THE AMERICAN MINERALOGIST
JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 28 MARCH, 1943 No. 3

SOME PETROLOGICAL CONCEPTS AND THE INTERIOR OF THE EARTH*

A. F. BUDDINGTON, *Princeton University, Princeton, New Jersey.*

INTRODUCTION

"A rock becomes alive to me only when I have grasped its relations to our planet and its history." This is a quotation from the writings of Rosenbusch, the founder of petrography, and it establishes a satisfactory precedent for the interest of petrologists in the interior of the earth.

Geochemists, geologists, and geophysicists have all drawn up hypotheses for the constitution and history of the interior of the earth, adjusted to fit the facts with which they are familiar and to take account of those interpretations and principles which seem most cogent to them. The result is a variety of earth models, seemingly sufficiently diverse and attractive to fit every taste. Certain pertinent concepts, however, have been developed in the field of petrology during the present century, and we may find it interesting and perhaps profitable to review and reconsider the problem more systematically in the light of these principles than has been done heretofore.

The concepts referred to are those of fractional crystallization, fractional melting, the *systematic* nature of the variation which the great thick mafic stratiform sheets such as the Bushveld, Duluth, and Stillwater have in common, and the necessity for providing a rational mechanism for the origin of such magmas as are considered primary, or in the words of Loewinson-Lessing, proto-magmas.

SURVEY OF 20TH CENTURY HYPOTHESES

We may first start with a quick survey of some 20th century hypotheses for the constitution of the interior of the earth.

The growth in detailed analysis by geophysicists of certain physical properties, such as the variation of the velocity of earthquake waves and of density with depth in the interior of the earth during the 20th

---

* Presidential address prepared for the twenty-third annual meeting of the Mineralogical Society of America. Due to the cancellation of the meeting the address was not delivered orally.

century, is portrayed in the series of representative models in the upper row of Figs. 1 and 2 while representative attempts to interpret these in terms of lithology are shown in the series of diagrams in the lower row.

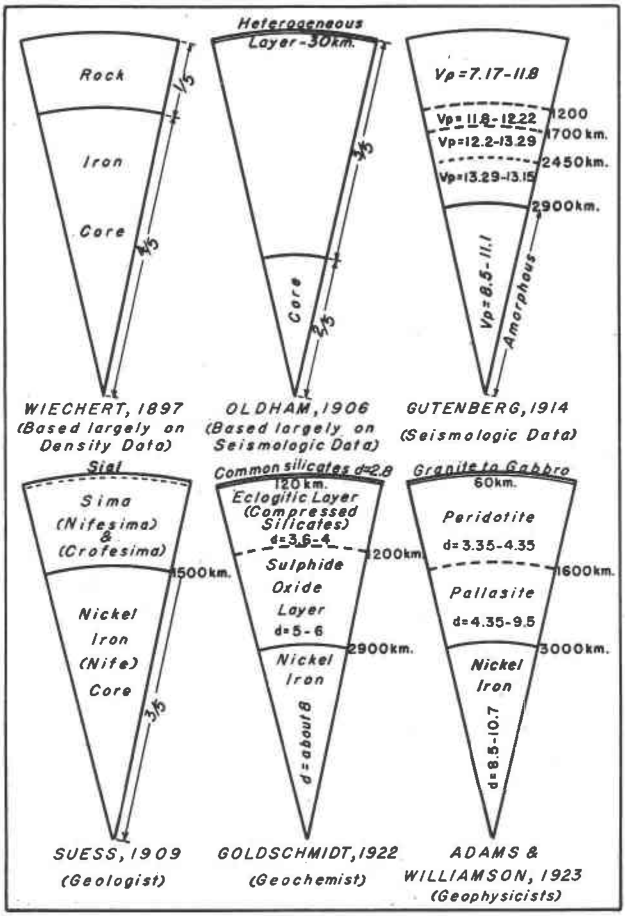

FIG. 1. Upper figures show geophysical data as interpreted by different authorities; lower figures show equivalent lithology as proposed by different men. d=density, Vp=velocity of compressional earthquake wave.

There is almost universal agreement that the most probable material forming the core of the earth is a nickel-iron comparable in character to the nickel-iron meteorites.

A thick sulphide-oxide layer is postulated by Goldschmidt on the basis of immiscibility of the sulphide melt with silicates and with nickel-iron, and gravity concentration of chromite, magnetite, ilmenite, etc. This has been criticized on the basis that it is improbable that so much sulphide exists in the earth, that if it does it should contain some metallic iron unless it also contains considerable alkali sulphide, and that trivalent

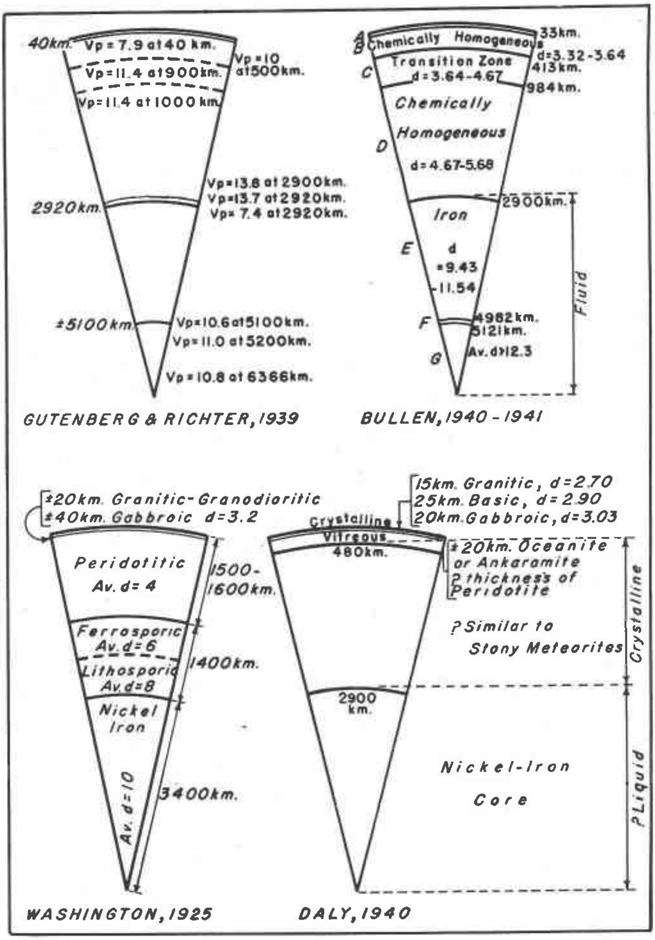

FIG. 2. Upper figures show geophysical data as interpreted by different authorities; lower figures show equivalent lithology as proposed by different men. d=density, Vp=velocity of compressional earthquake wave.

iron, such as is present in magnetite, would not be expected to form in such an environment. The criticism may also be made, by analogy with the mafic stratiform sheets, that as we shall see, magnetite and ilmenite would not be expected to crystallize at sufficiently early a stage from the mafic silicate magma to yield a concentration of them at its base. A *thin* as distinguished from a thick shell of ferrous sulphide, however, may, as suggested by Merwin (1941), be present as an amorphous or crystalline shell just outside the main core, since recent geophysical data indicate a distinct shell about 220 km. thick in this position according to Dahm, or 20 km. thick according to Gutenberg and Richter (1939). The eclogite layer, postulated by Goldschmidt, is based upon the idea that it is a deep seated high pressure facies of gabbro or peridotite. This started from the work of Fermor on the conditions for the formation of garnet and was especially expanded and developed by Eskola. The field evidence, however, shows that eclogite tends to occur locally in intensely folded mountain ranges under dynamo-metamorphic conditions and is not a characteristic member of deep seated metamorphic rocks, or of the Archaean complexes of the shield areas. Petrologists such as Backlund, Korjinsky and Dunn have raised serious objections to the validity of the concept.

