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THE CHEMICAL COMPOSITION OF THE EARTH.

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Of the many and somewhat varied suggestions that have been made as to the distribution of matter in the Earth, that which supposes a solid central core of nickel-iron surrounded by a series of solid progressively varying silicate shells now meets with the general acceptance of geophysicists. Such a distribution has been advocated, for example, by Oldham, Wiechert, Gutenberg, Suess, Daly, Clarke, Adams and Williamson, and the present writer.¹ There is difference of opinion as to details, such as the thickness of the several shells, their composition in detail, whether they are discontinuous or intergradient, and so on; but that the constitution of the Earth is, broadly, as stated above is now the practically unanimous belief.

This concept of the Earth's interior has been arrived at through several lines of evidence; especially, the velocity of transmission of earthquake waves through the interior; analogy with meteorites considered as fragments of a cosmic body; the density, rigidity, moment of inertia, magnetism, and other physical characters of the Earth; the compressibility of minerals and rocks; and the chemical and mineral characters of igneous rocks. These lines of evidence are convergent and they are mutually corroborative.

Within the last year or two a more detailed concept of the interior of the Earth has been arrived at, this being based more especially on analogy with meteorites, the velocity of earthquake waves at different depths, the

¹ For a statement of the various characters of the Earth's interior and theories as to its constitution see a forthcoming paper by the writer: "The Interior of the Earth and its Crust," to be published in the Journal of the Franklin Institute for 1925.

compressibility of minerals and rocks, and the chemistry of igneous rocks. The distribution of matter within the Earth, thus suggested, and as advocated by Adams and Williamson and the present writer is as follows.² It is illustrated schematically in Figs. 1 and 2, which represent a section of the Earth, from the center to surface,

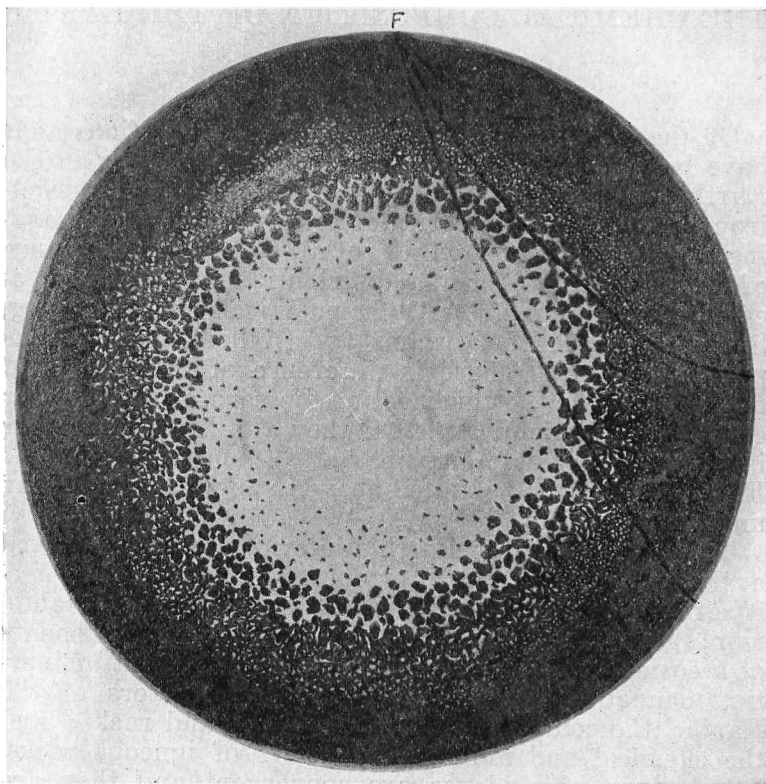


Fig. 1.—Section through the center of the Earth. The black lines represent the path of Earthquakes from the focus at F.

²L. H. Adams and E. D. Williamson, The Compressibility of Minerals and Rocks at high Pressures, *Jour. Franklin Inst.*, **195**, 475, 1923; Williamson and Adams, Density Distribution in the Earth, *Jour. Washington Acad. Sci.*, **13**, 413, 1923; Adams and Washington, The Distribution of Iron in Meteorites and in the Earth, *Jour. Washington Acad. Sci.*, **14**, 333, 1924; Washington, The radial Distribution of certain Elements in the Earth, *Jour. Washington Acad. Sci.*, **14**, 435, 1924.

shown at the Annual Exhibition of the Carnegie Institution at Washington in 1924, the colored original of Fig. 2 being 10 feet long.

At the center of the Earth is a core or nucleus of nickel-iron, similar in chemical composition and physical characters to the metal of the siderites or iron meteorites, although with possibly less nickel and more carbon. This metallic core has a radius of about 3,400 kilometers and an average density of about 10. It probably, from analogy with meteorites, contains a considerable amount, up to about 5 per cent or so, of phosphides (schreibersite, $(\text{Fe}, \text{Ni})_3\text{P}$), carbides (cohenite, Fe_3C), sulphides (troilite, FeS), and carbon (diamond and graphite).

The central core passes, by the presence of magnesium and iron silicates in gradually increasing amount, into an overlying lithosporic³ shell, composed mostly of olivine scattered sporadically (i. e. as discrete particles) through a sponge or continuum of metallic nickel-iron, the material resembling the meteoritic pallasites. The metal and the silicate are supposed (again in analogy with meteorites) to be present, on the average, in about equal amount. The average density of the lithosporic shell is about 8, and its thickness is estimated to be about 700 kilometers.

The lithosporic (pallasitic) shell passes gradually, by diminution in the amount of metal and increase in that of silicate, into a ferrosporic³ shell, composed chiefly of olivine and enstatite-hypersthene, and a little oligoclase, with from 25 to 10 or less per cent of metallic nickel-iron sporadic in the silicate continuum. In mineral composition this material resembles the chondritic stone meteorites, but it probably differs texturally in the absence of chondrules and tuffaceous texture. The average density of this ferrosporic shell is about 6 and its thickness is about 700 kilometers.

Above and intergradient with the ferrosporic shell, through gradual disappearance of the metallic nickel-iron, is a shell composed almost wholly of silicates, chiefly of iron and magnesium, forming enstatite-hypers-

³ The terms "lithosporic" and "ferrosporic" were proposed to denote material in which, respectively, the silicate is sporadic in a continuum of nickel-iron and one in which metallic nickel-iron is sporadic in a continuum of silicate. See Adams and Washington, *op. cit.* p. 336.

thene and less olivine, with some calcic pyroxene and feldspar, chiefly labradorite. This material is essentially peridotite. There is almost no nickel-iron in this shell, the general composition of which is similar to that of the achondritic meteorites. The average density of this peridotitic shell is about 4 and its thickness is 1,500 to 1,600 kilometers.

In all these more or less silicate shells, there is probably, by analogy with meteorites, a small percentage of non-oxide compounds, chiefly sulphides (troilite and oldhamite), phosphides (schreibersite), carbides (cohenite), and chlorides (lawrencite), with some chromite and magnetite, and possibly borides and nitrides, in the upper zones.

Above the peridotitic shell, and probably intergradient with it within narrow limits, is the "crust" of the Earth, the thickness of which is probably about 60 kilometers—almost certainly not over about 100 kilometers. The lower part of this crust, let us say about 40 kilometers, has a generally basaltic or gabbroic composition, both chemically and minerally, with a density of about 3.2. This grades upward into the outermost 15 or 20 kilometers, of average granitic or granodioritic composition and of density about 2.8, which is the only portion of the globe that is open to our direct inspection. It is this very thin, 20-kilometer, uppermost shell that has usually been meant in the numerous discussions of "the average igneous rock." The overlying strata of sedimentary rocks and the metamorphosed igneous and sedimentary rocks need not concern us here—they are both derived ultimately from the igneous rocks and their total amount is negligible in a discussion of the composition of the Earth as a whole.

