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THE COMPOSITION OF THE EARTH'S CRUST

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THE COMPOSITION OF THE EARTH'S CRUST.

By F. W. CLARKE and H. S. WASHINGTON.

INTRODUCTION.[1]

THE CRUST AND THE INTERIOR.

The term "crust of the earth" is a heritage from the days when the interior of the earth was generally conceived to be a "sea of molten rock" at an enormously high temperature covered with a relatively thin, solid crust of cooled matter. Various cogent reasons, which can not be considered here, have led to the abandonment of this concept, and we now have reason to hold the following tenets as to the conditions that exist in the earth's interior:

1. The interior mass is essentially or behaves essentially like a rigid solid, although it may possibly have a certain degree of fluidity.

2. The interior is probably hot, but it is of unknown temperature, and its temperature probably increases toward the center, but through gradients that are undetermined beyond very moderate depths and that are different in different places.

3. The density of the interior is greater than that of the known crust, for the mean density of the earth as a whole is about 5.52, whereas that of the crust is about 2.79.[2] The density at or near the center may possibly be set down as of the order of magnitude of 8 to 10, according to the assumptions that are made; or it may conceivably be even higher. The problem is at present insoluble, because we know nothing of the rate of change in density with depth; nor do we know whether the density varies continuously with depth, or whether it becomes constant below a certain depth.

4. The earth as a whole acts in many respects as a magnet, and as the rocks of the crust in general are not notably magnetic this action may be attributed to the character or composition of the material that forms the interior.

5. From a study of the propagation of the shocks or waves of earthquakes, we are led to believe that there is a change in the earth's physical properties at a depth of about 0.5 of its radius, the material below this depth not transmitting transverse vibrations. Studies of the compressibility of rocks and minerals made by Adams and Williamson,[3] in the geophysical laboratory of the Carnegie Institution, indicate that the high density of the interior can not be due to compression alone, so we must conclude that there is also a change in the actual substance of the earth toward its center.[4]

6. It has often been suggested, and it is more or less commonly believed, from a consideration of the density and the magnetic character of the earth and from a knowledge of the composition of many meteorites, that part, at least, of the earth's interior is composed largely of iron or of a nickel-iron alloy similar to that which constitutes the iron meteorites. An objection commonly made to this view is that iron loses its magnetism at 785°, but this objection is invalidated by our complete ignorance as to the magnetic behavior of iron at the enormous pressures that exist beneath the outer crust. Furthermore, by analogy with meteorites, such a metallic core would be composed of a nickel-iron alloy, not of pure iron; and it is well known that the nickel-iron alloys possess magnetic properties that are very different from those of iron or steel. The same is true of the manganese-iron alloys. It is thus quite within the bounds of reasonable

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[1] This introduction is taken bodily, except for some minor changes and additions, from a paper by H. S. Washington on "The chemistry of the earth's crust," published in the Journal of the Franklin Institute for December, 1920 (vol. 190, pp. 757-768).

[2] In the paper from which this introduction is taken the density of the crust was given as 2.77. Later computations give 2.79. See Washington, H. S., Isostasy and rock density: Geol. Soc. America Bull., vol. 33, pp. 375-410, 1922.

[3] Adams, L. H., and Williamson, E. D., The compressibility of minerals and rocks at high pressures: Franklin Inst. Jour., vol. 195, pp. 475-529, 1923.

[4] Williamson, E. D., and Adams, L. H., Density distribution in the earth: Washington Acad. Sci. Jour., vol. 13, p. 413, 1923.

possibility that the nickel-iron alloys which are here assumed to compose a zone in the interior of the earth may retain their magnetic susceptibility even at the high temperatures that are assumed to exist at great depths; and this possibility is enhanced when we consider the unknown influence of great pressure.

Leaving the interior of the earth for the present, we may concentrate our attention on the outer shell—the so-called "crust"—which is the only part of the earth that is directly open to our study, and which has been compared, with some reason, to a covering of slag or scoria over the interior. In dealing with this crust we shall consider primarily its chemical composition.

The thickness of this crust is unknown, is probably not uniform, and is presumably indeterminate. For purposes of computation we may assume an approximate thickness of 10 miles (16 kilometers), this being about the sum of the highest elevation of the land and the greatest depth of the ocean.

This solid crust is made up almost wholly of igneous rock—that is, rock that has solidified from a hot, liquid ("molten") condition, either as "plutonic" rock, found at different depths beneath the surface, as dikes or sills filling crevices, or as lava flows at the surface. Assuming a thickness of 10 miles, the composition of the rocks of the crust is estimated to be about as follows:

Proportion of rocks of different classes in the earth's crust.

Igneous rocks	95
Shales	4.0
Sandstones	.75
Limestones	.25
	100.00

The metamorphic rocks, such as gneiss and schist, are here included with the igneous rocks.

In a study of the chemistry of the crust as a whole such relatively small masses as beds of coal or deposits of salt and ore are negligible, though their presence is significant, and the coating of soil is also negligible.

GENERAL FEATURES OF IGNEOUS ROCKS.

Igneous rocks, as has been said, are those that have solidified from a state of fusion, or preferably liquidity, for the term fusion implies a previously solid condition. The liquid matter that eventually solidifies as a rock is called technically the "magma," a term that is in frequent use in petrology.

The magma comes up from below; from what depth we do not know, though there is some reason for thinking that the places of its origin are not very deep. Nor do we know whether it arises from the melting of parts of the earth that are actually solid but potentially liquid on relief of pressure, or whether it is in general derived from "reservoirs" of liquid magma.

The igneous magma is usually compared to a complex solution of salts in water. This comparison, which was first suggested by Bunsen in 1861, has been very fruitful of results in the study of the origin, formation, and character of igneous rocks.

The magma contains gases in solution, much as spring water contains air in solution, or as the waters of many mineral springs contain carbon dioxide, which escapes on relief of pressure.

Of these magmatic gases the one that has by far the greatest effect and that is generally the most abundant is the vapor of water. This vapor forms the greater part of the clouds that are given off by volcanoes in eruption and, with other gases, produces the spongelike structure seen in pumice and the cavities of vesicular lavas; an effect caused by expansion, due to relief of pressure in the lava as it reaches the surface. Some glassy lavas contain a rather large percentage of water, the magma having solidified so rapidly as not to permit its escape, and inclusions of water and liquid carbon dioxide are visible in the crystals of many granites and other rocks. The presence of water in volcanic magmas has been doubted by Brun and others who followed him, but its existence in lavas, especially in those of Kilauea, has been shown conclusively by the researches of Day and Shepherd[5] and is made evident by practically every rock analysis and in other ways, so that the existence of water in magmas may be regarded as one of the established truths of the chemistry of igneous rocks.

Volcanic exhalations contain not only the vapor of water but other gases—carbon dioxide, carbon monoxide, hydrogen chloride, sulphur trioxide and dioxide, hydrogen sulphide, carbon

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[5] Day, A. L., and Shepherd, E. S., Water and volcanic activity: Geol. Soc. America Bull., vol. 24, p. 573, 1913.

oxysulphide, hydrogen fluoride, ammonia, methane and possibly other hydrocarbons, sulphur vapor, hydrogen, nitrogen, oxygen.

The presence of these gases in the magma lowers its solidification point, so that a lava, on coming to the surface, may be and usually is liquid at a temperature considerably below the fusing point of the solid rock formed from it, for during its solidification much of the dissolved gas is lost. Either because of this loss or because of an increase in fluidity, or in some other way that is not yet well understood, the gases in the magma seem to promote the crystallization of minerals, so that they are often referred to as "mineralizers." Some of these gases also play an important part in the formation of many ore bodies.

The magma on solidification generally forms a mixture of minerals, substances of definite chemical composition and physical character, just as a solution of salts in water (such as sea water) forms a mixture of crystals of salts and ice on freezing. Frequently the magma cools too rapidly to permit complete crystallization or (as with obsidian) too rapidly for any crystallization, so that the rock is composed partly or wholly of glass. Such glassy rocks are found only as surface flows.