The H. S. Washington model of the earth shows a gradational decrease in the content of metal through the mantle from the upper border of the core to the base of the crust. Goldschmidt has raised the objections that a much cleaner separation of the much heavier immiscible metal from the lighter liquid silicate would be expected in place of the gradation proposed by Washington, and also that the geophysical data indicate a sharper discontinuity for the border of the core.

Daly originally postulated a layer of vitreous basalt as one shell of the earth and as a source for basaltic magma. In his 1940 model he proposed a vitreous shell supposed to vary in composition from that of vitreous oceanite (or ankaramite) in the upper part to viterous peridotite in the lower part, and also states that a relatively thin interrupted couche of vitreous basalt is not excluded by the geophysical data. No explanation is given of how such a differentiated vitreous shell was brought about. A vitreous shell of basaltic composition is still suggested by him as a possibility during former times.

MANNER OF VARIATION OF STRATIFORM SHEETS AND POSSIBLE ANALOGY FOR LAYERED STRUCTURE OF EARTH'S CRUST

At widely scattered localities in the world there are sheets of igneous rock which show a layered structure with certain systematic types of variation. These sheets have great thickness, for example the Duluth, 1 to 9 miles thick; the Stillwater, 3 miles with the top not shown; the Bushveld, 2–3½ miles; and the Sierra Leone, about 4 miles thick with neither base nor top exposed. Here are examples of layered structures several miles thick of such character and origin that they may be analogous to the layered structure of the crust of the earth itself and which need to be extrapolated only ten fold or so to be as thick.

Our detailed knowledge of the manner of rock and mineral variation within thick mafic noritic and gabbroic sheets has all come within the 20th century, and more remains to be done than has yet been accomplished. A comparison, however, of the vertical sequence within the different sheets (Table 1) shows that despite much diversity in detail there are nevertheless certain systematic variations which are common to all. Numerous hypotheses have been advanced to explain the variation. Two major ones have been, respectively, fractional crystallization with gravity sorting of crystals, and successive intrusions of magma varying in composition. Whatever the cause, the significant fact is that repeatedly natural processes have operated in such fashion as to give thick stratiform sheets with superposed layers having in common certain systematic variations.

Comparison of the mafic stratiform sheets shows that, in a general way, on a gross scale there is a common systematic variation from the bottom up which may be characterized by the following rock types; at the base a relatively undifferentiated gabbroic or noritic chill facies, then ultramafic rocks with or without minor chromite layers, norite or olivine gabbro variable in composition, anorthositic layers with or without minor ilmenite-magnetite layers, quartz- or granophyre-bearing augite gabbro, granophyre or granite. In the Skaergaard sheet there are iron-rich ferrogabbros near the top. In a number of examples there are local sulphide lenses at or near the base. In general, from near the base upwards the plagioclases increase in soda, the olivines and hypersthenes in iron, olivine diminishes to zero (with the local recurrence in some sheets at a higher level), the hypersthenes diminish and augite increases, and interstitial quartz and granophyre appear in the upper facies. This is of course a very much simplified scheme for in detail there is a complex diversification within each of the mafic zones and often extensive small and moderate scale rhythmic repetition of rocks.

The position of ilmenite-magnetite layers in the upper part of some sheets have been thought by many to be anomalous and out of keeping with what might, a priori, be expected. The question may be raised as to whether the extent to which iron-rich layers *systematically* occur in the

TABLE 1. COMPARATIVE VERTICAL SEQUENCE IN SOME STRATIFORM SHEETS

	(1) DULUTH, MINNESOTA	(2) STILLWATER, MONTANA	(3) SKAERGAARD, GREENLAND	(4) BUSHVELD, AFRICA	(5) METEORITE EQUIVALENTS
Top	*Granophyre*	UNKNOWN	*Granophyre* *Ferrogabbros* Andesine, (An$_{35-42}$) Hortonolite (Fa$_{60-66}$) Ferroaugite, (Wo$_{27}$En$_{23}$Fs$_{50}$) *Hypersthene-Olivine Gabbros* Labradorite (An$_{30-60}$) Hyalosiderite, (Fa$_{34-47}$) Hypersthene (En$_{55-69}$)	*Granite*	? *Tektites*
Upper Part	*Olivine Gabbro* with anorthositic layers	*Gabbroic Zone* (5000–7000′ ±) Local interstitial quartz Labradorite, An$_{61}$ Augite (Wo$_{41}$En$_{45}$Fs$_{14}$) Hypersthene (En$_{60-70}$)		*Gabbro*, in part with interstitial Granophyre Labradorite (An$_{60-45}$) Diopsidic Px	*Eucrite* (Pigeonitic), in part with interstitial tridymite or cristobalite Bytownite (An$_{80-92}$) Pigeonite (Wo$_{15}$En$_{35-45}$Fs$_{40-50}$)
Above Central Part	*Olivine Gabbro* with *Anorthositic* (An$_{72}$) and minor *ilmenite-magnetite* rich layers near central part	*Anorthositic Zone* (5500′) Bytownite (An$_{75-90}$) Hypersthene (En$_{70-75}$) Augite (Wo$_{41}$En$_{47}$Fs$_{12}$) Olivine (Fa$_{30}$)		*Norite*, with *anorthositic* and minor *ilmenite-magnetite* layers Labradorite (An$_{70-80}$) Hypersthene Diopsidic Px	*Eucrite (Hypersthenic)* Bytownite (An$_{73-84}$) Hypersthene (En$_{66}$)
Below Central Part	*Olivine Gabbro*	*Noritic Layered Zone* (5000′) Bytownite (An$_{75-85}$) Hypersthene (En$_{78-82}$) Augite (Wo$_{41}$En$_{49}$Fs$_{10}$)		*Norite*, etc. Bytownite (An$_{76-80}$) Hypersthene	
Lower Part	*Olivine Gabbro* with *Peridotite* layers	*Ultra Mafic Zone* (2500′) Lab-Bytownite Enstatite (En$_{85}$) Olivine (Fa$_{14}$) Largely Saxonite and Bronzitite with minor chromite layers		*Bronzilite* with layers of *Peridotite* *Anorthosite*, *Norite* and *Dunite* with minor *chromite* layers Local Sulphide lenses	*Diogenites* Hypersthene (En$_{72}$), (Bytownite) *Rodites* Hypersthene (En$_{77}$), (Olivine) *Ureilites* Olivine (Fa$_{17}$), (Hypersthene)
Chilled Facies	*Olivine Gabbro*	*Norite* (Chill Facies) Lab-Bytownite (An$_{68}$) Hypersthene (En$_{58}$) Diallage Local Sulphide Bodies	*Olivine Gabbro* Lab-Bytownite, An$_{67}$ Diopside, Wo$_{52}$En$_{30}$Fs$_{18}$ Hypersthene (En$_{63}$) Olivine, Fa$_{41}$	*Norite* Bytownite (An$_{73}$) Hypersthene (En$_{58}$)	*Olivine Eucrite* Bytownite (An$_{80}$) Hypersthene (En$_{64}$) Olivine

