Art. XLII.—*The Composition of Stony Meteorites compared with that of Terrestrial Igneous Rocks, and considered with reference to their efficacy in World-Making;* by George P. Merrill.

[Read before the Geological Society of Washington, March 24, 1909.]

Speculation relative to subjects the actual proof of which lies entirely beyond his reach, has ever been a favorite pursuit of the thinking man. Nowhere is this more manifest than in questions relating to the age and origin of the earth. Of all the theories which have been evolved, and which have stood the test of any considerable length of time, only that known as the Kant-Laplacean, and the more recent hypotheses of Professor Chamberlin of Chicago, need our present consideration. Any and all of these call for the world-making materials, whether gaseous or solid, from sources beyond our immediate universe. It is but natural, therefore, that those substances which reach our earth from space in a solid form, and which give the only really tangible illustrations of what materials of space may be, should be regarded as of value in aiding our arrival at the desired conclusions. This fact was recognized over one hundred years ago (1794) by Chladni, who regarded meteorites as remnants of cosmic materials employed in the formation of worlds, or, as he expressed it, as "Weltspäne." The idea, with various more or less important modifications, has been repeated by subsequent workers,* and is brought up for consideration with renewed force by the recent papers of Professor Chamberlin, which have been so clearly summarized under the heading of the "Origin of the Earth" in his work on geology.†

It should be stated, however, that Professor Chamberlin is not an advocate of the meteoric theory of the earth; in fact, he states definitely that the origin of meteorites is but an incidental result of stellar and planetary action, their genesis being wholly a secondary matter, and furnishing no grounds for regarding them as the parent material of great nebulæ or of stellar systems. Chamberlin inclines rather to what he calls the "planetesimal hypothesis," which assumes that the solar system was derived from a spiral nebula consisting of finely divided solid or liquid materials, which revolve independently about a common nucleus, and which are gathered into larger aggregates through the crossing of the elliptical orbits of the

*See Lockyer's Meteoric Hypothesis for discussion. Arrhenius' Worlds in Their Making is perhaps the latest work in which the matter is seriously considered.

† Geology, vol. ii, Earth History, pp. 1–81.

individual members. It is obvious, however, that whatever theory is adopted,—the Laplacean, meteoric, or the planetesimal—the kind of material, and presumably the ultimate origin of all, remains the same. It is this thought which has led me to enter upon the present discussion.

Meteorites as they come to our earth, as is well known, are roughly grouped into three general classes; first, those which consist essentially of nickeliferous iron nearly or quite devoid of silicate material; second, those which consist of a spongy mass of iron, including globular aggregates of silicates; and third, those which are nearly or quite all of silicate material, with more or less sporadic iron. These forms, it is true, grade into one another, but, nevertheless, the classification is much easier than one would be at first led to suppose.

Researches into the composition of our earth have led us to assume that it is composed of an outer zone of comparatively rich silicate material, in which free silica is an important constituent, and an inner zone of material which is essentially metallic, with perhaps an intermediate zone showing a transition between the two extremes. Regarding meteorites as world materials, as has been done by certain workers, we might consider the purely metallic varieties as representing the deep-seated, probably nucleal, material of some pre-existing planetary body; the stony meteorites as representing the crustal material; and the spongy irons with the mixed silicates (pallasites) as representing the intermediate portion. The fact, however, that a part, at least, of the iron of stony meteorites has been repeatedly shown to be of secondary origin—to result from the reduction of some compound subsequent to the consolidation of the silicates, is difficult to harmonize with any such view.

Inasmuch as the nucleal material of the earth is quite beyond reach for purposes of investigation, and as the intermediate zone, if such there be, is represented, if at all, only by extrusions of deep-seated igneous rocks, I have for the time being limited my considerations to a comparison of the stony meteorites with the great group of igneous rocks as existing to-day upon the earth's surface. It will be seen at once that in doing this, I have accepted for the purpose the most acid group of the ultra-terrestrial rocks.