MINERAL CONSTITUENTS OF IGNEOUS ROCKS.

It is a very significant and striking fact that although about a thousand different minerals are known, yet the number that compose over 99 per cent by weight of igneous rocks is very small. Indeed, the minerals that are really essential to form igneous rocks number less than a dozen.

These essential minerals are (1) quartz, silicon dioxide; (2) the feldspars, silicates of alumina and potash, soda, or lime, including the potassic orthoclase, the sodic albite, and the calcic anorthite, with isomorphous mixtures of these; (3) the pyroxenes, metasilicates of calcium, magnesium, and iron, sometimes with aluminum or sodium; (4) the amphiboles, in chemical composition much like the pyroxenes, but differing in crystal form and otherwise; (5) the micas, alumino-silicates, mostly the potassic muscovite or the potassium-iron-magnesium biotite, all containing hydroxyl; (6) the olivines, orthosilicates of iron and magnesium; (7) nephelite, an orthosilicate of sodium and aluminum; (8) leucite, a metasilicate of potassium and aluminum; (9) magnetite, ferrosoferric oxide, and ilmenite, oxide of iron and titanium; and (10) apatite, a phosphate of calcium containing a little fluorine or chlorine. Magnetite and apatite are found in nearly all rocks, but seldom in more than small amounts.

Certain kinds of igneous rocks contain other minerals, such as the silicates sodalite, haüyne, melilite, zircon, and garnet, and the oxides tridymite (a second form of silica), hematite, chromite, spinel, corundum, and rutile. But in a study of the igneous rocks that form the whole crust of the earth these minerals are practically negligible. Igneous rocks, then, in general, looked at in the broadest way, are formed almost wholly of a very few silicates of aluminum, iron, calcium, magnesium, sodium, potassium, and hydroxyl, with or without quartz (that is, excess of silica), with small amounts of a phosphate and of free iron oxide, and with or without traces of other constituents. Some of the essential minerals enumerated above (pyroxene, amphibole, mica, olivine, and magnetite) contain small amounts of manganese and titanium. From such a general survey of the rock-forming minerals, then, we obtain a broad conception of the chemical composition of the earth's crust as a whole.

Another important fact concerning the minerals that form igneous rocks is that, with two exceptions, any one of them may occur in rocks with any one or more of the others. The only exceptions are that neither nephelite nor leucite is known to occur with quartz, and a partial exception is that olivine seldom occurs with quartz and never in large amount.

Of the minerals named nearly all may be present in a rock in widely varying proportions, and each may be completely absent. We know igneous rocks that are composed entirely of quartz (northfieldite), feldspar (anorthosite), pyroxene (websterite), amphibole (hornblendite), or olivine (dunite), and almost entirely of nephelite (congressite), leucite (italite), or magnetite (some iron ores), and some rare igneous rocks are composed wholly of biotite. Of the essential rock minerals, only apatite does not form the whole or almost the whole of any known igneous rock.

We also know some igneous rocks that are composed of two minerals, more that are composed of three, and many that are composed of more than three, with the widest possible variations in the proportions of almost all, except, as noted above, that quartz does not occur with nephelite and leucite and that its occurrence with olivine is rare.

CHEMICAL CONSTITUENTS OF IGNEOUS ROCKS.

Although, as we have seen, most igneous rocks are composed of but few essential minerals and consequently of but few so-called "major" oxides (in terms of which the chemical composition of rocks is usually formulated) yet when we come to study the igneous rocks in detail we find that some rocks may contain a considerable number of chemical constituents. Altogether, about twenty-three are determined and recorded in rock analyses of the better class. Indeed, as has been said by Dr. W. F. Hillebrand, the foremost analyst of rocks, "a sufficiently careful examination of these [igneous] rocks would show them to contain all or nearly all, the known elements; not necessarily all in a given rock, but more than anyone has yet found." Proper study, therefore, of the chemistry of igneous rocks and their chemical analysis, if it is to determine all the constituents probably present, is evidently somewhat difficult and complicated.

About 13,000 chemical analyses of rocks have been made since their analysis was first attempted, near the beginning of the nineteenth century, and these analyses show us what are the chemical constituents of rocks and give us a good idea of their relative abundance and the ranges in their percentages.

The most abundant or "major" constituents, stated as oxides, in the order in which they are stated in the analyses, which is not quite the order of their abundance, are silica (SiO_2), alumina (Al_2O_3), ferric oxide (Fe_2O_3), ferrous oxide (FeO), magnesia (MgO), lime (CaO), soda (Na_2O), potash (K_2O), and water (H_2O). These nine oxides together make up about 98 per cent of the igneous rocks, and all occur in greater or less amount in practically every rock, so that the quantity of each must be determined in every rock analysis that makes the slightest pretense to good quality.

As the most abundant and essential rock minerals are either silica or silicates, and as all igneous rocks except some rare and small bodies of iron ore of magmatic origin (some of which may not be igneous) are consequently silicate rocks, silica shows easily the highest maximum and the widest range, both in extremes and in the usual run of occurrence. A few igneous rocks are composed almost entirely of quartz, and the highest percentages of silica recorded for truly igneous rocks are in one from Cumberland (England), where the border facies of a granitic mass shows 96.16; one from Massachusetts with 93.38; and one from Arizona with 92.59. In general, however, the percentage of silica ranges from about 75 to about 34, and it drops to zero only in some "magmatic" iron ores. In nearly all rocks it is the most abundant constituent. Veins of quartz are not considered here, as many of them are of nonigneous origin, in the ordinary sense of the word igneous.

Alumina, which is almost invariably the next most abundant constituent, reaches a maximum of about 60 per cent in some corundum-bearing syenites from Canada and the Urals and has a general range from about 20 to about 10. It is wholly absent only in the "magmatic" ores and in some rocks that are composed largely or entirely of olivine. The two oxides of iron, of course, reach their maxima in such rocks as the iron ores already spoken of, the highest figures recorded for Fe_2O_3 being 88.41 (Sweden) and 62.39 (Ontario), and the highest for FeO being 34.58 (Sweden) and 32.92 (Minnesota). Their general range is from nearly 15 for each (FeO generally higher than Fe_2O_3), and but little more than that for both together in any one rock, to less than one-half of 1 per cent. Iron is found in all but a very few rocks.

Magnesia reaches its maximum in the almost purely olivine rocks (dunite) of North Carolina, 48.58, and of New Zealand, 47.38, but it ranges in general from about 25 to much less than 1 per cent. Lime is highest (22.52) in some pyroxenites of the Urals, and almost as high (about 20) in the anorthosite of Canada and elsewhere, but it ranges in general from about 15 per cent to nearly zero.

Of the two alkalies, soda reaches a maximum of 19.48 in a rare almost purely nephelite rock from Canada and of 18.67 in another from Turkestan, but its general range is from about 15 per cent down to nearly zero. It is entirely absent in only a few rocks. Potash shows a somewhat smaller range than soda, its maximum being 17.94 in an almost purely leucitic lava (italite) from Italy, the next highest figure being 11.91 from Wyoming; but in general it seldom gets above 10 per cent, ranging from that down to zero. Its amount is generally less than that of soda.

As regards water, the last of the major constituents, a few volcanic glasses, which are perfectly fresh and undecomposed, contain as much as 10 per cent, and some fresh crystalline rocks contain from 3 to 5 per cent. Generally, however, a rock that contains more than about 2 per cent of H_2O has acquired the excess by alteration, and a few rocks contain no water.

Effusive rocks contain a considerably larger amount of water than the chemically equivalent intrusive rocks.[6]

The "minor" constituents are generally found in very small amounts, rarely more than 2 per cent for any one or as much as 5 per cent for all of them, in any one rock. Of these minor constituents, three are of special importance, partly because of their almost constant presence and partly because they are generally present in largest amount. These three constituents are titanium dioxide, phosphorus pentoxide, and manganous oxide, and in a good rock analysis all three should be determined.