The distribution of matter in the Earth as described above is, admittedly, tentative and a rough first approximation; but in its broad lines, and even in considerable detail, it is supported by so much convergent evidence (which cannot be stated here), that considerable confidence may be had as to its general correctness. Accepting it provisionally as true, the attempt is made to arrive at a notion of the general composition of the whole Earth by utilizing the data presented in the suggested distribution.

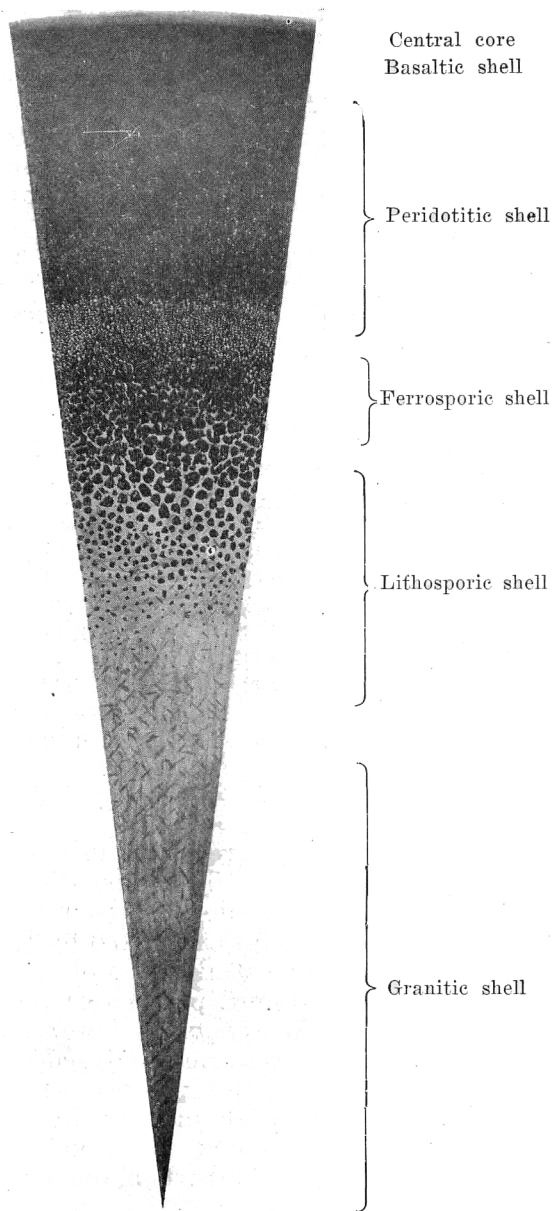


Fig. 2.—Sector of the Earth, from center to surface: showing the nickel-iron core and the gradual increase in silicate toward the surface. (Core is white or light gray, olivine black, peridotite dark gray.)

As a preliminary the volumes and the masses of the core and of the several shells must be known. The results of my calculations of these are given in Table 1. The Earth is assumed to be spherical, with a radius of 6,400 kilometers. That the assumed densities and calculated volumes and masses are approximately correct is indicated by the correspondence between the average density of the Earth deduced from them, 5.49, and the known density of the Earth, 5.52; the difference being about 0.5 per cent.

TABLE I.
Volumes and Masses of Earth Shells.⁴

	Thick- ness km.	Volume km ³ x10 ¹²	Den- sity	Mass tonsx10 ²¹	Mass per cent
Central core	3400*	.1646	10.0	1.646	27.30
Lithosporic shell ..	700	.0641	8.0	.513	8.51
Ferrosporic shell ..	700	.2345	5.8	1.360	22.55
Peridotitic shell ...	1540	.6043	4.0	2.417	40.08
Basaltic shell	40	.0203	3.2	.065	1.08
Granitic shell	20	.0102	2.8	.029	0.48
Whole Earth	6400*	1.0980	5.49	6.030	100.00

*Radius.

The following assumptions were made in calculating the composition of each shell. The composition of the nickel-iron central core was assumed to be that of the average of 318 iron meteorites, as calculated by Farrington.⁵ In this average, as in most analyses of iron meteorites, the percentages of sulphur, phosphorus, and carbon shown by the analyses are probably lower than the truth, because, as a rule, the material analysed does not include a due proportion of the nodules of troilite, schreibersite, and graphite which may be present. It is possible, also, that the amount of nickel as here assumed is too high and that of carbon too low, since

⁴ The densities of the lithosporic, ferrosporic, and peridotitic shells are taken from Williamson and Adams' density-depth curve *Jour. Washington Acad. Sci.*, 13, 425, Fig. 3, 1923.

⁵ Farrington, *Analyses of Stone Meteorites*, Field Columbian Mus., Pub. No. 151, 212, 1911.

the terrestrial basaltic irons, such as those of Ovifak and Buhl, contain less nickel and more carbon than is found in meteoritic irons.

The material of the lithosporic (pallasitic) shell was assumed to be composed, on the average, of equal weights of nickel-iron and of olivine, in analogy with meteoritic pallasite.⁶ The metal was supposed to have the same composition as that of the central core, and the olivine the ratio $\text{MgO}:\text{FeO} = 5:1$, which is about that of the olivine of pallasite. The results of a study by Chirvinsky⁷ of pallasitic olivine and of many pallasites agree closely with my assumed compositions.

The composition of the ferrosporic shell was assumed to be that of the average of stony meteorites, as calculated by Merrill,⁸ from 53 analyses. The method of averaging was that of dividing the sum of the percentages of each constituent by the number of determinations, a method that is preferable to dividing the sum by the number of analyses.⁹ Merrill's average includes seven analyses of achondritic meteorites, but the number is so small that they do not seriously affect the result. Prior has called attention to the remarkable uniformity in the chemical and mineral composition of chondritic meteorites.¹⁰

For the composition of the peridotitic shell I calculated the average of 20 analyses of achondritic meteorites, those of fair to good quality being used.¹¹ The method of averaging was that used by Clarke and Washington and by Merrill. The average differs considerably from Daly's average of terrestrial peridotites,¹² and most

⁶ The subgroups of siderolites that contain pyroxene with olivine (Iodranite and mesosiderite), and those that contain pyroxene with asmanite (tridymite, instead of olivine (siderophyre), are not considered here, because they are so rare as to be negligible in the general discussion.

⁷ Chirvinsky, *The Pallasites*, Min. Abstr., 2, 83, 1923.

⁸ Merrill, *Mem. Nat. Acad. Sci.*, 14, No. 1, 28, 1916.

⁹ Cf. Clarke and Washington, *The Composition of the Earth's Crust*, U. S. Geol. Survey, Prof. Paper 127, 10, 1924.

¹⁰ Prior, *Min. Mag.*, 17, 33, 1913.

¹¹ The analyses were of: Angra, Binda, Bishopville, Constantinople, Cumberland (white portion), Frankfort, Ibbenbüren, Jelica, Juvinas (Merrill), Manbhoom, Managaon, Mässing, Nakhla, Novo Urei, Peramiho, Petersburg, Shalka, Shergotty, Stannern (Merrill), Zmenj. The analysis of Jonzac by Michel (*Tsch. Min. Pet. Mitth.*, 31, 589, 1912) was, by an oversight, not included.

¹² Daly, *Igneous Rocks*, 1914, 29, No. 70.

resembles analyses of olivine diabase from New Jersey, hornblende hypersthene from Brazil and India, and olivine basalt from Hawaii.¹³

For the lower basaltic shell of the crust the composition of Daly's average basalt¹⁴ was assumed. For the composition of the uppermost granitic shell the latest calculation of the "average igneous rock" was taken.¹⁵ In both of these averages the minor constituents, except titanium, phosphorus, chromium, sulphur, and manganese, were neglected, as their amounts are negligible (for present purposes), when referred to the whole Earth.