Based on data by Grout for (1), J. W. Peoples and H. H. Hess for (2), Wager and Deer for (3), and Hall and Lombaard for (4). The olivine eucrite of (5) is based on the normative composition of the average of achondrites.

upper part of stratiform sheets has been properly appreciated. It will be recalled, furthermore, that many petrologists have concluded that the course of crystallization of a basalt leads to a concentration of iron in the residual liquid. This conclusion may be qualified, at least for one course of differentiation and restated as follows: there is one course of differentiation of basalt and norite, or gabbro, which leads to a concentration of iron and titanium in the residual liquid up to a maximum in the later stages of consolidation, followed by a sharp decrease of these constituents and the development of a salic residuum. This course of differentiation is excellently shown in successive stages in the crystallization of certain basalts, for example, that of Aziro, Japan, described by Kuno, where the aggregate of phenocryst (29%) has the composition of a bytownite anorthosite, the crystalline groundmass (59%) the composition of a gabbro with practically all the iron and titanium, and the interstitial glass (12%) the composition of a quartz diorite with very little iron and titanium. Many intrusive anorthosite and gabbro masses, other than sheets, show successive intrusions of more mafic fractions including melanocratic bodies rich in ilmenite and magnetite or in hyalosiderite, or in all three as at Split Rock in the Adriondacks; Mine Hill, R. I.; Kusa, U.S.S.R.; and Susimäki, Finland. The data given by Wager and Deer for the Skaergaard sheet show that during the consolidation of 60 per cent of the gabbroic magma there was relatively little change in the composition of the residual liquid, that most of the iron and titanium crystallized after 75 per cent and before 95 per cent was crystalline, and that the granophyric residuum amounted to only 5 per cent. The iron-rich mineral in the Skaergaard mass is an olivine. As Wager and Deer point out, however, greater oxidation of the iron should produce early solid fractions relatively enriched in iron ore and magnesium-rich ferromagnesian minerals, and this would probably affect the proportion of feldspar in the magma in the middle and late stages. If the percentage of silica remains the same, metasilicates may be expected to form instead of orthosilicates where the iron is oxidized. Whether ferrogabbro layers rich in iron-olivine are alternative or successive to anorthosite with intercalated ilmenite-magnetite layers, is a problem, but in either case the course of diversification in mafic stratiform sheets commonly leads to a maximum concentration of iron and titanium at an intermediate or relatively late stage.

The data for the variation of the velocity of earthquake waves with depth in three different sections of the country, experimentally determined data for the velocity of earthquake waves in different kinds of rock, and a proposed arrangement of rock layers consistent with the geophysical data and with the arrangement in stratiform sheets is given

TABLE 2. STRUCTURE OF OUTER SHELL OF EARTH

Km. Depth	(a) New England (Leet)		(a) Southern California (Gutenberg)	(e) E and NE of St. Louis (Walter and Birkenhauer)	PROPOSED EQUIVALENT ROCK LAYERS	d	Vp	Vs
0								
				(Sediments)	GRANITE-GRANODIORITE			
				Vp—5.62	(b) Tishomingo, Okla.		5.21	2.42
5			*Vp*—5.55	5 km.	(b) Yosemite, Cal.		5.50	
	Vp—6.13	*Vs*—3.45	*Vs*—3.23	*Vp*—6.03	(a) Quincy, Mass.	2.64	6.08	3.61
				Vs—3.63	(a) Rockport, Mass.	2.62	6.24	3.59
10					(a) Tonalite, Val Verde, Cal.	2.76		3.64
				13 km.	(c) Granodiorite	2.73	6.20	3.50
			14 km.					
15		15 km.						
	16 km.				QUARTZ GABBRO AND GABBRO			
			Vp—6.05	*Vp*—6.33	(b) Quartz Gabbro-Norite, Sudbury		6.22	3.49
20		*Vs*—3.93	*Vs*—3.39	*Vs*—3.74	(d) Quartz Dolerite, Whin Sill	2.937	6.34	
	Vp—6.77							
		25 km.	25 km.	25 km.	(a) Quartz Norite, Sudbury	2.86	6.49	3.65
25					(f) ANORTHOSITIC			
	29 km.		*Vp*—6.83		(a) Stillwater, Mont. ($Ab_{15}An_{85}$)	2.74		3.68
		Vs—4.27	*Vs*—3.66	*Vp*—7.19	(c) Plagioclase, Ab_3An_7	2.715	7.06	3.96
30			31 km.		NORITE OR OLIVINE GABBRO			
	Vp—7.17			*Vs*—4.08	(a) Olivine Diabase, Vinal Haven	2.962	*7.20	3.88
		35 km.	*Vp*—7.60		(a) Hypersthene Gabbro, French Crk.	3.033	*7.20	3.98
35	36 km.		*Vs*—4.24		(a) Feldspathic-Olivine Gabbro, Mellen	2.90	*7.45	3.71
				37 km.				
			39 km.		PYROXENITE			
40					(a) Bronzitite, Bushveld	3.289	*7.90	4.55
					(a) Bronzitite, Stillwater	3.272	7.83	4.58
45								
50			*Vp*—7.94	*Vp*—7.73				
	Vp—8.43	*Vs*—4.62			(g) PERIDOTITE AND DUNITE			
			Vs—4.45	*Vs*—4.40	(a) Dunite, Balsam Gap, N.C.	3.275	*8.00	4.57
55								
60								
65								
70								
75	Probably a slight decrease in velocity of *Vp* at a depth of about 80 km. for a limited range of depth, below which it again increases with depth (Gutenberg & Richter, 1939).				PERIDOTITE, SEMIVITREOUS-VITREOUS, ENRICHED IN HYPERFUSIBLES			
80								
85								
90								

Vp—Velocity of primary earthquake wave in km. per sec.
Vs—Velocity of secondary earthquake wave in km. per sec.
d—Density.

(a) Data from Handbook of Physical Constants. *Geol. Soc. Am., Sp. Paper* **36,** pp. 80–82, 99 unless otherwise stated.