There are many difficulties in the way of obtaining anything like an accurate average of the composition of these materials. This, for reasons which can be fully appreciated only by those who have attempted their study, and more particularly, the making of chemical analyses. One of the chief difficulties, it may be said, lies in the separation of the metallic from the non-metallic portion. The method of statement of the results, and the proper interpretation to be put upon the same, add to the difficulties. Several of the constituents, moreover, occur in such extremely small quantities, or like the chloride of iron (lawrencite), undergo such rapid deterioration, that their determination has been largely overlooked, particularly in the older analyses. Or, again, if such determinations were made, the results as given are at least open to doubt in the light of more recent investigations. In going over all of the literature available, I have found but ninety-nine analyses which were made, as it seemed to me, with sufficient care, were sufficiently complete, or stated in such a way as to render the results comparable with one another. Even in these ninety-nine, all of the constituents were not determined, and in many instances, where the presence or absence of a certain element was not stated, one is left in doubt as to whether such was looked for, or whether it was looked for and found lacking. Out of the ninety-nine analyses, however, silica, alumina, iron, ferrous oxide, lime, magnesia, potash and soda were found determined in a sufficient number of cases to make the matter of an average a fairly safe approximation, the metallic iron affording the most difficulty. Of the remaining constituents, as given in the table below (No. 1), the manganese is an average of forty-one determinations, the phosphorus of thirty-one, the chromic iron of sixty-seven, the sulphur of ninety-two, and the nickel-cobalt of ninety-three. The percentage amount of sulphur has, in many cases, been arrived at by calculation, since the results

Average composition of stony meteorites as calculated from 99 analyses for all constituents but P, which is from 31 determinations: MnO from 41 determinations, $Cr_2O_3+Fe_2O_3$ from 67 determinations: Ni,Co from 93 determinations; and S from 92 determinations.

	I Average of Results as given		II Recalculated on basis of 100
SiO_2	38·98		38·732
Al_2O_3	2·75		2·733
Fe	11·61		11·536
FeO	16·54		16·435
CaO	1·77		1·758
MgO	23·03		22·884
Na_2O	0·95		0·943
K_2O	0·33		0·328
$Cr_2O_3+Fe_2O_3$	0·84	Av. of 67 dets.	0·835
Ni,Co	1·32	" 93 "	1·312
S	1·85	" 92 "	1·839
P	0·11	" 31 "	0·109
MnO	0·56	" 41 "	0·556
	100·64		100·00

were sometimes given as simply ferrous sulphide and sometimes as sulphur. Where such calculations were necessary, the percentage of iron was added to the amount given in the analyses as existing in the metallic state.*

The following list shows the highest and lowest percentages of any given constituent in the analyses here averaged.

	Highest	Lowest
SiO_2	61·15	26·05
Al_2O_3	11·05	0·00
Fe	27·00	0·00
FeO	30·44	0·99
CaO	7·03	0·00
MgO	39·04	6·44
Na_2O	3·94	0·00
K_2O	4·31 †	0·00
$Cr_2O_3+Fe_2O_3$	6·33	0·00
NiCo	4·21	0·00
S	7·47	0·00

† It would seem that this must be an error, since the stone (that of Zsadany, Hungary) is described as consisting essentially of olivine and pyroxene, and no reference made to feldspars.

For comparison of these results with terrestrial rocks, the following are given:

Average composition of terrestrial igneous rocks as calculated by (III) Clarke and (IV) Washington.†

	III	IV
SiO_2	60·91	58·239
Al_2O_3	15·28	15·796
Fe_2O_3	2·63	3·334
FeO	3·46	3·874
MgO	4·13	3·843
CaO	4·88	5·221
Na_2O	3·45	3·912
K_2O	2·98	3·161
H_2O at 100°	0·41	0·363
" above 100°	1·49	1·428
TiO_2	0·73	1·039
P_2O_5	0·26	0·373
	100·61	100·583

† Bull. 330, U. S. Geol. Survey, 1908.

* The writer regards these results as only approximations, and suggestive. The recalculation of many of the analyses is attended with so many uncertainties, that it is even probable that slightly different results would be obtained in going over the same ground a second time. So far as the main constituents—the silica, alumina, lime, magnesia, potash and soda—are concerned, he believes the averages as good as can be obtained with available material.