The chemical and mineral compositions shown in Table 2, 3, and 4 are admittedly rough, first approximations. They are dependent on the assumptions made as to the masses and the composition of the several shells, which would seem to be fairly accurate, from the correspondence in the average density of the Earth. They are also affected by the difficulties incident to the analysis of meteorites, arising chiefly from the paucity of the material and from the irregular distribution of the constituents. Thus, the percentages given for sulphur, phosphorus, and carbon, in the averages for the core, the lithospheric shell, and the whole Earth, are presumably below the truth, because these elements occur, in iron and in lithospheric meteorites, chiefly as components of nodules, which are not always included in the material used for analysis or are not properly allowed for in the general reckoning. The amount of chlorine is probably too low, because this constituent is seldom determined, although it is present (as FeCl_2) in many iron and iron-stone meteorites, to the annoyance of museum curators. Nickel and cobalt are often not properly determined or separated, especially in the older analyses of meteorites, many of which are otherwise faulty or incomplete, although they may be the only ones available. Indeed, so many complete, modern analyses of meteorites are needed that it is to be desired that

¹³ Cf. Washington, U. S. Geol. Survey, Prof. Paper 99; Subrang IV.1.2.1.2 (hilose), 707, 1917.

¹⁴ Daly, *Igneous Rocks*, 1914, 27, No. 53.

¹⁵ Clarke and Washington, *The Composition of the Earth's Crust*, U. S. Geol. Survey, Prof. Paper 127, 16 and 20, 1924.

directors and curators of museums should regard meteorites, not as "specimens" to be shown in a glass case, but as objects to be studied, even if much of the material is thereby used up. But, on the whole, in spite of such errors and defects, the figures given, derived from analyses of many meteorites, probably present a fairly correct general idea of the composition of the Earth, if this is constituted in general according to the views here set forth. The textites are left out of account in the present discussion because their origin, whether meteoritic or terrestrial, is still debatable, although it is the opinion of the writer that they are of meteoritic origin and that they represent the outer crust of the (or a) cosmic body from which meteorites are derived. Their relative amount is, also, very small, so that they may be regarded as negligible.

Let us consider the elements first (Table 2). Four elements, iron, by far the most abundant, oxygen, silicon, and magnesium, make up 90.7 per cent of the Earth. These, with three others, nickel, calcium, and aluminum, make up 98.2 per cent; and with five others, sulphur, sodium, cobalt, chromium, and potassium, each in amount of less than one per cent, make up 99.8 per cent of the Earth. To this list phosphorus is almost certainly to be added, to the extent of about 0.1 per cent, and probably also carbon and chlorine, to the extent of about 0.05 per cent for both. It thus appears that the whole Earth is composed almost exclusively of but 12 or 14 elements, and that the percentage of the 80 or 78 others is almost negligible quantitatively, as they, altogether, do not constitute very probably more than about 0.1 per cent of the Earth.

Clarke¹⁶ has estimated the composition of the whole Earth on the assumption of a nickel-iron core surrounded by a lithosphere, the two being of equal volume and their masses (as assumed by Clarke) in the ratio 71:29. Clarke's estimate is shown in Table 3. Farrington¹⁷ suggests that the composition of the Earth

¹⁶ Clarke, F. W., *The Evolution and Disintegration of Matter*, U. S. Geol. Survey, Prof. Paper 132-D, 76, 1924. Clarke assumes practically the distribution of Wiechert (Ueber die Massenverteilung im Innern der Erde, *Nachr. Ges. Wiss. Göttingen*, 1897, 221).

¹⁷ Farrington, *Analyses of Stone Meteorites*, Field Museum Nat. Hist., Publ. No. 151, 213, 1911.

may be represented by the average composition of meteorites; and he averages, for this purpose, 318 analyses of iron and 125 of stony meteorites, with the result shown in Table 3. Harkins¹⁸ suggests a modification

TABLE II.
Composition of the Earth in Terms of Elements.

	Central core	Litho- sporic shell	Ferro- sporic shell	Perid- otitic shell	Basal- tic shell	Gran- itic shell	Whole Earth
Fe(met.) ...	90.67	45.34	12.18	1.18	....	....	31.82
Ni(met.) ...	8.50	4.25	1.57*	0.33	....	....	3.16
Co(met.) ...	0.59	0.30	0.07	0.04	....	....	0.23
O .....	....	21.11	37.10	42.05	44.24	46.59	27.71
Si .....	....	9.35	18.34	23.00	23.24	27.72	14.53
Al .....	....	....	1.55	3.26	8.46	8.13	1.79
Fe(sil.) ....	....	6.18	10.37	12.33	8.86	5.01	**7.94
Mg .....	....	13.36	13.88	10.91	3.78	2.09	8.69
Ca .....	....	....	1.72	5.09	6.51	3.63	2.52
Na .....	....	....	0.65	0.50	2.35	2.85	0.39
K .....	....	....	0.14	0.22	1.28	2.60	0.14
Ti .....	....	....	....	....	0.83	0.63	0.02
Cr .....	....	....	0.34	0.31	+	0.04	0.20
Mn .....	....	....	....	0.18	0.25	0.10	0.07
S	0.04	0.01	1.82	0.54	+	0.05	0.64
P	0.17	0.09	0.12	0.06	0.20	0.13	0.11
C	0.03	0.01	0.15	....	....	0.09	0.04
Incl .....	....	....	....	....	....	0.34	....
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Includes Ni of NiO. +Probably about 0.10; not reckoned by Daly.

** Total Fe = 39.76.

of Farrington's estimate, based on the relative number of falls, and expressed in atomic percentages. Chirvinsky¹⁹ has suggested a supposititious "terrium," or

^{17a} G. Linck (Aufbau des Erdballes, Jena, 1924, p. 15) estimates the composition of the Earth to be: Fe 50, O 22, Si 11.5, Mg 9, Ni 6, Ca 1.3, Al 0.6, S 0.5-1.0, Na 0.1-0.2, K 0.1, H (max) 1.0. Added during reading of proof.

¹⁸ Harkins, W. D., The Evolution of the Elements, Jour. Amer. Chem. Soc., 39, 864, 1917.

¹⁹ Chirvinsky, On the Question of the Laws of Formation of the chemical Elements in the Universe, Abstr. in Min. Abstr., 2, 84, 1923, (original in Russian).

primordial matter, representing the composition of the Earth as a whole. These estimates resemble each other in their broad features, but differ from mine in their assumed much greater proportion of iron, because of the different (somewhat arbitrary) basal assumptions.^{19a}

The most abundant elements in the Earth, then, as well as those most abundant in the crust, are all of low

TABLE III.^{17a}
Composition of the Earth as a whole.

	Washington 1925	Farrington 1911	Clarke 1924
Iron (metal)	31.82	68.43	67.20
Nickel (metal)	3.16	6.50	6.04
Cobalt (metal)	0.23	0.44	0.41
Oxygen	27.71	10.10	12.77
Silicon	14.53	5.20	6.98
Magnesium	8.69	3.80	2.13
Iron (silicate)	7.94	3.63	in metal
Calcium	2.52	0.46	1.12
Aluminum	1.79	0.39	1.86
Sulphur	0.64	0.49	0.96*
Sodium	0.39	0.17	0.58
Chromium	0.20	0.09	0.07
Potassium	0.14	0.04	0.39
Phosphorus	0.11	0.14	0.16
Manganese	0.07	0.03	0.08
Carbon	0.04	0.04	*
Titanium	0.02	....	0.15
	100.00	100.00+	100.00

* "Sulphur, carbon, copper." +Includes "other elements 0.05."