(b) Field determinations for shallow depths, *Geol. Soc. Am., Special Paper* **36,** p. 97.

(c) From data by Adams and Williamson (1932), *Jour. Franklin Institute*, pp. 492 and 520, velocities for 10,000 megabars.

(d) *Bull. Volcanologique*, Ser. II, Tome III, p. 47 **(1938).**

(e) Walter, E. J., and Birkenhauer, H. F., *Trans. Am. Geoph. Union*, p. 406, (1941).

(f) With minor intercalated layers of ilmenite-magnetite.

(g) With minor intercalated layers of chromite and local sulphide lenses near base.

* Data for 900°C and pressure equivalent to depth of 40 km, Daly, Architecture of the earth, p. 55, **(1938)**

in Table 2. The major new feature introduced as compared with other models is the layer of bytownite-anorthosite. Ilmenite-magnetite layers or lenses up to a total of several score of feet in thickness may be intercalated in the anorthosite and chromite layers and lenses of similar aggregate in thickness may be associated with the peridotite and dunite. Local sulphide lenses may also be present in the latter ultramafic horizons.

NATURE AND VARIATIONS OF METEORITES

Analogy with the major kinds of meteorites has played so important a part in formulating our ideas concerning the nature of the interior of the earth that it is pertinent first to review their nature and the hypotheses as to the manner and cause of their variations. All the major types of meteorites are presented in Table 3. There are a number of additional kinds, but for several of these only a single specimen is known, and others, such as the mesosiderites, have been reasonably interpreted by Prior as one type injected by another so as to constitute a mechanical equivalent of our terrestrial migmatites. These are not included. Actually, nearly all types of meteorites are comprised within those chosen.

We may first see whether the manner of variation of the meteorites is amenable to interpretation as a product of fractional crystallization on the basis of our present data on the course of variation of composition arising from this cause.

TABLE 3. MAJOR MINERALS OF NORMATIVE COMPOSITION OF MOST MAJOR CLASSES OF METEORITES

METEORITE GROUP		Number of Analyses	Total Metal Fe+Ni	Molecular Ratio Fe/Ni in Metal	Molecular Ratio MgO/FeO in Silicates	Olivine	Hypersthene	Diopside	Plagioclase	Free SiO_2	Troilite	TERRESTRIAL EQUIVALENT OF SILICATES
ACHONDRITES												
(8) EUCRITES	A	9			0.7	—	43.1	15.8	37.0	1.44	.39	Bytownite quartz basalt
	B	2	.59		1.0	—	38.6	17.0	39.4	1.26	.64	Bytownite quartz basalt
	C	5			2.0	3.2	55.2	10.0	28.8	—	.50	Bytownite norite
(7) DIOGENITES		4			2.6	8.3	85.0	3.4	3.5	—	.37	Hypersthenite
(6) RODITES		2			3.4	21.3	62.0	4.2	9.0	—	1.17	Saxonitic hypersthenite
(5) UREILITES		2	7.10		5.0	68.8	18.7	2.7	1.7	—	.40	Saxonitic chrysolite dunite
CHONDRITES												
(3) SOKO-BANJA	A	5	2.8	5.2	1.7	68.2	6.0	5.0	7.6	—	5.2	Pyroxenic hyalosiderite dunite
	B	9	4.1	3.9	2.3	40.7	31.7	4.4	9.9	—	5.2	Chrysolite saxonite
(3) BAROTI		19	8.0	6.5	3.5	42.8	23.0	5.1	11.2	—	5.7	Chrysolite saxonite
(3) CRONSTAD		17	16.0	11.3	4.1	33.3	27.7	4.5	8.2	—	4.8	Chrysolite saxonite
(3) DANIELS KUIL		4	21.4	12.0		1.4	53.8	3.2	8.8	—	8.4	Enstatolite
AVERAGE FOR GROUPS OF METEORITES												
(4) ACHONDRITES		26	.9		1.8	8.6	50.6	12.1	25.3	—	.6	Melanocratic bytownite norite
(3) CHONDRITES		77	11.6	9	2.8	45.5	20.9	4.2	11.2	—	5.5	Oligoclase saxonite
(2) PALLASITES		17	48.9	9	5.7	51.0					.03	Dunite
(1) SIDERITES		318	98.3	11							.12	

(1) Farrington **(1911).**
(2) Chirvinsky, *Min. Abst.* **2,** 83 (1923).
(3) Based on data for fair to good analyses given by Prior (1916) and Farrington (1911).
(4) Average of achondrites listed plus Shergotty and Padvarninkai.
(5) Goalpara and Novo Urei meteorites.
(6) Rodite (Raoult) and Elwell (Whitfield).
(7) Shalka (Av. of Rammelsberg and von Foulon), Manegaon (Maskelyne), Ibbenbuehren (vom Rath) and Tatouine (Raoult).
(8-c) Le Teilleul (Raoult), Frankfort (Mixter), Binda (Mingaye), Cachari (Ducloux) and Lubimowka (Doklady).
(8-b) Moore County (Henderson) and Macibini (v.d. Walt).
(8-a) Juvinas, Peramiho, Stannern Constantinople, Bereba (Raoult), Jonzac (Raoult), Petersburg, Pasamonte (Foshag) and Cachari (Ducloux).

ORIGIN OF VARIATIONS WITHIN CHONDRITIC METEORITES

We shall first consider the chondritic group of meteorites. The normative olivine of chondritic meteorites as given in Farrington's (1911) tables was plotted against the ratio of FeO to MgO in the olivine, and it is found that in general as the quantity of olivine increases in amount, the olivine itself is richer in fayalite, varying from forsterite of about Fo_{85} in some of the olivine-poor Cronstad type to hyalosiderite of about Fo_{63} in the very olivine-rich members of the Soko-Banja type. This is a relationship which is the opposite of that found in terrestrial stratiform sheets. The olivine occurring in concentrated masses in the stratiform sheets is the forsterite-rich olivine, whereas that in concentrated masses in the chondritic meteorites is a hyalosideritic type. In the members of the Soko-Banja meteoritic type, however, there is a wide range in the percentage of olivine present without a concomitant change in the fayalite content of the olivine, as though there had been sorting and local concentration of the hyalosiderite crystals.

Again, Chirvinsky has shown that the percentage of troilite is about constant in the chondrites and shows no correlation with the variation in the percentage of metal as would be expected if there had been any concentration by gravity.

In striking contrast to the iron-rich character of the olivine and pyroxene of the chondritic olivine-rich rocks, the pyroxene-rich chondritic rocks are enstatolites with an enstatite extraordinarily poor in iron. There is indeed a general increase in the percentage of magnesia in the pyroxene with an increase in the amount of pyroxene in the meteorite. This is the only major relationship which might be considered consistent with the idea of fractional crystallization.

The relationships between the concentration of olivine and its composition, and the constancy in amount of troilite, however, all tend to emphasize the inapplicability of the hypothesis of fractional crystallization to explain the mode of variation of composition of the chondritic meteorites.