Titanium dioxide (TiO_2) reaches a maximum in some very rare rocks from Virginia (69.67 and 65.90) and Quebec (53.35), but its percentage is seldom over 5 and generally ranges from about 2 to nearly zero. Probably not one of the many rocks of all kinds that have been analyzed contained no titanium; in some rocks the quantity is very small, but in almost all it is easily determinable. This fact is shown by the work of Hillebrand [7] and by the work, as well, probably of every other experienced analyst of rocks.

The maximum for phosphorus pentoxide (P_2O_5) is a little above 16 per cent in some highly unusual rocks from Sweden and Virginia that are composed largely of apatite, with which is found titaniferous magnetite or rutile. In few rocks, however, is it above 3 per cent, and its general range is from about 0.5 per cent to zero. It does not seem to be present so constantly as titanium or manganese, as one occasionally meets a rock that shows no trace of it, although this may be because of the more delicate tests required for the other two.

Manganese, as manganous oxide (MnO), is present in practically every rock that has been analyzed, but its maximum is much lower than the maxima of titanium and phosphorus oxides. Some of the high figures reported for it are almost certainly due to analytical errors, and the highest recorded trustworthy figures are 1.90 and 1.46, shown by two rocks from Bahia, Brazil. Its general range is from 0.3 per cent to almost zero.

The other minor constituents that are readily determinable, many of which, indeed, are determined in good analyses, are carbon dioxide (CO_2), zirconia (ZrO_2), chromium sesquioxide (Cr_2O_3), vanadium sesquioxide (V_2O_3), the "rare earths" ($(Ce,Y)_2O_3$), nickel oxide (NiO), strontia (SrO), baria (BaO), lithia (Li_2O), sulphur as both sulphide (S) and sulphur trioxide (SO_3), chlorine (Cl), and fluorine (F). To these might be added boron, cobalt, copper, glucinum, lead, molybdenum, nitrogen, and zinc, the quantities of which, however, are generally so very small or the analytical difficulties for the separation of the trifling quantities of them that occur are so great that their determination is rarely attempted.

The maxima and ranges of some of these constituents may be briefly stated. Carbon dioxide may be a component of a few minerals (such as primary calcite and cancrinite) in some unaltered rocks, but its presence is generally due to alteration by weathering or to the assimilation of limestone by the magma, as in the nephelite syenite of the Haliburton area, Ontario,[8] and probably the alnöite of Alnö.[9] There are, however, some rocks in which the calcite is apparently of primary origin, as a trachyte of Mount Axpe, near Bilbao (unpublished) and a calcite alaskite of Alaska.[10] The Bilbao trachyte contains 7.69 per cent of CO_2, and in rocks with primary cancrinite carbon dioxide may reach 1.70 per cent, but in general

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[6] Washington, H. S., in Allen, E. T., Chemical aspects of volcanism: Franklin Inst. Jour., vol. 193, p. 41, 1922.

[7] Hillebrand, W. F., The analysis of silicate and carbonate rocks: U. S. Geol. Survey Bull. 700, p. 25, 1919.

[8] Adams, F. D., and Barlow, A. E., Geology of the Haliburton and Bancroft areas, Province of Ontario: Canada Geol. Survey Mem. 6, p. 233, 1910.

[9] Tornebohm, A. E., Melilithbasalt fran Alnö: Geol. Foren. Stockholm Forhandl., vol. 6, p. 240, 1882. Högbom, A. E., Ueber das Nephelinsyenitgebiet auf der Insel Alnö: Idem, vol. 17, p. 234, 1895.

[10] Wright, C. W., Geology and ore deposits of Copper Mountain and Kasaan Peninsula, Alaska: U. S. Geol. Survey Prof. Paper 87, p. 81, 1915.

carbon dioxide is to be regarded as a measure of the alteration of the rock by weathering or otherwise. Brögger[11] has recently described a series of intrusive rocks from Norway that contain large amounts (up to 80 per cent) of calcite, which he regards as primary.

Zirconia is much less abundant than the closely related titanic oxide, and, although it reaches a maximum of nearly 5 per cent in some rocks in Greenland, its amount is rarely more than 1 per cent and is usually much less, and it is quite absent from most rocks. It forms one of the most striking illustrations of the concomitant occurrence of elements in different kinds of rocks.

Baria and strontia are very commonly found, although they are seldom determined in analyses made outside of the United States, Canada, Great Britain, and Australia. The amount of baria is almost invariably much greater than that of strontia, this being an exception to a general rule as to the occurrence of related elements. They both reach their maxima in certain exceptional highly potassic rocks of Wyoming, which contain about 1 per cent of baria and 0.3 of strontia; though usually the percentage of baria amounts to only a few tenths of 1 per cent and that of strontia is measurable in hundredths of 1 per cent.

Sulphur is present as sulphide in amounts up to about 9 per cent in a peculiar pyrrhotite-bearing rock from Maine and probably in similar amounts in some sulphide ore bodies of magmatic origin in Norway, which have not been fully investigated, but its amount is seldom over 1 or 2 per cent, and it is usually found in tenths of 1 per cent. The highest figures for sulphur trioxide are about 2.5 per cent, in rocks from Apulia and Cameroon, and percentages somewhat lower in rocks from Tahiti, but sulphur trioxide is usually present only in tenths or hundredths of 1 per cent. Much the same can be said of chlorine, the highest figures for which are those for a rock from Turkestan (about 7), one from Quebec (4.47), and one from French Guinea (2.80). It is present in many rocks, especially lavas, but only in a few tenths or hundredths of 1 per cent.

Chromium sesquioxide is present up to about 4 per cent in some ores from Greece, which are possibly of magmatic origin, and it is reported as forming between 2 and 3 per cent of some undoubtedly igneous rocks from Baden. But these are highly exceptional, for about 0.5 may be taken as its usual maximum. It is generally quite absent. Vanadium sesquioxide is widely diffused in the igneous rocks but principally in the more femic kinds. The oxides of the rare earth metals, chiefly ceria and yttria, reach a maximum of 1.79 in a rare type of rock from Madras, 0.6 in one from Sweden, and 0.4 in one from the islet of Rockall, but the usual maximum is only one or two tenths of 1 per cent. They are less often determined than they should be. Nickel oxide is present in some rocks up to about 0.2 per cent. The maximum amount of each of the other minor constituents may be placed at not over 0.2 per cent, and they are almost always found only as one or two tenths or still more often as hundredths of 1 per cent, or they are absent. Indeed, for most of the minor constituents the quantities usually yielded by analysis are so small as to be significant only as to their actual presence or absence.

AVERAGE COMPOSITION OF IGNEOUS ROCKS.

AVERAGES COMPUTED.

More than 30 years ago the senior author of this paper[12] attempted to estimate the relative abundance of the chemical elements by averaging analyses of certain classes. This estimate included the lithosphere (as represented by igneous rocks), the ocean, and the atmosphere. For the igneous rocks 880 analyses were taken, of which 207 were made in the laboratories of the United States Geological Survey and 673 were made at other places. These were divided into groups, each group representing a definite geographic area, and it was shown that these groups of averages agreed fairly well with one another. That is, the composition of the earth's crust as thus determined is approximately the same in its different parts, provided large enough areas are taken to eliminate purely local variations. Since this first attempt was made other averages have been computed with more abundant data and by different methods. All these averages may be briefly summarized as follows:

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[11] Brögger, W. C., Die Eruptivgesteine des Kristianiagebietes; IV, Das Fengebiet in Telemark, Norwegen, Kristiania, 1921.

[12] Clarke, F. W., The relative abundance of the chemical elements: Philos. Soc. Washington Bull., vol. 11, p. 135, 1889.