(but not the lowest) atomic weight and atomic number; the highest atomic weight represented is 59 (cobalt) and the highest atomic number is that of nickel (28). Oddo²⁰ and Harkins²¹ have called attention to the fact that in

^{19a} An average composition of meteorites based on that of known falls of iron and stone meteorites is invalidated by the fact that iron meteorites are more easily recognized as meteorites and are less subject to weathering than are stone meteorites, as has been pointed out by Merrill and others. Such an average would, thus, be presumably higher in iron than the truth.

²⁰ Oddo, G. Die Molekularstruktur der radioaktiven Atome, Zeitschr. Inorg. Chem., 87, 266, 1914. Cf. Vernadsky, La Géochimie, Paris, 1924, 18.

²¹ Harkins, W. D., The Evolution of the Elements, Jour. Amer. Chem. Soc. 39, 877, 1917.

the crust and in the Earth the elements of even atomic number are many times more abundant than are those of odd atomic number, a feature that Harkins considers to be confirmatory of the hydrogen-helium structure of the atoms, but on which Oddo reserves opinion.

The composition of the whole Earth is specially nota-

TABLE IV.

Composition of the Earth in Terms of Oxides, etc.

	Central core	Litho- sporic shell	Ferro- sporic shell	Perid- otitic shell	Basal- tic shell	Gran- itic shell	Whole Earth
Fe (met.) ...	90.67	45.34	12.15	1.18	....	....	31.82
Ni (met.) ...	8.50	4.25	1.57	0.33	....	....	3.16
Co (met.) ...	0.59	0.30	0.07	0.04	....	....	0.23
SiO ₂ .....	....	19.90	39.24	48.93	49.06	59.12	30.94
Al ₂ O ₃ .....	....	....	2.92	6.15	15.70	15.34	3.27
Fe ₂ O ₃ .....	....	....	....	....	5.38	3.08	0.07
FeO .....	....	7.95	14.79	15.86	6.37	3.80	10.47
MgO .....	....	22.15	22.99	18.17	6.17	3.49	14.43
CaO .....	....	....	2.45	7.12	8.95	5.08	3.53
Na ₂ O .....	....	....	0.89	0.67	3.11	3.84	0.52
K ₂ O .....	....	....	0.21	0.27	1.52	3.13	0.20
H ₂ O .....	....	....	....	....	1.62	1.15	0.03
TiO ₂ .....	....	....	....	....	1.36	1.05	0.02
Cr ₂ O ₃ .....	....	....	0.48	0.45	....	0.06	0.29
P ₂ O ₅ .....	....	....	0.27	....	0.45	0.30	0.11
MnO .....	....	....	....	0.23	0.31	0.12	0.12
S	0.04	0.01	1.82	0.54	....	0.05	0.64
P	0.17	0.09	....	0.06	....	....	0.11
C	0.03	0.01	0.15	....	....	0.10*	0.04
Incl .....	....	....	....	....	....	0.29	....
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* CO₂.

ble for the very small amount of some of the elements that are among the most abundant in the crust, notably aluminum, sodium, potassium, titanium, and manganese; oxygen, silicon, and iron (in silicates) are about the only ones that are present in about the same relative amounts and order in the whole Earth and in its crust.

The composition of the whole Earth in terms of oxides and minerals (Tables 4 and 5) need not detain us long

here. The general features of distribution that are shown by the elements are shown by the oxides, except that ferric oxide is practically non-existent in the Earth as a whole, the iron oxide being almost wholly ferrous. The mineral composition of the four outer shells (Table 5) are based on the norms calculated from the data in

TABLE V.
Composition of the Earth in Terms of Minerals.

	Central core	Litho- sporic shell	Ferro- sporic shell	Perid- otitic shell	Basal- tic shell	Gran- itic shell	Whole Earth
$\text{Fe}_{11}(\text{Ni}, \text{Co})$	98.34	49.24	10.55 ¹	1.57 ²	....	....	34.03 ³
$2(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$ ....	....	50.00	42.20	12.82	0.48	....	18.92
$(\text{Mg}, \text{Fe})\text{OSiO}_2$ .....	....	....	23.26	43.92	12.88	8.78	23.03
$\text{CaO} \cdot (\text{Mg}, \text{Fe})\text{O} \cdot 2\text{SiO}_2$ .....	....	....	5.59	18.33	14.11	6.56	8.79
$\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ....	....	....	3.34	13.23	25.10	15.54	6.39
$\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ ....	....	....	7.34	5.83	26.80	33.12	4.45
$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ ....	....	....	1.11	1.69	8.95	18.65	1.12
FeS	0.12	0.03	4.99	1.53	....	....	1.77
$(\text{Fe}, \text{Ni})_3\text{P}$	1.12	0.59	....	0.40	....	....	0.52
Fe_3C	0.42	0.14	....	....	....	....	0.22
$\text{FeO} \cdot \text{Cr}_2\text{O}_3$ .....	....	....	0.70	0.68	....	....	0.43
$\text{FeO} \cdot \text{Fe}_2\text{O}_3$ .....	....	....	....	....	10.67 ⁴	6.49 ⁴	0.15 ⁴
Apatite .....	....	....	0.67	....	1.01	0.68	0.13
SiO_2 (free) .....	....	....	....	....	....	10.18	0.05
	100.00	100.00	100.00 ⁵	100.00	100.00	100.00	100.00

¹ $\text{Fe}_6(\text{Ni}, \text{Co})$. ² $\text{Fe}_3(\text{Ni}, \text{Co})$. ³ $\text{Fe}_{10}(\text{Ni}, \text{Co})$. ⁴ Includes $\text{FeO} \cdot \text{TiO}_2$. ⁵ Includes 0.15 C.

Table 4. This is so, in part, because no sufficiently exact or concordant modal data are available, and in part because the compositions of the different shells are, thus, better compared with one another, being referred to the same mineral constituents.

When the figures given in Tables 2, 3, and 4 are considered, some fairly definite and regular progressions in the amounts and kinds of the different constituents from the center to the surface of the Earth are evident—a feature to which I have called attention in a brief note,²² for which the present detailed data were not available.

²² Washington, The radial Distribution of certain Elements in the Earth, Jour. Washington Acad. Sci., 14, 435, 1924.

These progressive distributions apply especially to the most abundant constituents, and they appear to have some bearing on our interpretation of the general constitution of the Earth and of how its structure originated. It may be said preliminarily that the present detailed figures confirm the previous conclusions.

The amount of metallic nickel-iron decreases steadily from almost totality at the center to disappearance in the peridotitic shell and in the crust. Concomitantly, the silicates, which begin to appear in the outer part of the core, increase at first rapidly in the lithosporic shell, then more slowly to a maximum of practical totality in the peridotitic shell, beyond which in the crust they slightly decrease, because of the entrance of magnetite and quartz into the composition.

Of the minor non-oxide constituents, iron sulphide (troilite) is apparently at a maximum in the ferrosporic shell, below and above which it decreases gradually; nickel-iron phosphide (schreibersite) and iron carbide (cohenite) both decrease from the center outward; while chromite increases outward to a maximum in the peridotitic shell. These progressions are in harmony with the relative abundance of these minerals in meteorites; schreibersite, cohenite, and graphite being most common in the irons, chromite in the stones, and troilite common in both kinds.