Prior (1916) has made a systematic study of the chondritic meteorites and showed that for them, in general, with a decrease in the total amount of metal there is correlated an increase in the ratio of nickel to iron in the metal, and an increase in the ratio of FeO and MgO in the magnesian-silicates, as if there was a partition of the iron between the silicate and the metallic portions as a result of increasing oxidation. He drew the conclusion "that all meteorites have had a common origin from a single magma which is most nearly represented by that which gave rise to the Daniel's Kuil type of meteoric stone, and that from this magma all other types have been produced by progressive oxidation of the nickeliferous iron." The Daniel's Kuil type of meteorite is predominantly enstatite and the reaction of ferrous oxide with enstatite would be expected to yield olivine and a pyroxene richer in iron, and a relationship whereby the olivine becomes richer in the fayalite molecule as the quantity of olivine increases. This gives a reasonable explanation for the relationships which actually obtain in the chondrites.

Prior has postulated that the achondrites, in general, represent a higher stage of oxidation than the chondritic meteorites. The achondrites average conspicuously higher in alumina and lime, and markedly poorer in sulphur and metallic iron than the chondrites, and the hypothesis that the former are the result of oxidation seems probable.

A striking contrast, however, is found in the mode of variation of composition within the chondritic and the achondritic meteorites, respectively. The variation within the chondrites is reasonably explained in terms of increasing degrees of oxidation, whereas the variations within the achondrites are not reasonably interpreted in terms of increasing degrees of oxidation but do have systematic relationships comparable to what would be expected from a process of fractional crystallization.

Comparison of Nature of Variation in Achondrite Meteorites and in Stratiform Sheets

The major types of achondrites comprise varieties similar to most major rock types found in thick stratiform mafic igneous sheets. If, as has been done in Table 1, we arrange the meteorite varities in comparable order of superposition and compare in detail the manner of variation of their minerals from bottom to top, we find a surprising similarity to that which is found within the terrestrial sheets. For example, in both meteorites and terrestrial sheets the mafic minerals, olivine and hypersthene, become increasingly richer in the ratio of iron to magnesia from the dunitic rocks at the base to the basaltic or gabbroic facies near the top. Also, the monoclinic pyroxenes increase in quantity in the gabbroic rocks near the top in both cases, commonly pigeonite in the meteoritic eucrites and augite in the terrestrial gabbros. Cristobalite and tridymite occur as interstitial minerals in some eucrites as quartz occurs interstitially in some of the upper gabbros of stratiform sheets. There is also a relative concentration of ilmenite, magnetite, and apatite in the feldspathic rocks as compared with the ultramafics. So far as has been ascertained, however, the plagioclase of the meteorites does not become systematically of a more sodic variety in progressing from the ultramafic to the basaltic facies, as it does in most of the terrestrial bodies. The terrestrial Duluth sheet, however, is also reported to show little variation in the composition of the bytownite plagioclase except in the uppermost felsic facies, though detailed study of this has yet to be made.

As might be expected, there are some meteorites whose relationship is doubtful. Chassignite is commonly classified as an achondrite. It is a hyalosiderite dunite and does not fit into the general pattern of the achondrites. Only one specimen has been described. The amphoterites (Jelica and Ibbenbühren) are commonly classified as achondrites. They have an oligoclase feldspar, however, and are grouped with the chondrites by La Croix. The augitic meteorites, El Nakhla and Angra, are also usually classed as achondrites but they too have a sodic plagioclase and only one meteorite of each type is known. The enstatolites such as Bishopville, Busti, Aubres, Shallowater, are classified as achondrites but do not fit appropriately into the scheme.

The composition of the chilled facies of the stratiform sheets, assumed to represent approximately the undifferentiated magma, differs from the average of the achondrites primarily in being over twice as rich in plagioclase (also somewhat more albitic); otherwise the two are similar. The more feldspathic nature of the terrestrial magma thus gives a reasonable explanation for the development of anorthosite layers in the stratiform sheets, whereas meteorites of the composition of anorthosite have never been found. The meteoritic eucrites, in general, at least in their later stages of consolidation also show characters indicative of relatively quick chilling, so that it is not intended to imply necessarily that they are unmodified fragments of the upper part of a stratiform body differentiated in place through fractional crystallization, but only that material of comparable composition may so have originated. Some of the ultramafic meteoritic achondrites, on the other hand, are coarse grained and may actually have originated as crystal accumulates. By analogy with the chromite layers of terrestrial rocks one might predict it possible that a meteorite with the composition of chromite may eventually be found, though because of its small volume the chances would be small.

The important point is that the achondrite meteorites whose average composition has been taken as equivalent to the upper part of the earth's mantle, show a kind of diversity which is consistent with the principles of fractional crystallization and gravity sorting as here assumed to be exemplified in the terrestrial stratiform sheets, and permits the hypothesis that the variations of stratiform sheets and of achondritic meteorites have had a fundamentally similar mode of origin.

A Layered Earth Suitable for Derivation of Primary Magmas

The structure of the interior of the earth must be such that it will yield by some reasonable mechanism the primary magmas which have been demonstrated to exist. Unfortunately petrologists are in wide disagreement as to how many and what are the primary as distinguished from secondary magmas. By primary magmas we here mean those derived by partial or complete melting of, or originating in, the primordial layers of the earth.

Daly has presented us with such convincing field evidence that basalt is a major primary magma, and Bowen, on the basis of the work of the Carnegie Geophysical Laboratory, has with a wealth of experimental data so logically and ingeniously shown how practically all types of igneous rock may theoretically be formed as secondary derivatives of basaltic magma, that the field evidence for the existence of other types of primary magma tends to be lost sight of or overshadowed.

However, such cogent evidence for the existence of primary magmas of the composition of peridotite and ultramafic rocks, of gabbroic anorthosite, as well as of quartz basalt on the one hand and of olivine or alkali-basalt on the other hand, has recently been presented (Hess 1938; Buddington 1939; Kennedy 1938) in detailed manner that the concepts are considered to warrant at least tentative acceptance without further discussion. We do not have an adequate thoroughgoing discussion of the hypothesis of possible pyroxenite magmas and for this reason they will not be considered. The initial magma for many of the great stratiform sheets was noritic. The proposal has been made that noritic magma originates from gabbroic magma, through the reaction with, and assimilation of, aluminous shales or schists. Adequate evidence that this has happened on so large and uniform a scale as required in each case is yet to be presented. It seems highly probable that a primordial norite zone lies at the base of the earth's gabbroic shell, and that primary norite magma would be derived therefrom. Parenthetically it may be noted that norite for some reason rarely appears as flows, in this particular being similar to anorthosite and peridotite. There appears to be no adequate basis for a decision at present as to whether a primordial granitic layer was formed, and if so, how thick. If present, its remelting would yield primary granitic magma.