1. The original average, made as described above.

2. An average of all the analyses of igneous rocks, partial or complete, made in the laboratories of the United States Geological Survey up to October 1, 1918.[13] Some other averages of the same order were made but need not be mentioned here.

3. An average, computed by Harker,[14] of 536 analyses of igneous rocks from British localities. Many of these analyses were incomplete, especially with regard to titanium, phosphorus, and manganese.

4. An average, computed by Washington,[15] of 1,811 analyses from all parts of the world.

To this method of averaging serious objections have been raised. All analyses are given equal weight, without regard to the areas occupied by the rocks analyzed, and therefore to their relative abundance. One rock, say a granite, is exceedingly abundant; another may be represented by one small dike. The inequality is obvious, but what does it really signify? In the first place, the relatively insignificant rocks vary in composition from persilicic to subsilicic just as the most abundant rocks do. In the average these variations tend to offset one another and so to give an approximately true mean. Furthermore, the surface exposure of a rock is no certain measure of its real volume and mass, for a small exposure may be merely the peak or crest of a large subterranean body and a large exposure may represent only a thin layer.

Another objection is that the igneous rocks of large parts of the earth are quite or almost unknown, at least in an exact chemical way. This is true of the interiors of several of the continents, notably Asia, Africa, South America, and Australia. The rocks of many countries, also, are inadequately represented by chemical analyses. Examples are China, India, Asia Minor, Arabia, Egypt, Spain, Brazil, Argentina, Chile, Central America, Mexico, and northern Canada. In making the average analysis of the rocks of all such countries it is tacitly assumed that the whole of the area (continent or country) is represented by the few analyses available. This assumption may or may not be true; for some countries it would appear to be decidedly erroneous.

Still another objection is that the data considered include an undue proportion of analyses of the more "interesting" types of rock and that, on the other hand, the more ordinary (and hence less "interesting") kinds are not sufficiently represented. Although this objection is valid, yet it would seem not to be so serious as has been asserted, for the analyses of rocks of the satellitic dikes and other small bodies that are most likely to furnish "interesting" types tend to complement one another and so to give approximately the true mean. Again, it is by no means uncommon that analyses of the more abundant kinds of rocks in a given district have been made and none of the small dikes. Furthermore, the more subsilicic rocks, many of which are of the more "interesting" types, are most subject to alteration, so that the analyses of many of them would be excluded from the data here used, which include only analyses of fresh, unaltered rocks.

Averages based on a quite different method of computation have also been made. Daly [16] has made separate averages of many rock types, and he shows that the mean composition of an average granite combined with that of an average basalt is almost identical with the average given by Washington. Mead,[17] applying a peculiar graphic method to some of Daly's data, concludes that a mixture of 65 per cent of the average granite with 35 per cent of the average basalt will have a composition very close to the general average of all igneous rocks as computed by Clarke. A similar result is reached by Loewinson-Lessing,[18] who regards the crust of the earth as derived from two fundamental magmas, one granitic and one gabbroic. These are supposed to have existed in about equal proportions, and their mean composition is nearly that here found for all igneous rocks.

Such averages as these, however, are arbitrary, and the correspondences would seem to be in reality fortuitous. The same result as,

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[13] Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 26, 1920.

[14] Harker, Alfred, Tertiary igneous rocks of the Isle of Skye: United Kingdom Geol. Survey Mem., p. 416, 1904.

[15] Washington, H. S., Chemical analyses of igneous rocks, published from 1884 to 1900, with a critical discussion of the character and use of analyses: U. S. Geol. Survey Prof. Paper 14, p. 106, 1903.

[16] Daly, R. A., Average chemical composition of igneous-rock types: Am. Acad. Arts and Sci. Proc., vol. 45, p. 211, 1910; and Igneous rocks and their origin, pp. 19-46, 168-170, New York, 1914.

[17] Mead, W. J., The average igneous rock: Jour. Geology, vol. 22, p. 772, 1914.

[18] Loewinson-Lessing, F., The fundamental problems of petrogenesis: Geol. Mag., new ser., decade 5, vol. 8, p. 248, 1911.

let us say, that of Daly may be arrived at by an infinite variety of combinations of various kinds of magma. Thus, if one starts with a mixture of 10 parts of average granite and 1 part of average basalt, the high silicity and other peculiar chemical features of the granite (as contrasted with those of the basalt) may be counterbalanced by the introduction of appropriate portions of, say, peridotite, pyroxenite, and anorthosite; or these, with possibly a little nephelite syenite, might replace the basalt entirely and give the same result; and so on, ad infinitum. Indeed, the averages that have been obtained by the method here adopted illustrate the results of such a procedure. By judicious qualitative and quantitative selection of data one may arrive at any "average rock" desired. Such averages, based on arbitrarily adjusted selection of data, mean little, and they would seem to be an illogical and unsafe basis for generalizations as to the average composition of rocks. It is still more illogical to argue from the coincidence that a given mixture has the same composition as that of the general magma, and that the earth magma is made up of such a mixture of submagmas.

In order to meet the objection mentioned above Knopf[19] took Daly's averages for the various rock types and weighted each type by its area, as determined by Daly for the igneous areas in the Appalachian and Cordilleran regions, as shown in the folios of the United States Geological Survey, and then combined the results so determined to form a general mean. Theoretically, Knopf's method is highly plausible, and it would be the best if it could be generally utilized, but for the purpose of calculating the average of a shell of any given depth it is open to two serious objections; it assigns as much weight to comparatively thin lava flows as to exposures of batholithic masses, and also it takes no cognizance of the igneous rocks that underlie the sedimentary beds. But in spite of these objections this method is a distinct improvement on the original method of obtaining an earth or regional average.

Now, if we include the estimates made by Daly, Loewinson-Lessing, and Knopf, there are seven averages to be compared. Mead's figures are omitted, for the reason that he neglected titanium and phosphorus, which appear in all the others. Manganese, which is given in the original computations, is rejected here but will be considered later, along with the other minor constituents of the igneous rocks. Water is also left out of account for the present, because in too many analyses there was no discrimination between extraneous and essential water. In Table 1 the averages are all recalculated to 100 per cent.

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[19] Knopf, Adolph, The composition of the average igneous rock: Jour. Geology, vol. 24, p. 620, 1916.

TABLE 1.—*Previously published estimates of the average composition of igneous rocks.*

	1	2	3	4	5	6	7
SiO_2	59.97	61.69	60.76	58.96	60.18	59.73	62.52
Al_2O_3	15.39	15.47	15.87	15.99	15.55	16.53	15.93
Fe_2O_3	4.03	2.71	4.92	3.37	3.56	2.42	2.95
FeO	3.56	3.54	2.78	3.93	4.07	3.86	3.30
MgO	4.60	3.87	3.82	3.89	3.57	4.40	3.01
CaO	5.41	4.98	4.97	5.28	5.63	6.67	5.14
Na_2O	3.28	3.48	3.28	3.96	3.29	2.95	3.45
K_2O	2.97	3.14	2.85	3.20	2.89	2.50	2.69
TiO_2	.56	.82	.53	1.05	.90	.68	.74
P_2O_5	.23	.30	.22	.37	.36	.26	.27
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1. Clarke, 1889.
2. Clarke, United States rocks, 1918.
3. Harker, British rocks, 1904.
4. Washington, 1903.
5. Daly, granite-basalt average, 1914.
6. Loewinson-Lessing, granite-gabbro average, 1911.
7. Knopf, Appalachian and Cordilleran rocks, 1916.

Columns 2 and 4 include the largest number of trustworthy analyses. They are, however, not strictly comparable. Column 4 includes analyses of rocks from all over the earth and includes only analyses that were nominally complete and that were made in many laboratories by somewhat diverse methods. Column 2 includes analyses of rocks from the United States alone, and the analyses are the homogeneous work of one laboratory; moreover, it includes many partial analyses. In analyses of the simpler salic rocks determinations of silica, lime, and alkalies are sometimes all that are needed for petrographic purposes. The femic rocks are chemically and mineralogically more complex and require more complete analyses. The partial analyses, therefore, represent chiefly salic rocks, and their inclusion in the average tends to raise the proportion of silica and to lower the proportion of the other oxides. The salic rocks, however, are the most abundant, and so the higher figure for silica given in column 2 seems to be the more probable.