Of the silicates, the orthosilicate olivine decreases steadily from a maximum in the lithosporic (pallasitic) shell outward to the basaltic; in the ferrosporic shell it is partly replaced by the metasilicate pyroxene, which almost entirely replaces olivine in the basaltic shell and wholly so in the granitic shell. At the same time, there is a gradual outward increase in the amount of diopside relative to that of hypersthene, and still more so relative to that of olivine. The feldspars appear in small amount in the ferrosporic shell, whence outwardly they increase steadily, becoming dominant in the granitic shell. In the ferrosporic shell albite dominates over anorthite, the usual feldspar in the chondritic meteorites being oligoclase; in the next outer shell anorthite dominates over albite, the common feldspar of the achondritic meteorites being labradorite; above which albite increases rapidly.²³

²³ Michel, H., *Die Feldspäte der Meteoriten*, Tsch. Min. Petr. Mitth., 31, 563, 1912; Farrington, *Meteorites*, 1915, 169.

Orthoclase, which is scarcely present in the ferrosporic shell, increases steadily upward, until it becomes abundant in the granitic crust. Quartz, an abundant mineral in the granitic crust, is an exceptional rarity in meteorites,²⁴ although asmanite (tridymite) is occasionally present in rare iron-stone meteorites.

These various mineral progressions are evident also in the distribution of the elements and oxides. Iron, both as metal and as silicate, is by far the most abundant element near the center, but its amount decreases steadily outward until it is the fourth most abundant element in the granitic crust, having disappeared as metal in the peridotitic shell. Oxygen, which is not present in the central core, rapidly assumes second place in the lithosporic shell, and thence outward is the most abundant element, although with a very slightly increasing gradient. It is highly noteworthy that ferric oxide, Fe_2O_3 , is not present in meteorites, stone or iron, except as an alteration product, the chief oxide of iron being FeO , with rarely Fe_3O_4 . Parallel with these inverse progressions of metallic iron and oxygen are the occurrence and apparently gradual decrease of non-oxide compounds (schreibersite, cohenite, graphite) in the core and in the lithosporic shell, and the appearance of oxides (chromite, magnetite) in the ferrosporic and more outward shells, quartz appearing in the outermost, granitic shell. The sulphides occupy a position intermediate between the phosphides and carbides and the oxides, daubréelite ($\text{FeS.Cr}_2\text{S}_3$) occurring only in irons, troilite (FeS) in both irons and stones, and oldhamite (CaS) only and rarely in stones.

Goldschmidt²⁵ and Tammann²⁶ suggest the presence of an intermediate shell, of about the combined thickness and depths of my supposed lithosporic and ferrosporic shells, but composed mostly of sulphides with some oxides. I cannot accept the very great importance and abundance thus attributed to sulphur, because it does not seem to me to conform to the evidence of igneous rocks and other geological observations, or to be in harmony with the analogy with meteorites.

²⁴ Cf. Merrill, Quartz in meteoric stones, *Amer. Mineral.*, 9, 112, 1924.

²⁵ Goldschmidt, *Der Stoffwechsel der Erde*, Vid.-selsk. Skrifter, 1922, No. 11, and *Geochemische Verteilungsgesetze der Elemente*, idem, 1923, No. 3.

²⁶ Tammann, *Zur Analyse des Erdinnern*, *Zeitschr. Anorg. Chem.*, 131, 96, 1923.

Silicon follows a course almost exactly parallel to that of oxygen, the progressive increase in silica being, of course, very similar. Near the center, in the lithosporic shell, the silicate is practically all orthosilicate olivine, $2(\text{Mg,Fe})\text{O} \cdot \text{SiO}_2$, in which there is (molecularly) twice as much basic oxide as there is silica. The metasilicate pyroxene, $(\text{Mg,Fe})\text{O} \cdot \text{SiO}_2$, then begins to enter prominently, its amount being about three times that of olivine (with metasilicate diopside four times) in the peridotitic shell, until olivine almost vanishes in the granitic crust. A similar relative progression in the feldspars, between orthosilicate anorthite and polysilicates albite and orthoclase, will also be noted although albite seems to be more abundant than anorthite in the deep ferrosporic shell.

The relations of magnesium and iron (in the silicates) are especially noteworthy. Together, they are at a maximum of 39 per cent in the lithosporic shell, whence they decrease steadily to the outermost, granitic shell. Concomitantly with this decrease outwardly the molecular ratio $\frac{\text{Mg}}{\text{Fe}}$ steadily decreases in the outwardly successive

shells, as follows: 5.05, 3.07, 2.07, 1.00, 0.97, the ratio in the whole Earth being 2.54. Thus, the amount of ferrous oxide in the meteoritic pyroxenes is greater than in the olivines, and the amount of iron relative to that of magnesium increases with the increase in the amount of pyroxene relative to that of olivine. To give some illustrations:²⁷ the average ratio Mg:Fe in pallasitic olivines is about 7:1, that in chondritic olivines is more variable but, on the average, is about 3:1. The ratio in the orthorhombic pyroxenes of chondrites is so variable, and it is so difficult to separate the material in sufficient purity for analysis that the data are unsatisfactory, but the average may be placed at 6:1 to 4:1.

Prior²⁸ has shown by many analyses that "the less the amount of nickel-iron in chondritic stones, the richer it [the metal] is in nickel and the richer in iron are the

²⁷ For analytical data on these points see: Cohen, *Meteoritenkunde*, Heft 1, pp. 263, 266, 281, 284, 1894; and Prior, *On the Genetic Relationship and Classification of Meteorites*, *Min. Mag.* 18, 27-36, 1916.

²⁸ Prior, *On the genetic Relationship and Classification of Meteorites*, *Min. Mag.*, 18, 26, 1916; and *The Classification of Meteorites*, *Min. Mag.*, 19, 51, 1920.

magnesium silicates." He attributes this to a progressive oxidation and silication, in which "the nickel escaped oxidation so long as any iron remained in the metallic state and consequently this residual iron became increasingly enriched in nickel," the silicates becoming concomitantly richer in iron. This conclusion of Prior is in harmony with the broad progressions that have been set forth above. The greater tendency of iron over nickel to oxidise and form silicates has also been invoked by Wahl²⁹ and by Farrington³⁰ to explain the fact that meteoritic olivine is lacking in nickel, whereas much terrestrial olivine carries small amounts of nickel. The absence of nickel from meteoritic olivine is especially remarkable in view of the abundance of nickel in the meteoritic metal.

Other progressions, such as those shown by aluminum, by sodium, and by potassium, may be noted, but they need not be discussed here.

On the basis of the assumed constitution, the Earth, as regards its material composition, may be compared to the mass of slag and pig iron in a cooled blast furnace—a comparison that has often been suggested. The presence of metallic iron in the smelted mass is brought about by the reduction of the iron oxide ore by carbon, the silica and alumina of the slag coming from the ore, the limestone, and the ash of the coke. This comparison introduces the topic of the origin of the nickel-iron in meteorites or, rather, in the cosmic body of which they are (supposedly) fragments, and, *ex hypothesi*, in the interior of the Earth. Is the meteoritic and intratelluric nickel-iron due to the reduction of original iron silicate, let us say, or did it, in metallic form, make up part of the original mass that finally consolidated into the Earth?

An origin for meteoritic iron, by reduction or desilication, has been urged by Daubrée,³¹ Meunier,³² Merrill,³³

²⁹ Wahl, W. Beiträge zur Chemie der Meteoriten, Zeitschr. Anorg. Chem., 69, 70, 1911.

³⁰ Farrington, Meteorites, 1915, 187.

³¹ Daubrée, Géologie Experimentale, Paris, 1879, 517-523, 580, 596.

³² Meunier, Météorites, Paris, 1884, 346.