The principles and results of fractional melting have not been investigated with the same intensity as those of fractional crystallization. One must exercise caution in attempting to apply directly to geological problems of the depths only such physico-chemical data as we now have, especially in view of the fact that there is considerable field evidence which at present cannot be strictly interpreted in terms of such solidus and liquidus relationships as have been experimentally determined for the common mineral compounds. Yet we may proceed to use these data to see what their implications would be.

Fractional or partial melting of the diverse primordial layers would be expected to yield a varied suite of primary magmas, interstitial and mechanically separable from the crystalline part, if melting does not proceed too far. Bowen (1928) has discussed in detail the derivation of gabbroic magma through the partial melting of peridotite. Similarly partial melting of pyroxenite or melanocratic norite would yield a noritic magma. Again, fractional melting of bytownite anorthosite to the proper degree would yield a gabbroic or noritic magma; further melting of such an anorthosite horizon would yield an andesine or labradorite gabbroic anorthosite magma without necessarily rendering the whole mass mobile. Partial melting of olivine gabbro would give a diorite magma, whereas quartz gabbro would give a quartz dioritic (andesitic) magma, and, as so adequately discussed by Eskola (1932), a granophyric gabbro would yield a small amount of primary granitic magma in the early stages of melting.

The problem of ultramafic magmas is a peculiarly enigmatic one and deserves especial consideration. It has been discussed by many. On the one hand we have the field evidence which appears to necessitate the hypothesis of ultramafic magmas as well as ultramafic crystal accumulates, and on the other hand the physico-chemical difficulties of understanding how there can be ultramafic magmas with the properties postulated by the field petrologist. H. H. Hess has recently (1938) discussed the problem and shown that the ultramafic magmas have a ratio of MgO/FeO of 9 or 10 to 1 in comparison to a ratio of 5 or 6 to 1 for the ultramafic crystal accumulate type from gabbroic or noritic magmas. In other words, the ultramafic magmas are richer in the higher melting component whereas the evidence is that their temperatures were actually lower than those of the gabbros and norites. Sosman (1938) has even suggested 600°C. as the temperature for an alkali peridotite dike at its site of emplacement.

Many petrologists, trying to get the temperature of ultramafic magmas as low as possible in order to facilitate their derivation, but mindful of the high melting point of forsterite-rich olivine have set the ultramafic magma temperatures as low as, but not lower than 1350°–1500°C. for surface pressures, (1500°–1600° for depth).

Daly (1940, p. 413) has postulated a vitreous peridotite layer at a depth of 80 km., more or less (Gutenberg 1939, p. 162 mentions 60–70 km.), which would have a temperature at complete melting of 1350°C. for surface pressures or 1590°C. at this depth.

This is unsatisfactory as it would presumably yield a magma at the place of intrusion with a temperature too hot to be consistent with the field evidence. The problem is to devise a mechanism for deriving a magma of forsteritic composition with a temperature not exceptionally high. One approach to the problem that leads to an interesting result is to follow through an hypothesis such as follows for the history of development of the earth during its early stages.

Tripartite Differentiation on Liquefaction

We will adopt the hypothesis that the earth passed through a liquid stage by condensation from a gas. Data are not available to specify the exact course of differentiation during liquefaction and preceding the beginning of crystalization, but it is perhaps a not unreasonable speculation to assume that the product was a liquid mass consisting in a very rough way of a nickel-iron core surrounded by two successive largely silicate shells each varying in composition, but distinct as a whole from each other. The composition of the inner silicate shell was essentially comparable to a mixture of magnesian silicates and nickel-iron, like the pallasites and chondritic stony meteorites, with increasing degree of oxidation toward the outer border, while the second outer silicate shell represented the most intense stage of oxidation and was of noritic composition, analogous to but somewhat less melanocratic than the achondritic meteorites, and at most not over 50–70 km. thick. The two silicate shells did not become homogenized because of lack of time for diffusion to effect this, and convection currents would be restricted to the respective shells because of the contrast in densities. The contrasting character of the three major parts here proposed is paralleled by three groups of meteorites; the siderites, the pallasites and chondritic meteorites, and the achondrites, respectively. True transitional types between these three groups are effectively absent. Iron sulphide may have formed a fourth shell of minor thickness between the nickel-iron core and the inner silicate shell.

Differentiation on Crystallization

Crystallization succeeded the initial differentiation of the liquid phases and is assumed to have started at or near the base of the inner, ultra magnesian-rich silicate shell and gradually worked out toward the surface with some concomitant differentiation as a product of fractional crystallization and gravity sorting. This results at a late stage in a residual bipartite liquid shell, at most a few hundred kilometers thick, consisting of the outer primary shell of noritic magma overlying the remaining uncrystallized portion of the inner shell and now of peridotitic composition. It is postulated that crystallization is now initiated at the outer surface of the noritic shell which is the same as the surface of the earth itself and consolidation works inwards at the same time that consolidation and growth of the peridotitic layer continues to increase outwards. Concomitant differentiation of the noritic shell yielded a primordial layered crust comparable to the stratiform sheets. At a certain stage of consolidation, while the solid peridotite and noritic differentiated layers are growing toward each other, the temperature of crystallization of the upper surface of the peridotitic shell will be reached and we will have the complex relationship of an upper and lower solid shell growing toward each other within the peridotitic zone, the upper peridotite layer at the same time acting as a false bottom for the differentiating noritic magma shell above (Fig. 3). The crystallization of the peridotitic shell may be expected to result in a concentration of hyperfusibles (substances of low or exceptionally low melting temperatures, such as albite, water, etc.) within the last residual liquid fraction, and similarly there may be expected a concentration of hyperfusibles in the last part of the noritic shell to consolidate.

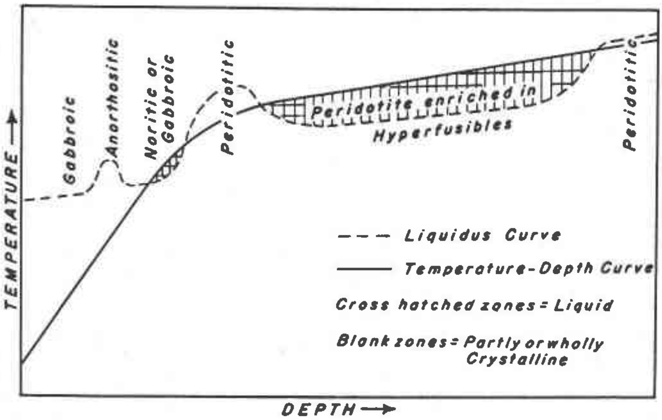

FIG. 3. Schematic diagram showing possibility for two liquid shells in outer part of earth at one stage of cooling. Blank areas between the two curves represent partly or wholly crystalline material.