Though 2 and 4 are alike in their general features, yet there are some differences notable, especially in the silica. In this respect 4 resembles 1, which also includes many rocks from outside the United States. Such differences are due to regional peculiarities. Harker's British average, as computed here free from water and manganese, differs considerably from his complete computation, which is given on page 54. The two averages of Daly and Loewinson-Lessing have already been discussed very briefly; they would seem to be more of interest as coincidences than as of scientific value. The very high value for silica and some other minor features shown by Knopf's average (column 7) arise from his selection of analyses from only two mountainous areas in the United States, the averages of whose rocks show these special features in a marked degree.

In spite of all divergences, however, the seven averages are in fair agreement in their essential features. An absolute agreement is, of course, not to be expected. The different estimates give similar percentages to the important constituents of the rocks and so encourage us to believe that the method of averaging here adopted is truly representative of the rocks of the earth's crust. With larger masses of data, however, and with wider geographic range, better results ought to be obtainable, and as the data are now at hand their discussion by geographic groups will be attempted.

In a work compiled by the junior author[20] more than 8,600 analyses of igneous rocks are brought together and classified, and of these more than 5,000 are available for present use. In the work just cited the analyses are rated as superior, incomplete, and inferior.[21] The inferior analyses we may disregard; their inferiority is due to lack of completeness, lack of accuracy, or to both together. None of them have been included in the data here considered. The superior analyses are those which are satisfactory (according to certain standards adopted) as to both completeness and accuracy and which are therefore deemed to be usable if the rock analyzed is unaltered. None of the superior analyses of altered rocks or of tuffs have been used. There is a small group of analyses which are incomplete as to the determination of some one constituent but which are otherwise superior. These can be used, for they are incomplete only as regards certain details that do not affect the percentages of the other constituents. The analyses considered number 5,159, only 302 of which are slightly incomplete. The effort has been made to base averages on good data, the number of the data used being considered secondary to their quality.

In making the averages, determinations of hygroscopic or unessential water (H_2O-) have been rejected. If a constituent is definitely reported as absent, it is given zero value in the summations. A "trace" of any constituent has been counted as 0.01 per cent. The term "trace," it should be noted, is much misused. It frequently means only that the analyst has reason to think that the constituent is present but has neglected to determine its amount. As applied to all constituents except lithium, the presence of which is usually ascertained spectroscopically, the amounts covered by "trace" are more than 0.01 per cent, which is the usual limit of weighing. In the great majority of analyses "trace" means one or more tenths of 1 per cent and not uncommonly, especially as to titanium, one-half to possibly

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[20] Washington, H. S., Chemical analyses of igneous rocks published from 1884 to 1913, inclusive: U. S. Geol. Survey Prof. Paper 99, 1917.

[21] For a discussion of the "rating" of analyses, the standards of quality adopted, and the division of the collection of analyses into "superior" and "inferior" parts, see pp. 18-28 of Professional Paper 99.

5 per cent. The procedure adopted therefore gives figures that are too low; that of counting 0.1 per cent for "trace" would have been better and would have allowed for the many nondeterminations.

METHODS OF AVERAGING.

Before the averages computed are given it is necessary to consider a very important point—that is, the method of averaging adopted. In practically all the analyses that served as the fundamental data, all the major constituents were determined. These include silica, alumina, ferric oxide, ferrous oxide, magnesia, lime, soda, potash, and water. Indeed, the determination of all these was essential to admission of an analysis to the grade of "superior," the grade to which attention was confined. In only a very few of the analyses used were there exceptions to this rule. They included a few "incomplete, but otherwise superior" analyses, in which the iron oxides had not been separately determined, and also a few analyses of ultrafemic rocks (such as dunite) in which the alkalies were not determined. The method adopted for obtaining the averages for these major constituents—that of dividing the sum of the amounts of any given constituent by the number of its determinations—therefore yields results that are practically free from error, at least so far as the data at hand are concerned.

In considering the "minor" constituents, however, from titanium dioxide down to the end of the list, the conditions are quite different. In many analyses some or all of these constituents were not determined, yet their omission does not exclude the incomplete analyses so rigorously from the "superior" class as would the omission of the "major" constituents; but determinations of titanium, phosphorus, and manganese oxides are requisite for the best ratings and should always be made in analyses of rocks in which they are abundant. Furthermore, the number of determinations of the minor constituents differ widely, as will be seen in Table 2, which presents the data concerning the most important minor constituents shown by the analyses here used. Titanium, phosphorus, and manganese were determined in most of the analyses, sulphur and carbon dioxide in many, but the other minor constituents were neglected in the great majority of the analyses made in all countries, especially those made in continental Europe. Baria, for example, was determined in few analyses except those made in the United States, Great Britain, and Australia.

TABLE 2.—*Average percentages of the minor constituents shown by 5,159 analyses.*

	1	2	3	4	5	6
TiO_2	3,926	76.0	4,724.03	1.20	0.91	1.05
P_2O_5	3,375	65.4	1,225.35	.36	.24	.30
MnO	3,016	60.0	481.77	.16	.09	.125
S[a]	1,621	31.4	130.38	.08	.025	.052
CO_2	1,319	25.6	258.94	.199	.05	.102
BaO	1,160	20.0	104.29	.09	.02	.055
Cl	857	16.6	82.55	.096	.002	.048
SrO	802	15.6	30.23	.038	.006	.022
ZrO_2	631	12.2	44.41	.07	.009	.039
Cr_2O_3	477	9.2	48.73	.102	.009	.055
Li_2O	449	8.7	6.13	.014	.001	.007
NiO	421	8.0	19.57	.046	.004	.025
F	223	4.3	33.99	.15	.006	.078
V_2O_3	200	3.9	12.37	.061	.002	.026
Cu	169	3.3	2.98	.018	.001	.010

[a] Includes SO_3.

1. Number of actual determinations.
2. Percentage of determinations in whole number of analyses considered.
3. Sum of the percentages.
4. Sum divided by the number of determinations. (Second method.)
5. Sum divided by the whole number of analyses considered; that is, 5,159. (First method.)
6. Mean of averages 4 and 5. (Third method.)

There are three methods of averaging these minor constituents. In the oldest method, which was that originally used by the senior author,[22] the sum of the percentages of any given constituent is divided by the whole number of analyses, it being assumed that a constituent is not present if it is not reported or, in other words, that each analysis is complete. This assumption, however, is not justified, and the method will give too low results for the minor constituents and too high results for the major ones.

In the second method, which was used later by both the senior and the junior author separately,[23] the sum of the percentages of each constituent is divided by the number of analyses in which it was determined. This method deals only with the data actually at hand, the data for the minor constituents being treated just as those for the major constituents are treated. The data used are the only pertinent data known and are therefore the only data that can properly be used for this purpose. The only assumption made in this method is that the average amount of any constituent represents the average amount of this constituent in all the analyses in which it was not determined. This assumption, however, is also made in any method of determining an average and is fundamental to the idea of making averages. It may or may not be true, and though it is quite valid as to some of the constituents it is less valid as to others, and it furnishes an average based solely on known data.

In the third method the average amount of any constituent is the mean between those determined by the two other methods. This method is based on the justifiable assumption (or rather the knowledge) that the first method yields results that are too low and the possibly justifiable assumption that the second method yields or may yield results that are too high, so that a mean between them will probably be nearer the truth than either of them. Although this conclusion may be true with respect to some constituents, yet it is unquestionably erroneous with respect to others. The method is fundamentally faulty in bringing in elements that are unknown and arbitrary.