³³ Merrill, The Cumberland Falls Meteorite, Proc. U. S. Nat. Museum, 57, 100, 1920; Notes on the Meteorite of Estherville, ditto, 58, 368, 1920; On Metamorphism in Meteorites, Bull. Geol. Soc. America, 32, 412, 414, 1921.

and others. This applies especially to the iron of the stony (chondritic) meteorites, and also probably to that of siderites and siderolites. Daubrée obtained grains of metallic iron and, it is to be noted, crystals of enstatite on fusing olivine and peridotite in a graphite crucible. Merrill gives examples of metallic iron in chondritic meteorites for which no other than a secondary origin, by reduction, seems to be possible, Daubrée and Meunier suggest both carbon and hydrogen as the reducing agent, while Merrill favors hydrogen and thinks that the iron of chondritic stones is derived from lawrencite (FeCl_2), rather than from iron silicates.

That carbon and hydrogen are possible, if not the most probable, reducing agents, if the presence of metallic iron has been brought about by reduction, is suggested by the following considerations. Carbon, as diamond, graphite, and cohenite (Fe_3C), is common in the iron and siderolitic meteorites and, to a less extent, partly as hydrocarbons, in the stony meteorites. In the Earth carbon is abundant at the surface, chiefly as calcium (and magnesium) carbonate in limestone and dolomite, as carbon dioxide in the atmosphere, and in springs and volcanic emanations, in coal and other organic matter. Hydrogen is the most abundant gas, with less carbon monoxide, occluded in iron meteorites, whereas carbon dioxide, with less hydrogen, is the most abundant in the stony meteorites.³⁴ On the Earth, hydrogen is abundant in the surface region; as water and hydroxyl in rocks, as water in the hydrosphere and in volcanic gases, as the element in the atmosphere, and in organic matter. Neither water nor hydroxyl are present in meteorites, either iron or stone, except through alteration after reaching the Earth.

Sulphur and phosphorus also suggest themselves as possible reducing agents. They are present in considerable amount in meteorites, the phosphide, schreibersite, especially in the irons, and the sulphide, troilite, in both stones and irons. At the surface of the Earth the phosphate, apatite, is ubiquitous, although in very small amount, in igneous rocks; sulphides are present in

³⁴ Cohen, *Meteoritenkunde*, 1, 169, 1894; Chamberlin, R. T., *The Gases in Meteorites*, Carnegie Inst. Publ. No. 106, 1908. Farrington, *Meteorites*, 190, 1915.

igneous rocks and as magmatic segregations, sulphur gases are common at volcanoes and in hot springs, and calcium sulphate, gypsum, is a common secondary mineral. These elements are not considered by the authors mentioned above and, so far as I know, the reducing action of sulphur or phosphorus on iron silicate has not been investigated. Vogt³⁵ does not consider it in his studies of the solubility of sulphides in silicate magmas. Wahl³⁶ suggests as the origin of the rare oldhamite, CaS, that calcium has withdrawn sulphur from ferrous sulphide (troilite). It seems to be highly improbable that either sulphur or phosphorus could reduce ferrous silicate to metallic iron, the heat of formation of ferrous sulphide being much lower than that of ferrous oxide, so that by the action of sulphur or phosphorus on ferrous silicate ferrous sulphide or phosphide would be formed and not metallic iron. In any case, in the absence of experimental proof or theoretical discussion, and in view of the above suggestion, neither sulphur nor phosphorus will here be further considered as reducing agents in producing meteoritic or intratelluric metallic iron.

To return to carbon and hydrogen, it is well known experimentally and theoretically that they are both capable of reducing the iron of ferrous oxide or silicate to the metallic state. As regards meteorites or the interior of the Earth, this action may be accepted qualitatively. But the data now at hand render it possible to study the matter quantitatively as to the Earth, so as to decide the question whether all or part of the metallic iron³⁷ was originally present as such or was present as ferrous silicate.

It is purposed to consider the following questions. (1) Is there sufficient silica available in the whole Earth to combine with the metallic iron to form ferrous silicate? (2) Is there sufficient oxygen available in the whole Earth to form ferrous oxide from the metallic

³⁵ Vogt, Die Sulfid-Silikatschmelzlösungen, Norsk Geol. Tidsskr., 4, 151, 1917 and Videnskaps selsk. Skr., 1918, No. 1, 1919.

³⁶ Wahl, Beiträge zur Chemie der Meteoriten, Zeitschr. Anorg. Chem., 69, 71, 1911.

³⁷ In the present discussion nickel will not be considered, as its mass is much less than that of the iron, and it unnecessarily complicates the problem, which, after all, is tentative and suggestive, not final.

iron? (3) If all the iron was originally in combination as ferrous oxide or ferrous silicate, is there sufficient carbon or hydrogen, or both, available in the whole Earth to yield, by reduction, the supposed mass of metallic iron in the Earth?

In the whole Earth, with a total mass of about 6×10^{21} tons, the *metallic* iron is distributed as follows, the figures being based on the data in Tables 1 to 4.

TABLE VI.
Distribution of *metallic* iron in the Earth.

	Mass Tonsx10 ²¹	Per cent Fe (met.)	Iron Tonsx10 ²¹
Central core	1.65	90.7	1.50
Lithosporic shell	0.51	45.3	0.23
Ferrosporic shell	1.36	12.2	0.17
Peridotitic shell	2.42	1.2	0.03
Whole Earth	6.03	31.3	1.93

(1) The most obvious and most abundant supply of silica that is conceivably available to combine with the (supposedly) present metallic iron to form original silicate is that which may be freed by desilicating hypsorthene to form olivine, according to the equation: $2(\text{Fe, Mg})\text{SiO}_3 \rightleftharpoons (\text{Fe, Mg})_2\text{SiO}_4 + \text{SiO}_2$. This reversible equation was involved in Daubrée's experiment mentioned above, in which enstatite was formed along with metallic iron on reducing olivine with carbon, and it is also the fundamental equation in the so-called Bowen-Andersen effect, by which enstatite at high temperatures melts incongruently and splits up into olivine and excess silica in the liquidus, so that olivine may be present in highly silicic lavas or a more than normative amount of olivine may be present in basalt.³⁸

Another conceivably possible source is the silica freed by desilicating orthoclase to form leucite and albite to form nephelite; although these last two sources are improbable in the highest degree, as neither orthoclase, leucite, nor nephelite is found in meteorites. Silica

³⁸ Bowen and Andersen, The Binary System MgO-SiO_2 , this Jour., 37, 496, 1914; Andersen, The System Anorthite-Forsterite-Silica, this Jour., 39, 453, 1915; Washington, Petrology of the Hawaiian Islands, this Jour., 5, 469, 1923 and 6, 355, 1923.

might also be gained from the diopside molecule if this were desilicated and split up to form olivine and calcium orthosilicate, and similarly anorthite would yield silica if it were desilicated to form melilite. But these two sources are even more improbable than the feldspars and the total amount gained would be negligible; so that they need not be considered further.

The ferrosporic and the peridotitic shells are the only ones that can be considered as possible regions from which to draw silica; the lithosporic shell is supposed to contain olivine as practically the only silicate, and the total combined mass of the outer basaltic and granitic shells is so small that the amount of free silica (quartz) possibly to be derived from them is entirely negligible.

The total amount of silica that is possibly available from the hypersthene and feldspar molecules in the ferrosporic and the peridotitic shells is as follows:

Ferrosporic shell	{ Hypersthene	.09x10 ²¹ tons
	{ Feldspar	.05x10 ²¹ "
Peridotitic shell	{ Hypersthene	.26x10 ²¹ "
	{ Feldspar	.07x10 ²¹ "
Total available silica		.47x10 ²¹ tons

The amount of silica needed to form ferrous silicate from the total amount of metallic iron in the Earth (the extra oxygen needed not being here considered), is 2.06×10^{21} tons. So that the amount of available silica, as calculated above, is inadequate to silicitize more than about one-fourth of the total metallic iron present in the Earth. The calculated amount of available silica ($.47 \times 10^{21}$ tons) is, however, more than twice as much as that needed to silicitize the iron in the ferrosporic and the peridotitic shells ($.20 \times 10^{21}$ tons), and is about equal to that needed for the purpose in these and the lithosporic shell together ($.43 \times 10^{21}$ tons). This agreement may justly be held to be coincidental, or it may not; but it seems to be clear that there does not exist in the Earth sufficient silica to silicitize the iron of the central core.