PERIDOTITE MAGMA RICH IN HYPERFUSIBLES

What would be the nature of the hyperfusibles in the peridotitic magma? The chondritic meteorites average about 10 per cent oligoclase. Some sodic compounds may well have been concentrated in the residual peridotitic magma. The processes of fractional crystallization and gravity sorting would probably result in an increase of ferrous iron relative to magnesia, and a MgO/FeO ratio in the peridotite somewhat less than that found by Hess for the ultramafic magmas. The probable percentage of volatiles and their nature is extremely speculative, but there seems considerable basis for the validity of the concept of their concentration,

The nature of the dissolved gases does deserve some consideration. however, as it may be that they play a significant role in the formation of a forsterite-rich melt such as characterizes the ultramafic magmas. The principle that there is a qualitative similitude in the chemical composition of the sun, earth, and other members of the solar system is a currently accepted hypothesis. Hydrogen has been found to be a most important element quantitatively in the sun, stars, and the atmosphere of Jupiter and the larger planets. Russell (1942) estimates that on present data hydrogen forms at a minimum 35 per cent by weight and at a maximum 61 per cent of the sun, and that the sun now contains nearly as much helium as hydrogen. Hydrogen and carbon dioxide are the major constituents of the gases obtained at high temperatures from stony meteorities (Farrington, 1915) and Jaggar (1940), on the basis of studies of the composition of the gases in the liquid lava at Kilauea, has strongly urged the probable quantitative significance of hydrogen and carbon dioxide in primary magmatic gases. It is recognized, however, that the evidence for the presence of hydrogen as such instead of as compounds is suggestive only rather than proof. At the high temperatures assumed to prevail during the condensation of matter to form the earth, hydrogen would tend to escape from a mass of its size. Yet this would take time and it seems probable that some hydrogen would be dissolved and retained in the liquid mass of the earth. Part of this would in turn be subsequently lost, part may enter into reactions to yield new minerals but part would be expected to remain to be concentrated in the residual liquid peridotitic layer protected by the crystalline shell. This retained hydrogen could react with part of the ferrous iron of fayalite to yield a more forsterite-rich magma and a few per cent of bronzite and metallic iron. The latter would sink and rarely appear in an intrusive magma. Part of the hydrogen will become oxidized to H_2O.

Tamman (1924) has calculated that if the whole of the water, ice and snow at present on the earth were put back to the temperature we may imagine prevailing at the time when the earth was still hot and the crust had not formed, its vaporization would yield a partial pressure of water vapor of about 270 atmospheres and there would be enough water molecules dissociated to provide all the free oxygen at present in the earth's atmosphere. The earth during its condensation to a liquid would certainly have had an opportunity to dissolve gases under conditions of high gas pressure.

The proposed hypothesis would thus account for a residual layer of forsterite-rich olivine peridotite, at a relatively low temperature because of a high percentage of dissolved volatiles and other hyperfusibles, and semi-vitreous to vitreous because it was at a temperature above that prevailing for the depth (Fig. 3).

If differentiation of the noritic shell yielded a granitic layer beneath an outer solidified gabbroic shell, the arrangement would be unstable, the granitic magma would flow to and rise through local fractured areas in the heavier overlying gabbro and the possibility for the segregation of continental-like sial masses would be intiated.

CONCLUSIONS

The preceding discussion of the nature of the interior of the earth has thus led to proposals for modification of current earth models whereby there is a layer of bytownite-anorthosite at or near a depth of 25 to 30 kilometers, and probably a relatively thin vitreous peridotitic or dunitic shell rich in hydrogen and other hyperfusibles beginning at a depth around 60–80 kilometers, of unknown thickness but not over a few hundred kilometers at a maximum and perhaps much thinner. The modified model thus proposed is shown in Fig. 4.

We may now proceed further and see what the consequences might be in the way of production of primary magmas from such an earth.

Kennedy and Anderson (1938) have given us a most stimulating discussion of how different kinds of magma may originate, dependent upon the interrelationship between the fusion curves for different types of rocks at their appropriate depths, and the temperature-depth curves. A modification and expansion of one of their diagrams constructed to fit the ideas developed here is given in Fig. 5. The temperature-depth curves will very likely have been different at different periods of earth history and in different structural units and will not have the smooth curve pictured. Local distortion may arise from the different conductivity of and different intensities of radio-thermal heating in different layers, and so forth. In orogenic belts there may be at least temporary thickening of the sial with a consequent local rise of the temperature in the upper part of the crust due to the multiplication of this relatively strong heating element. Also, if any of the sial is a product of subsequent differentiation during geologic time from the primordial layers, then the temperature curves would be modified thereby. Deformation of the earth layers will have essentially the effect of displacing the fusion curves for each rock layer with respect to the temperature-depth curve. A down fold for example would in effect shift them to the right. The curves may also be affected by the diffusion of hydrogen or perhaps other light molecules into the various rock layers from below. The relations shown in the diagram are such that when and where the temperature-depth curve is raised relatively to and lies above the line (fusion curve) for the respective kind of rock, the appropriate magma will be formed.

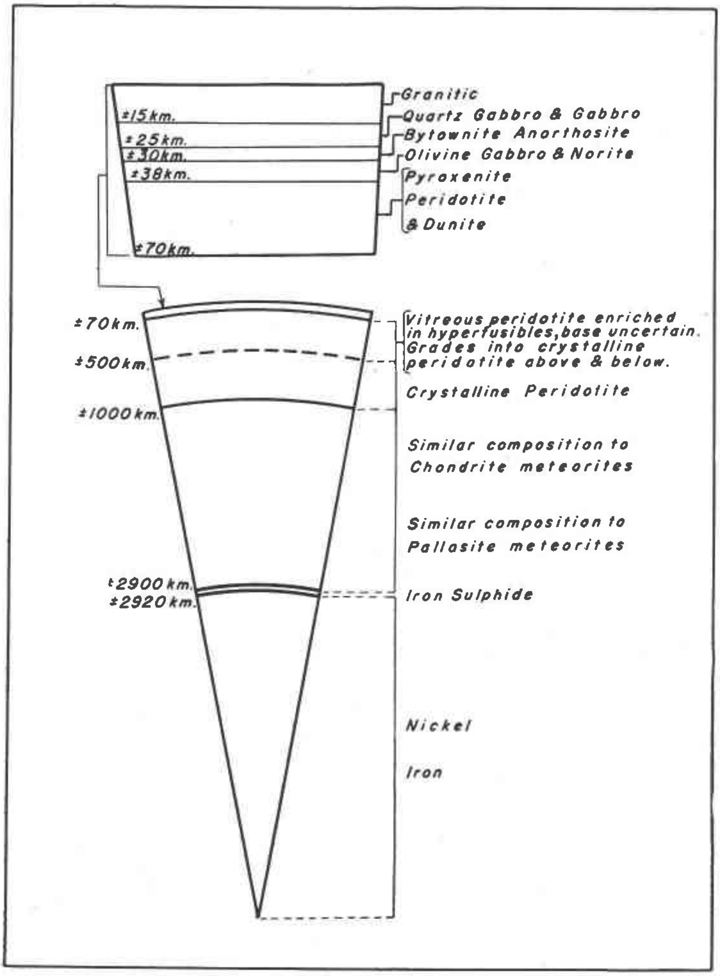

FIG. 4. Sector of earth beneath continents to illustrate proposed hypothesis for constitution of interior of the earth. Depths of shell boundaries are largely based on data by Gutenberg and Richter. The anorthosite zone may be expected to contain thin intercalated layers of ilmenite-magnetite, and the first (±38 to ±70 km.) peridotite and dunite zone thin layers of chromite and lenses of sulphide.