It would appear, then, that the second method, that of dividing the sum of the percentages by the number of determinations, in which we use only data actually known and avoid the introduction of the unknown and the arbitrary, is the most logical and the safest and the one which should give the most reliable averages. It may be said that, even in dealing with those constituents for which the third method may yield possibly better approximations to the truth, the better and safer course is to use the second method, with the admission that some constituent may be a little high, rather than to introduce the admitted uncertainty of the third method. We may leave the correction of the departure from the truth to the future accumulation of more data.

The matter is somewhat more complex, however, than it may appear to be at first sight. When we consider the data for the several minor constituents in the light of our knowledge of the chemical analyses of rocks and the quantitative and selective distribution of the various elements among rocks of different general chemical character, we find that, besides the number of determinations, another factor should be taken into account in ascertaining correctly the averages of the minor constituents. This factor is the unequal or selective distribution of these elements among magmas of different general chemical character. Considered from this point of view the minor constituents may be referred to several different categories.

Some of them are present to a greater or less amount and one easily determinable by analysis in all or almost all igneous rocks, whether high or low in silica, whether notably high in alkalies, lime, magnesia, iron, and so on. This is preeminently true of titanium, phosphorus, and manganese, the minor constituents which are almost always present in greatest amount, and in a modified degree of some others. Other minor constituents are

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[22] Clarke, F. W., Relative abundance of the chemical elements: Philos. Soc. Washington Bull., vol. 11, p. 131, 1889; Report of work done in the division of chemistry and physics, mainly during the fiscal year 1889–90: U. S. Geol. Survey Bull. 78, p. 34, 1891; Analyses of rocks, with a chapter on analytical methods: Bull. 148, p. 13, 1897; Analyses of rocks: Bull. 168, p. 15, 1900. Also Harker, Alfred, On the average composition of British igneous rocks: Geol. Mag., new ser., decade 4, vol. 6, p. 220, 1899, and Tertiary igneous rocks of Skye, p. 416, 1904.

[23] Washington, H. S., Chemical analyses of igneous rocks: U. S. Geol. Survey Prof. Paper 14, p. 106, 1903. Clarke, F. W., Analyses of rocks: U. S. Geol. Survey Bull. 228, p. 16, 1904; Analyses of rocks and minerals: Bull. 419, p. 6, 1910; Analyses of rocks and minerals: Bull. 591, p. 18, 1915.

selective in their occurrence, one being most abundant in highly silicic rocks and another in rocks low in silica, one prevalent in sodic and another in magnesic rocks, and so on.

As examples to illustrate these differences in occurrence we may note that molybdenum is found in highly silicic rocks and that vanadium is found in the less silicic; that zirconium is most abundant in sodic rocks but is analytically absent from highly calcic or magnesic ones; and that nickel especially affects the rocks rich in iron and magnesia but is not found in the alkalic ones.

It appears, then, that the second method of averaging—that of dividing the sum of the percentages by the number of determinations—is the most rational one to employ to show the amounts of the minor constituents that are contained in all rocks. The data for these constituents are fairly numerous and cover rocks of all kinds of chemical character. This statement applies preeminently to titanium, phosphorus, and manganese and almost equally to barium, strontium, sulphur, and fluorine, and probably to chlorine as well. It would seem to be justifiable also to use this method for carbon dioxide, because, although its reported presence is due mostly to alteration (so that for it the first method might seem the most appropriate), yet the maximum figure given by the second method would cover inclusions of liquid carbon dioxide that would otherwise be omitted but that should be considered.

In dealing with the less common minor constituents, of which zirconium may be taken as an example, it appears that the third method of averaging (that of taking the mean of the figures given by the first and second methods) is the proper one to adopt, because the second method gives figures that are almost certainly high, for this constituent is nowadays determined mostly in analyses of sodic rocks (nephelite syenite, phonolite, etc.), in which its presence is to be expected, whereas the first method gives figures that are unquestionably low, so that some intermediate figure must more nearly represent the truth. But the nondetermination of such a constituent in the incomplete analysis of many rocks in which the constituent is almost certainly present in determinable amount, and the assumption here made that a recorded "trace" is equivalent to a percentage of 0.01, weaken the force of this argument.

The determination of a truly representative average is thus complex and difficult and involves the recognition of several factors whose application may not at first sight be obvious. The computations of the averages for the continents and for certain smaller areas were made by the first method, that of dividing the sum total of each major constituent and of the oxides of titanium, phosphorus, and manganese by the total number of analyses, the other minor constituents being lumped together and their total determined similarly. The error in the results thus obtained is slight, and furthermore the data at hand for most of the minor constituents are too few to be quite satisfactory. The average for the earth, however, has been determined by a modification of this procedure, as will be explained later.

AREAL AVERAGES.[24]

The averages computed for the continents and for smaller areas include those for only the major constituents and for TiO_2, P_2O_5, and MnO, except for areas in the United States that are represented by a large number of very detailed and complete analyses that give the percentages of other minor constituents, especially ZrO_2 and BaO.

In order to make the averages comparable all of them have been reduced to the standard of 100 per cent. The minor constituents are lumped together under the caption "Inclusive," except TiO_2, P_2O_5, MnO, and (if they are stated) ZrO_2 and BaO.

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[24] The areal averages in Tables 3 to 9 (inclusive) have been published by F. W. Clarke and H. S. Washington (The average chemical composition of igneous rocks: Nat. Acad. Sci. Proc., vol. 8, pp. 109-111, 1922).

TABLE 3.—*Average composition of the igneous rocks of northern North America.*

	1	2	3	4	5	6
SiO_2	60.19	57.14	63.31	56.29	52.80	58.34
Al_2O_3	15.76	15.48	16.13	16.67	16.38	15.79
Fe_2O_3	2.87	3.93	2.18	3.31	4.58	2.21
FeO	3.67	4.72	2.46	4.65	5.83	3.99
MgO	3.16	1.55	2.25	3.39	3.27	4.57
CaO	4.80	3.51	5.05	5.34	5.29	5.66
Na_2O	3.90	6.98	3.85	4.40	4.88	3.54
K_2O	3.07	3.25	2.82	3.00	2.65	3.18
H_2O+	1.01	1.12	.78	1.08	1.09	1.14
TiO_2	1.01	1.50	.77	1.25	2.20	.69
ZrO_2	.01	.12	....	....	....	....
P_2O_5	.26	.19	.18	.19	.21	.33
MnO	.10	.21	.10	.13	.17	.14
BaO	.04	....	....	.04	.06	.11
Inclusive	.15	.30	.12	.26	.59	.31
	100.00	100.00	100.00	100.00	100.00	100.00

1. North America, including Greenland, Mexico, Central America, and West Indies; 1,709 analyses.
2. Greenland, including East and West Greenland and Ellesmere Land; 41 analyses.
3. Alaska; 24 analyses.
4. Canada, including Alaska, East Canada, and British Columbia; 188 analyses.
5. East Canada, including Ontario, Quebec, Maritime Provinces, and Newfoundland; 99 analyses.
6. British Columbia, including Alberta; 60 analyses.