(2) But, in order to form ferrous silicate, FeO.SiO_2 , from metallic iron oxygen is needed, in molecular amount equal to that of the iron. Therefore, about $.55 \times 10^{21}$ tons of oxygen are required to silicitize the 1.93×10^{21}

tons of intratelluric metallic iron. The only large sources of supply for oxygen that seem to be available are: the water of the hydrosphere, that in igneous rocks (including hydroxyl), the oxygen of the atmosphere, and the oxygen of the carbon dioxide of limestone. The mass of the hydrosphere is about 1411×10^{15} tons,³⁹ containing about 86 per cent of oxygen,⁴⁰ so that the mass of the hydrospheric oxygen is about $.00121 \times 10^{21}$ tons. The mass of the 60-kilometer, basaltic and granitic, crust is $.094 \times 10^{21}$ tons and, assuming the figures for the percentage of water⁴¹ given in Table 3, this contains $.00122 \times 10^{21}$ tons of oxygen and $.00015 \times 10^{21}$ tons of hydrogen. The mass of the atmosphere is 5×10^{15} tons,³⁹ with an oxygen content of $.000001 \times 10^{21}$ tons, on the assumption that the whole atmosphere has the composition of the lowermost troposphere. Limestone makes up about 0.25 per cent of the 10-mile, outermost crust,⁴² the total mass of the limestone being $.00057 \times 10^{21}$ tons, of which $.00018 \times 10^{21}$ tons is oxygen of the carbon dioxide and $.00007 \times 10^{21}$ tons is carbon. The total amount of oxygen available from these sources is $.00261 \times 10^{21}$ tons. This amount is, obviously, far too small to oxidize more than an almost infinitesimal fraction of all the intratelluric iron; indeed, it is only about one-tenth of that needed to oxidize the small amount of metallic iron in the peridotitic shell. All the other sources of available oxygen could supply but a very small fraction of the amount calculated above and would thus be still more negligible. Such sources would include the oxygen present, free or combined, in volcanic gases, that in all animal and vegetal beings, that dissolved in oceanic and fresh waters, and that occluded in, or present in crevices of, rocks. It will be noted also that the mass of oxygen calculated to be present in the water of the crust is too high, because it was assumed that the percentage of water shown by the superficial rocks analysed extends down to the bottom of the crust, and it is known, from the evidence of deep mines, etc., that below a very shallow depth the rocks are dry and that they do not contain secondary minerals,

³⁹ Clarke and Washington, *The Composition of the Earth's Crust*, U. S. Geol. Survey, Prof. Paper 127, 17, 1924.

⁴⁰ Clarke and Washington, *op. cit.*, 33.

⁴¹ Clarke and Washington, *op. cit.*, 16.

⁴² Clarke and Washington, *op. cit.*, 32.

to whose presence much of the water in the surface rocks is due. The total amount of available oxygen is, therefore, wholly inadequate to oxidize the total iron, or even that of the three intermediate shells, for which about $.14 \times 10^{21}$ tons are needed.

(3) We may now take up the question whether, if all the intratelluric iron had originally been combined as ferrous oxide or ferrous silicate (which amounts to the same thing), there is sufficient available carbon or hydrogen, or both, to reduce the iron oxide to the metallic state. The amount of ferrous oxide, FeO ,⁴³ corresponding to the total amount of metallic iron in the Earth would demand $.035 \times 10^{21}$ tons of hydrogen or $.21 \times 10^{21}$ tons of carbon for complete reduction.

The chief and the only possibly adequate sources on which we can draw for the hydrogen that may be supposed to have acted as reducing agent are the water of the hydrosphere and the water and hydroxyl present in the minerals and rocks of the crust; the amount of hydrogen in the atmosphere,⁴⁴ that in animals and plants, and that in volcanic emanations being wholly negligible. The mass of the hydrogen of the hydrosphere is about $.00015 \times 10^{21}$ tons, and the mass of the hydrogen in the 60-kilometer crust, as previously calculated, is about $.00016 \times 10^{21}$ tons; together they amount to about $.0003 \times 10^{21}$ tons.

The only adequate supply of carbon is that in the 60-kilometer crust, including especially the carbon of limestones and other sedimentary rocks; the amount of carbon in coal-beds, oil-shales, oil basins, the carbon dioxide of the atmosphere, and the carbon in living beings is entirely negligible. The percentage of carbon in the 10-mile crust, including sedimentary rocks,⁴⁵ is 0.094, so that, if it is assumed that the whole 60-kilometer crust contains the same percentage, the total amount of carbon from this source would be $.008,8 \times 10^{21}$ tons.

The total amount of available hydrogen and carbon, then, would be about $.009 \times 10^{21}$ tons, whereas there is needed either $.035 \times 10^{21}$ tons of hydrogen or $.21 \times 10^{21}$

⁴³ Ferric oxide, Fe_2O_3 , or magnetite, Fe_3O_4 , would demand more reducing agent than would ferrous oxide.

⁴⁴ The atmosphere constitutes 0.03 per cent of the 10-mile crust, and hydrogen 0.01 per cent of the atmosphere by volume.

⁴⁵ Clarke and Washington, *op. cit.*, 34.

tons of carbon for the reduction of ferrous oxide to the total amount of metallic iron in the Earth. The figures for the several shells 10^{21} tons are:

	C	H	O
Lithosporic	.025	.004	.066
Ferrosporic	.018	.003	.048
Peridotitic	.003	.0005	.008
Earth	.210	.0345	.008

It will thus be seen that there is not enough of either hydrogen or carbon, or of both together, to reduce the assumedly original ferrous oxide of the three intermediate shells, and little more than enough to account for the minimal amount of metallic iron in the peridotitic shell. It may be noted, also, that the estimates of carbon and hydrogen are maxima, because it is certain that the lower two-thirds of the crust contain less carbon and hydrogen than does the upper one-third.

From the data presented in the preceding pages it seems to be clear that there is too little available silica to have originally silicatized more iron than that in the three intermediate shells, that there is not enough available oxygen to have formed ferrous oxide from more iron than that in the peridotitic and part of the ferrosporic shells, and that there is not enough carbon and hydrogen to have reduced more ferrous oxide or silicate than what may have been present in the peridotitic and part of the ferrosporic shells. There was certainly not enough silica, oxygen, or reducing agents, to account for the great mass of the iron in the central core and in the lithosporic shell.

This result, as regards oxygen, is in full accord with the generally accepted, indeed obvious, view that the solidification and formation of the Earth took place under largely non-oxidizing conditions, as is shown analogically by the presence of metallic nickel-iron and such non-oxide compounds as phosphides, sulphides, carbides, and chlorides in meteorites.

The comparison of the Earth with a mass of slag-surrounded metal does not, thus, seem to be altogether apt. The comparison is just if the material composition alone is considered, but if the origin of the metal, by reduction from a previously oxidized condition, is an essential fea-

ture the analogy breaks down, because reduction can account, apparently, for only a very small proportion of the metal present.