From the relationships shown we would anticipate that gabbroic (or basaltic) magma would be a dominant and recurrent type, inasmuch as it may form throughout such a very wide range of environment. A peridotite magma would be expected to rise only under exceptional structural dynamics. This is consistent with the evidence. An andesine or labradorite gabbroic anorthosite magma may originate through partial melting of bytownite anorthosite. The relationships of the anorthosite shell are such that anorthositic magma should also be expected to form only under extra exceptional conditions, and that melting sufficient to render the entire mass eruptible would scarcely occur. This is pre-eminently true, for rocks formed from intrusive anorthositic magma have been found almost exclusively in the pre-Cambrian and they are andesine to labradorite types. It may also be noted that magmas derived by partial melting may be formed but once from a given mass for only the constituents of higher melting intervals remain as a residue. Again, we see that there are potentialities for the coexistence of two or more primary magmas of different compositions formed at different levels. Such primary magmas if injected at similar horizons in the crust would consolidate in the same order of succession as members of a magma series differentiated from a single common type and might give rise to a set of similar structural phenomena. The granitic magma derived from melting of the sial may, by definition, be primary only if part of the sial were primordial.

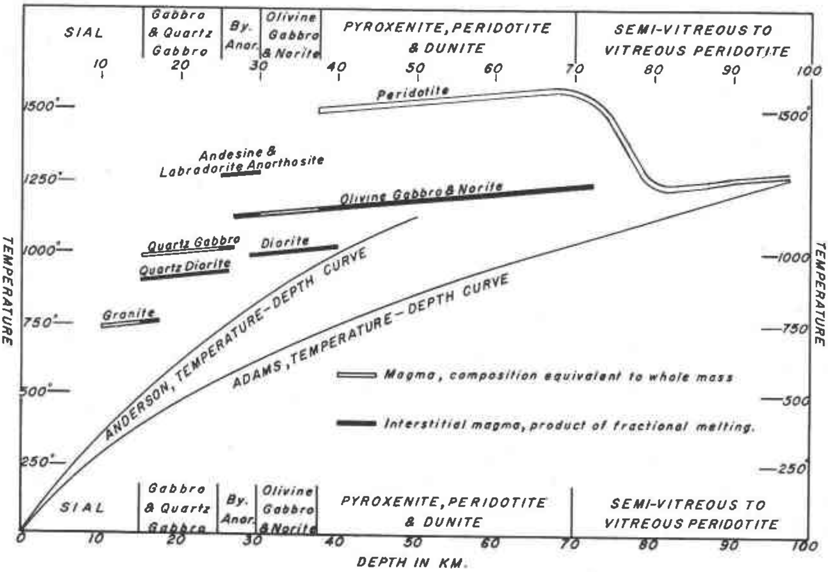

FIG. 5. Schematic fusion curves and temperature-depth curves to illustrate possible origin of primary magmas. Two temperature-depth curves are shown as proposed by their respective authors.

The picture postulated is admittedly highly speculative and schematic. Yet it may have value in emphasizing the possibilities for genesis and diversity of composition of primary magmas and for relating different types of magma to different structural dynamics.

SELECTED BIBLIOGRAPHY

ADAMS, L. H., Temperatures at moderate depths within the earth: *Jour. Wash. Acad. Sci.*, **14,** 468 (1924).

ADAMS, L. H., AND WILLIAMSON, E. D., Density distribution in the earth: *Jour. Wash. Acad. Sci.*, **13,** 413–428 (1923).

BOWEN, N. L., The Evolution of the Igneous Rocks, 303–322 (**1928**).

BUDDINGTON, A. F., Adirondack igneous rocks and their metamorphism: *Geol. Soc. Am., Mem.* **7,** 201–221 (1939).

DALY, R. A., Igneous Rocks and the Depths of the Earth, pp. 173–239; 311–356. McGraw Hill, *New York* (**1933**).

DALY, R. A., Strength and Structure of the Earth, pp. 1–21, 353–415 (**1940**).

FARRINGTON, O. C., Meteorites (**1915**).

GOLDSCHMIDT, V. M., Über die Massenverteilung im Erdinnern, vergleichen mit der Struktur gewisser Meteoriten. Die Naturwissenschaften, Heft **42** (1922).

GROUT, F. F., A type of igneous differentiation: *Jour. Geol.*, **26,** 626 (1918).

GUTENBERG, BENO, Internal Constitution of the Earth. Physics of the Earth VII, McGraw Hill, *New York* (**1939**).

GUTENBERG, BENO, AND RICHTER, C. F., On seismic waves: *Beitrage Zur Geophysique,* **54,** 134–135 (1939).

HALL, A. L., The Bushveld igneous complex of the Central Transvaal, South Africa: *Geol. Survey, Mem.* **28** (1932).

HESS, H. H., A primary peridotite magma: *Am. Jour. Sci.*, **35,** 321–344 (1938).

HOLMES, ARTHUR, The origin of igneous rocks: *Geol. Mag.*, **69,** 543–558 (1932).

JAGGAR, T. A., Magmatic gases: *Am. Jour. Sci.*, **238,** 313–353 (1940).

KENNEDY, W. Q., AND ANDERSON, E. M., Crustal layers and the origin of magmas: *Bull. du Volcanologique*, Ser. II, Tome **III,** 24–82 (1938).

LOMBAARD, B. V., On the differentiation and relationships of the rocks of the Bushveld complex: *Geol. Soc. South Africa, Trans.* **37,** 5–52 (1934).

MERWIN, H. E., General Geophysics, Chapter in 50th Anniversary Vol., *Geol. Soc. Am.*, 421 (**1941**).

OLDHAM, R. D., Constitution of the interior of the earth: *Quart. Jour. Geol. Soc. London*, **62,** 456–473 (1906).

PEOPLES, J. W., The geology of the Stillwater Igneous Complex: Doctorate dissertation, Princeton University.

PRIOR, G. T., On the genetic relationship and classification of meteorites: *Mineral. Mag.*, **18,** 26–43 (1916).

RUSSELL, H. N., The cosmical abundance of the elements: *Science*, 375–381 (**1941**). Present state of the theory of stellar evolution: *Scientific Monthly*, 236 (**1942**).

SLICHTER, L. B., Cooling of the earth: *Bull. Geol. Soc. Am.*, **52,** 561–600 (1941).

WAGER, L. R., AND DEER, W. A., The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland: *Medd. om Grønland*, Bd. **105,** Nr. 4 (1939).

WASHINGTON, H. S., Chemical composition of the earth: *Am. Jour. Sci.*, **9,** 351–378 (1925).