TABLE 4.—*Average composition of the igneous rocks of the United States.*

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	61.41	62.98	57.81	58.54	60.37	60.03	60.09	65.80	61.39	59.97	62.49	60.77
Al_2O_3	15.20	14.74	15.43	16.36	15.26	16.16	15.94	15.52	16.24	15.90	15.71	15.44
Fe_2O_3	2.47	1.86	4.60	3.74	2.53	2.91	3.41	2.17	2.84	2.11	1.97	2.77
FeO	4.21	3.69	5.98	2.36	3.07	2.44	2.86	1.60	2.85	4.13	3.01	3.46
MgO	3.01	3.70	3.52	2.54	3.77	3.26	2.34	1.52	2.74	4.38	3.67	3.15
CaO	4.46	4.69	4.64	4.11	4.80	4.49	4.85	3.44	4.81	6.11	5.67	4.82
Na_2O	3.94	3.30	3.60	5.35	3.82	4.08	3.86	3.49	4.18	3.71	3.57	3.78
K_2O	3.30	2.97	2.31	4.68	3.99	3.81	3.90	4.10	3.04	1.55	2.03	3.23
H_2O+	.74	.82	.98	1.04	1.03	1.49	1.12	1.40	.69	1.11	1.05	1.01
TiO_2	.91	.89	.73	.76	.58	.64	.88	.55	.72	.66	.45	1.01
ZrO_2	.01	.01	....	.03	....	....	.01	.01	....	....	....	....
P_2O_5	.11	.20	.08	.19	.32	.30	.34	.13	.31	.17	.15	.29
MnO	.09	.08	.16	.10	.10	.06	.12	.04	.11	.06	.09	.10
BaO	.01	.01	.01	.02	.15	.08	.07	.05	.04	.05	.05	.05
Inclusive	.13	.06	.15	.18	.21	.25	.21	.18	.04	.09	.09	.12
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1. New England and New York; 213 analyses.
2. Appalachia (New Jersey and Pennsylvania to Georgia); 188 analyses.
3. Algonkian region (Michigan, Wisconsin, and Minnesota); 66 analyses.
4. Arkansas-Texas, including Missouri; 50 analyses.
5. Wyoming, including South Dakota and Yellowstone Park; 134 analyses.
6. Montana, including Idaho; 133 analyses.
7. Colorado; 171 analyses.
8. Utah and Nevada; 79 analyses.
9. Arizona and New Mexico; 79 analyses.
10. Washington and Oregon; 51 analyses.
11. California; 175 analyses.
12. United States; 1,351 analyses, including figures for 12 highly femic and titaniferous rocks omitted from the other columns.

TABLE 5.—*Average composition of the igneous rocks of Central and South America.*

	1	2	3	4	5	6
SiO_2	59.11	58.70	61.34	61.05	61.85	54.94
Al_2O_3	16.58	18.30	15.20	15.17	16.51	16.29
Fe_2O_3	2.88	2.85	3.03	2.42	3.03	4.05
FeO	4.11	4.20	3.30	4.07	2.28	3.53
MgO	3.07	3.36	3.47	4.65	2.29	4.33
CaO	5.73	7.08	4.88	5.91	4.55	5.28
Na_2O	4.10	3.15	4.09	3.29	4.47	5.11
K_2O	2.32	.99	2.69	1.74	2.69	3.57
H_2O+	1.04	.79	1.05	.73	1.11	1.55
TiO_2	.63	.45	.56	.49	.75	.87
P_2O_5	.25	.08	.11	.07	.25	.11
MnO	.06	.02	.12	.18	.22	.37
Inclusive	.12	.03	.16	.23	....	....
	100.00	100.00	100.00	100.00	100.00	100.00

1. Mexico and Central America; 47 analyses.
2. West Indies; 82 analyses.
3. South America; 138 analyses.
4. British Guiana; 45 analyses.
5. Andes Mountains; 56 analyses.
6. Eastern Brazil; 20 analyses.

TABLE 6.—*Average composition of the igneous rocks of Europe.*

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	59.84	59.10	62.39	56.89	59.83	64.04	60.58	58.84	56.93	60.69	58.98	54.22	64.73
Al_2O_3	15.12	13.80	15.16	15.54	16.08	14.24	16.43	14.44	15.86	14.67	16.28	16.30	15.92
Fe_2O_3	3.17	3.14	2.40	2.69	3.65	3.65	2.75	3.35	3.72	2.76	2.53	4.28	3.15
FeO	3.67	4.57	3.04	3.57	3.21	3.41	2.88	3.91	3.78	3.28	3.44	5.54	2.28
MgO	3.61	4.80	3.79	4.57	2.26	1.82	2.16	4.63	4.15	4.56	3.03	5.02	1.76
CaO	4.97	5.41	3.92	4.43	3.64	3.25	3.35	5.56	6.45	4.37	5.16	7.60	4.49
Na_2O	3.73	3.55	3.70	4.56	5.10	3.70	6.11	3.45	3.61	3.52	3.72	2.99	3.69
K_2O	3.40	2.68	3.23	4.47	3.52	3.82	3.96	3.04	2.96	3.56	4.67	1.92	2.56
H_2O+	1.24	1.44	1.46	1.19	.75	.84	.71	1.40	1.45	1.68	.94	1.17	1.03
TiO_2	.83	.97	.75	1.34	1.64	.73	.56	.87	.58	.65	.85	.66	.31
P_2O_5	.23	.22	.12	.34	.12	.25	.27	.29	.27	.19	.22	.07	.03
MnO	.08	.14	.01	.07	.10	.15	.19	.04	.14	.03	.04	.14	.03
Inclusive	.11	.18	.03	.34	.10	.10	.05	.18	.10	.04	.14	.09	.02
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1. Europe; 1,985 analyses.
2. British Islands; 171 analyses.
3. France, including Corsica; 163 analyses.
4. Iberia (Spain and Portugal); 33 analyses.
5. Norway, 107 analyses; including Iceland.
6. Sweden, including Spitzbergen; 206 analyses.
7. Finland, including Kola; 59 analyses.
8. Germany; 474 analyses.
9. Austria-Hungary-Bohemia, excluding Tyrol; 148 analyses.
10. Switzerland, including Tyrol; 217 analyses.
11. Italy, including Sicily, Sardinia, and islands; 276 analyses.
12. Russia, including Ural region and Caucasus, excluding Finland and Siberia; 98 analyses.
13. Balkania, including Greece and Archipelago; 33 analyses.

TABLE 7.—*Average composition of the igneous rocks of Africa and Asia.*

	1	2	3	4	5	6	7	8
SiO_2	58.21	54.67	50.59	56.02	61.92	61.82	59.72	61.02
Al_2O_3	15.28	16.21	15.81	15.68	15.49	15.74	16.51	15.97
Fe_2O_3	3.52	3.02	4.44	3.48	3.17	2.07	3.18	2.92
FeO	3.73	4.93	5.79	4.41	2.75	4.41	2.95	3.21
MgO	3.51	4.21	5.79	4.04	2.63	2.47	3.03	2.76
CaO	5.09	6.51	7.36	5.87	4.50	5.16	5.76	5.17
Na_2O	4.83	4.36	4.27	4.60	4.10	3.11	3.78	3.69
K_2O	3.28	3.05	2.31	3.07	3.23	2.51	3.05	2.99
H_2O+	1.26	1.13	1.47	1.25	1.23	1.48	1.11	1.24
TiO_2	.84	1.44	1.63	1.14	.68	.76	.50	.62
P_2O_5	.20	.35	.43	.27	.12	.27	.18	.18
MnO	.07	.01	.04	.05	.10	.17	.14	.15
Inclusive	.18	.11	.07	.12	.08	.03	.09	.08
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1. Africa, continental; 223 analyses.
2. Madagascar, including Reunion; 140 analyses.
3. South Atlantic Islands (Azores, Canaries, Madeira, Cape Verde, Ascension, St. Helena); 56 analyses.
4. Africa and islands, including Madagascar and Atlantic Islands; 419 analyses.
5. Asia, continental; 114 analyses.
6. Japan; 69 analyses.
7. Malaysia, including Philippines; 129 analyses.
8. Asia, including continent, Malaysia, and Japan; 312 analyses.