It may be well to add that the approximate weight, so far as known, of all the stones represented by these ninety-nine analyses, was 4,014 kilograms or about 4·4 metric tons. An average of 77 determinations, as given, of specific gravities gave 3·51, of which the lowest, that of the Orgueil, France, carbonaceous stone was 2·50, and the highest, that of Limerick, Ireland, 3·92.

It will at once be noted that there is a wide and striking difference in composition between the meteorites and the terrestrial rocks,—a difference not merely in the relative proportion of the various elements, but also, in one case at least, in their method of combination. The most striking feature is, for the meteorites (columns I and II), the low silica content, and the high percentage of metallic iron, ferrous oxide, and magnesia, with the corresponding low percentages of alumina, lime, and the alkalies.* Compared with Washington's averages for terrestrial rocks, it will be noted that there is a difference of nearly twenty per cent in the amount of silica in favor of the latter, and of some thirteen per cent in the amount of alumina. These differences are so striking that they cannot be considered as due to errors of analyses, or of their interpretation. They must be fundamental.

Should we disregard entirely the metallic iron of the meteorites with its included nickel, cobalt, and phosphorus, and also the iron disulphide (amounting all together to 14·79 per cent), and recalculate Analyses II on the basis of 100, we get the results shown in column V below. In column VI is given the average of seven analyses of terrestrial peridotites† which, as will be at once apparent to the petrographer, afford the closest approximation, in chemical as well as mineral composition, to meteorites. These, it should be stated, have been recalculated on a water-free basis. It is scarcely necessary, however, to call attention to the fact that the peridotites represent the most basic of known terrestrial rocks, while the meteoric analyses which I have given represent the most acid type that have come to us from space. It is evident, therefore, that

* The composition as shown by these analyses does not, so far as sodium is concerned, seem to harmonize with spectroscopic analyses, or Arrhenius' statement to the effect that the nucleus of comets, like the meteorites falling upon our earth, consists essentially of silicates, and *particularly of the silicates of sodium.* See Worlds in Their Making, pp. 104–105. For the benefit of those not familiar with the subject, it may be well to state that the principal mineral constituents of meteorites, aside from the metallic portions, are the silicates of magnesia and iron, olivine and enstatite, with less commonly monoclinic pyroxenes and basic feldspars. Silicates of sodium must be rare, as shown by a simple glance at the analyses given.

† The number was limited, since nearly all reported analyses were of altered and highly hydrated examples, while for purposes of comparison materials as nearly anhydrous as possible were needed.

	V	VI
SiO_2	45·46	43·59
Al_2O_3	3·21	5·30
FeO	19·29	8·40
Fe_2O_3	----	2·03
CaO	2·06	4·11
MgO	26·86	35·62
Na_2O	1·11	0·60
K_2O	0·38	0·36
MnO	0·65	----
$Cr_2O_3 + Fe_2O_3$	0·98	----
	100·00	100·01

as world-making materials they are insufficient, and if we are to regard our earth as an aggregate of cosmic matter, we must assume that the materials were of a much more highly siliceous type than any that have been reaching us from space within historical periods. This is presumably the proper interpretation to be placed upon the results here shown.

It is impossible through any process of magmatic differentiation to derive from such materials, in even approximate proportions, a series of rocks as widely variant and, in extremes, as highly siliceous, aluminous and alkaline, as are the igneous rocks of the earth. In fact, it would seem that they (the meteorites) themselves must represent an extreme phase of magmatic differentiation from a more acid magma.

Whether we consider the meteorites that have reached us within this period as but the fragmental remains of comets, or whatever their origin, it is certainly not going beyond the realm of legitimate hypothesis to assume that the relative proportions of the elements which go to make up the mineral matter in these various bodies in remote space, may vary widely; that the earth to-day, in its course, is but passing through* and receiving from space a deposit of materials representing one and the same original body, and that body one of an exceedingly basic nature, not necessarily resembling, in percentage composition, the materials which may have reached us during past and earlier stages of earth history.

* "Meteoriten und Planetoiden sind daher die vorübergehenden Zeugen einer vorübergegangenen Episode in der Geschichte unseres Planetensystems." Ed. Suess, Ueber Einzelheiten in der Beschaffenheit einiger Himmelskörper, Sitz. kais. Akad. der Wiss., vol. cxvi, 1907.