From the discussion above it follows that the original mass out of which the Earth coalesced contained a large amount, roughly about 30 per cent, of uncombined iron, even after the originally dissociated matter had cooled sufficiently to form compounds. There is, of course, no reason why all the elements in the mass, even the few most abundant ones, should have been present in such exactly stoichiometrical ratios as to be capable of fully satisfying each other. On the contrary, starting with such a complex dissociated mass as is to be supposed under either the nebular or the planetesimal hypothesis, the chances would be greatly against this and strongly in favor of one or more of the elements being present in excess of the amount needed for complete combination.

It is reasonable to suppose that the more easily oxidizable elements first took all the oxygen that they could get, leaving only a small part for the overwhelmingly abundant iron, so that only about one-fifth of this was oxidized and eventually silicitized.⁴⁶ There is also the possibility of some evolutionary process being at work, giving rise to all or many of the elements of higher atomic weight, as has been advocated by Clarke.⁴⁷ In any case, the great predominance of iron over any other single element in the mass of the Earth (40 per cent) is the most outstanding feature of its constitution; the next being the small number of elements that make up almost all the Earth, and their positions in the periodic table. But discussion of these and other similar points must await another occasion.

That the original mass of matter which formed the Earth greatly resembled, chemically, the Sun's atmosphere is indicated by the striking correspondence between the most abundant elements in the Earth and those in the atmosphere of the Sun, as judged from the intensity of their spectral lines.⁴⁸ This correspondence

⁴⁶ In a paper received just as this paper was being sent off, Barnett (*The Chemistry of the Earth's Core*, *Jour. Geol.*, 32, 615, 1924) discusses the effects of the differential oxidizability of the elements, especially iron.

⁴⁷ Clarke, *The Evolution and Disintegration of Matter*, U. S. Geol. Survey, Prof. Paper 132-D, 1924.

⁴⁸ See Abbott, *The Sun*, New York, 1911, 91.

is seen in Table 7, in which the most abundant elements in the Sun's atmosphere, and in the whole Earth and in its crust, are arranged in the order of their abundance.

In considering the data presented in Table 7, especially those in Columns 1 and 2, the great differences in physical condition and state of matter between the Sun's

TABLE VII.

Order of Abundance of the Elements.

1 Sun's Atmosphere	2 Whole Earth	3 Earth's Crust
1. Calcium	1. Iron	1. Oxygen
2. Iron	2. Oxygen	2. Silicon
3. Hydrogen	3. Silicon	3. Aluminum
4. Sodium	4. Magnesium	4. Iron
5. Nickel	5. Nickel	5. Calcium
6. Magnesium	6. Calcium	6. Sodium
7. Cobalt	7. Aluminum	7. Potassium
8. Silicon	8. Sulphur	8. Magnesium
9. Aluminum	9. Sodium	9. Titanium
10. Titanium	10. Cobalt	10. Phosphorus
11. Chromium	11. Chromium	11. Hydrogen
12. Strontium	12. Potassium	12. Manganese
13. Manganese	13. Phosphorus	13. Sulphur
14. Vanadium	14. Manganese	14. Barium
15. Barium	15. Carbon	15. Chlorine
16. Carbon	16. Titanium	16. Chromium

atmosphere and the whole Earth must be remembered. The one is a mass of gas, at enormously high temperatures; in which ionization or dissociation (that is, liberation of electrons), to a greater or less degree, is possible, with consequent effect on the spectral lines. The other is a solid mass—the cold, frozen product of what was, presumably, originally such a hot gaseous mass as is now the atmosphere of the Sun.

The relative abundance of the different elements in the Sun's atmosphere (Column 1, Table 7) has been estimated from the intensity of their spectral lines; in the Earth the order of abundance has been arrived at gravimetrically and by analogy with meteorites. But, in spite of the differences in physical conditions, state of matter, and method of estimation, the correspondences

between the composition of the Sun's atmosphere and that of the whole Earth are many and striking. There are, it is true, some notable discrepancies, some of which seem to be possible of explanation on physical grounds.

Of the eleven most abundant elements in the Earth, nine (Fe, Si, Mg, Ni, Ca, Al, Na, Co, and Cr) are among the eleven most abundant in the Sun's atmosphere; oxygen and sulphur do not appear in Column 1, and hydrogen and titanium do not appear in Column 2. Iron stands at or next to the top in both lists, and nickel and magnesium are very close together and very abundant in both, these three elements making up 51.6 per cent of the whole earth. Iron, nickel, and cobalt, the three most distinctive elements of meteorites, especially of the siderites and of the pallasites, are prominent in both columns, and they are present in the same order. The highly placed calcium and sodium of Column 1 are lower down in Column 2, but in both they are present in the same order and about the same distance apart. Below the six most abundant elements in both columns there are some cases of about the same order of magnitude of relative abundance; namely, cobalt, chromium, manganese, titanium, and carbon.

Turning to the discrepancies, the most striking are the large amounts of calcium, hydrogen, and sodium shown in the Sun's atmosphere, and of oxygen and silicon in the Earth; hydrogen being absent from the list of the 16 most abundant elements in the Earth and oxygen from that of the Sun. The apparent great abundance of calcium in the Sun may be attributable to partial ionization or dissociation of the element, which, according to some modern hypotheses, gives rise to the very intense H and K lines belonging to this element;⁴⁹ which thus produce an exaggerated idea of great abundance. In the scheme of the Sun's atmosphere suggested by St. John and Babcock ionized calcium (H and K lines) is shown in the uppermost level, whereas "neutral calcium" is much lower down, close to sodium. The apparently great abundance of hydrogen and of sodium in the Sun's atmosphere may, likewise, be reasonably attributable to the comparatively ready ionizability of these elements and the consequent intensity of their spectral

⁴⁹ St. John and Babcock, *Proc. Nat. Acad. Sci.*, 10, 390, 1924.

lines. The absence of oxygen,⁵⁰ and also of sulphur and phosphorus, from among the apparently most abundant elements in the Sun's atmosphere does not imply that they are absent or not abundant, for it is well known that the negative elements do not give spectra under conditions in which the positive elements readily reveal themselves.⁵¹ That is, in modern parlance, the ionization potential, or the ability of the negative elements to part with electrons, is less than that of the positive elements.

Another resemblance between the composition of the Earth and that of the Sun is indicated by some recent investigations. St. John and Babcock⁵² have suggested a scheme of the distribution of some of the elements (and other factors) in the Sun's atmosphere. In this scheme, based on spectroscopic data, which embraces only a few elements, iron (vapor) is at the bottom of the Sun's atmosphere, extending up to about 1,500 kilometers; above it comes a thin layer of aluminum; still higher come "neutral" (that is, non-ionized) calcium, and above this sodium; then, still higher, is a thick shell of hydrogen; and finally an outermost shell of ionized calcium ("H and K lines"). The position of magnesium is not stated.

One cannot but be tempted to see in this suggested order an analogy with the arrangement of matter in the Earth, namely, a central iron core, surrounded by successive, intergradient shells of, first, iron mixed with silicate, then silicates alone, the lower silicate layers being of iron and magnesium, and aluminum with calcium and sodium gradually entering in upward, so that the uppermost crust is the lightest shell. The shell of hydrogen, shown in the sun's atmosphere, would correspond to the atmosphere of the Earth, which, because of its small mass, has possibly lost some of its original hydrogen, and in which according to modern views,⁵³ hydrogen forms the uppermost part.

⁵⁰ The presence of oxygen in the Sun's atmosphere has recently been definitely established. Lines of oxygen are prominent in many stellar spectra.

⁵¹ See Abbott, *The Sun*, pp. 94, 95, 255.

⁵² St. John and Babcock, *Note on the Pressure and Currents in the Sun's Atmosphere*, *Proc. Nat. Acad. Sci.*, 10, 389, 1924.

⁵³ See Humphreys, *The Physics of the Air*, Philadelphia, 1920, 68.