkevich and co-workers (1969) commendably published their final and much more refined analysis just prior to the Apollo landing they noted significant departures from basaltic composition. What is particularly clear from these later data is that a combined extreme value of $(Ca+K)/Na$ with high Fe/Mg , along with very high Ti absolutely ruled out precise analogy with any terrestrial igneous rock in the SiO_2 range 42–60 percent. This is certainly true for the Apollo samples whose analyses have since been made available. This does not exclude the possibility that lunar rocks include some that all of us would call basalt. To me, however, the possibility seems remote, even though it was put forward by highly competent geologists. Their prediction seems to be based on an assumption of or

quest for conformity to pattern—and terrestrial pattern at that. It implies that the lunar and terrestrial systems of petrogenesis must be closely similar, and that common lunar rocks must resemble common rocks of our own planet. If such a concept of lunar-terrestrial unity be valid, then we can expect to find basalts on the moon. If so I shall be surprised; even though not sharing the gratification expressed in one of the statements just cited.

POSTSCRIPT

How, in conclusion, can the student, the instructor and the research worker in petrology pay due attention to the unique as well as to the general characteristics of events, situations and processes in petrogenesis? I suggest that some study be given to case histories. Well documented accounts, for example, of the history and products of volcanism in the Hawaiian Islands, Iceland, and southwestern Germany give a picture of basaltic eruptions truer and more complete in many respects than comprehensive generalization expressed in terms of several standard magma-types. The same may be said for reconstruction of gradients in place and time for individual metamorphic provinces. To appreciate the differences in character between metamorphism in the southeast Dalradian, the Alpine schist zone of New Zealand and the Sanbagawa Belt of Japan is more important than to place each into some specific category designated—a facies series. As for moon rocks, we are dealing at present—and will for some time—with small samples. Here it will prove more profitable to compare and contrast these with individual specimens of terrestrial rock than to attempt to place them in some broad category such as a supposedly universal magma-type.

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