TABLE 8.—*Average composition of the igneous rocks of Australasia, Polynesia, and the Antarctic Continent and islands.*

	1	2	3	4		1	2	3	4
SiO_2	60.16	58.04	50.03	53.66	H_2O+	1.19	1.70	1.16	0.93
Al_2O_3	14.74	15.30	15.51	16.82	TiO_2	1.01	.71	1.96	.87
Fe_2O_3	2.60	3.83	3.88	4.01	P_2O_5	.26	.19	.25	.17
FeO	4.41	3.99	6.23	5.34	MnO	.15	.09	.15	.03
MgO	3.76	3.95	6.62	4.67	BaO	.02	....	....	....
CaO	5.03	5.39	7.99	7.59	Inclusive	.14	.10	.12	.01
Na_2O	3.50	3.78	4.00	3.58					
K_2O	3.03	2.93	2.10	2.32		100.00	100.00	100.00	100.00

1. Australia, including Tasmania; 287 analyses.
2. New Zealand, including dependent islands; 134 analyses.
3. Polynesia (Hawaiian Islands, etc.); 72 analyses.
4. The Antarctic Continent and adjacent islands; 103 analyses.

TABLE 9.—*Average composition of the igneous rocks of the continents and oceanic islands and of the earth.*

	1	2	3	4	5	6	7	8	9	10
SiO_2	60.19	61.34	59.84	58.21	50.59	61.92	60.16	50.03	53.66	59.12
Al_2O_3	15.76	15.20	15.12	15.28	15.81	15.49	14.74	15.51	16.82	15.34
Fe_2O_3	2.87	3.03	3.17	3.52	4.44	3.17	2.60	3.88	4.01	3.08
FeO	3.67	3.30	3.67	3.73	5.79	2.75	4.41	6.23	5.34	3.80
MgO	3.16	3.47	3.61	3.51	5.79	2.63	3.76	6.62	4.67	3.49
CaO	4.80	4.88	4.97	5.09	7.36	4.50	5.03	7.99	7.59	5.08
Na_2O	3.90	4.09	3.73	4.83	4.27	4.10	3.50	4.00	3.58	3.84
K_2O	3.07	2.69	3.40	3.28	2.31	3.23	3.03	2.10	2.32	3.13
H_2O+	1.01	1.05	1.24	1.26	1.47	1.23	1.19	1.16	.93	1.15
TiO_2	1.01	.56	.83	.84	1.63	.68	1.01	1.96	.87	1.05
P_2O_5	.26	.11	.23	.20	.43	.12	.26	.25	.17	.30
MnO	.10	.12	.08	.07	.04	.10	.15	.15	.03	.12
Inclusive	.20	.16	.11	.18	.07	.08	.16	.12	.01	.50
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1. North America, including Greenland, Mexico, Central America, and West Indies; 1,709 analyses.
2. South America; 138 analyses.
3. Europe; 1,985 analyses.
4. Africa, continental; 223 analyses.
5. South Atlantic Islands; 56 analyses.
6. Asia, continental; 114 analyses.
7. Australia including Tasmania; 287 analyses.
8. Polynesia; 72 analyses.
9. Antarctic Continent; 103 analyses.
10. The earth; 5,159 analyses. For a final and more detailed earth average see page 16.

THE GENERAL AVERAGE.[25]

The final average given below for the chemical composition of the igneous rocks of the earth's crust, expressed (with a few exceptions) in terms of oxides arranged in the order in which they are usually given in an analysis of an igneous rock, has been determined by assembling all the data presented in the preceding pages. The averages for the major constituents, those from SiO_2 to H_2O+, inclusive, were determined by the first method described above—that of dividing the sum total of percentages for each constituent by the total number of analyses. The averages for the minor constituents (with a few exceptions) were determined by the third method—that of taking the mean of the sum total of percentages divided by the total number of analyses and the sum total of percentages divided by the number of determinations. The averages for the minor constituents are therefore those given in column 6 of Table 2 (p. 10), but slight changes have been made in the figure for F (see p. 21), and figures based on data yet to be considered (see p. 22) are given for the rare earths ($(Ce, Y)_2O_3$) and for zinc and lead.

This average of the composition of the igneous rocks includes all the constituents that may be found in weighable amounts (0.01 per cent or more) in truly igneous rocks, as well as some rather rare constituents. It is the average on which further discussions in this paper are based.

TABLE 10.—*Average chemical composition of igneous rocks.*

SiO_2	59.12	S	0.052
Al_2O_3	15.34	$(Ce,Y)_2O_3$	.020
Fe_2O_3	3.08	Cr_2O_3	.055
FeO	3.80	V_2O_3	.026
MgO	3.49	MnO	.124
CaO	5.08	NiO	.025
Na_2O	3.84	BaO	.055
K_2O	3.13	SrO	.022
H_2O+	1.15	Li_2O	.007
CO_2	.102	Cu	.010
TiO_2	1.050	Zn	.004
ZrO_2	.039	Pb	.002
P_2O_5	.299		
Cl	.048		100.000
F	.030		

RELATIVE ABUNDANCE OF THE ELEMENTS IN THE EARTH'S CRUST.

The figures just given to show the average chemical composition of the igneous rocks become more significant when they are restated to show the composition of the earth's crust in terms of the elements and when they are combined with figures showing the composition of the sedimentary rocks, the hydrosphere, and the atmosphere. By such a combination we shall obtain an estimate of the average composition of the known outer part of the earth—all of it that is directly accessible to our observation; but in order to make such a combination we must assign definite masses or volumes to the several components.

MASSES OF THE LITHOSPHERE, THE HYDROSPHERE, AND THE ATMOSPHERE.

Mass of the lithosphere.—The volume of the lithosphere, the rocky crust of the earth, calculated for an assumed thickness of 10 miles (16 kilometers) and a computed mean elevation of the continents, is given by Dr. R. S. Woodward [26] as 1,633,000,000 cubic miles, or about 6,811,000,000 cubic kilometers.

Various estimates have been made of the average density of the rocks of the earth's crust. The senior author [27] has obtained the density 2.737 as the average of 958 determinations of the specific gravity of igneous rocks, and the junior author [28] has obtained a density of 2.761 as the average of 1,849 similar determinations. A calculation [29] made from the average chemical composition of the igneous rocks showed a density of 2.77, and a more recent calculation [30] by the same method, made from the 5,159 analyses used for the computation of average chemical composition here considered, showed a density of 2.792, which, expressed as 2.79, may be accepted here for reasons given in the paper last cited. In brief, these reasons are as follows: The method of determining the density of rocks by calculating it from their chemical

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[25] The average in Table 10 has been published by F. W. Clarke and H. S. Washington (The average chemical composition of igneous rocks: Nat. Acad. Sci. Proc., vol. 8, p. 112, 1922).

[26] Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 22, 1920.

[27] Clarke, F. W., Some geochemical statistics: Am. Philos. Soc. Proc., vol. 51, p. 226, 1912.

[28] Washington, H. S., Isostasy and rock density: Geol. Soc. America Bull., vol. 33, p. 402, 1922.

[29] Washington, H. S., The chemistry of the earth's crust: Franklin Inst. Jour., vol. 190, p. 802, 1920.

[30] Washington, H. S., Isostasy and rock density: Geol. Soc. America Bull., vol. 33, p. 388, 1922.

composition is reliable and gives results concordant with the ascertained densities of compact, holocrystalline plutonic rocks. It eliminates the effects of the presence of glass in effusive rocks and of alteration and porosity, which tend to lower the density. For these last reasons, especially, it gives results that are presumably more concordant than the other method with the rocks as they exist at considerable depths. It is based on a much larger number of data, which pertain to rocks that are scattered more widely over the surface of the earth. The higher density is more in accord with the probability that the density of the crust increases with depth through pressure and, to a much greater degree, through change in composition, whether brought about by "gravitative adjustment" or not.

By combining the volume of the 10-mile crust, 6,811,000,000 cubic kilometers, with the density, 2.79, we find that the mass of the crust of the earth amounts to 19,002.69 $\times 10^{15}$ metric tons.

Mass of the hydrosphere.—The estimates of the total volume of the oceanic waters vary somewhat widely.[31] The earliest reliable estimate is that of Murray,[32] who gives the volume 323,722,150 cubic miles, or 1,353,806,031 cubic kilometers. The latest estimate is that of Kossinna,[33] whose estimate is 1,370,323,000 cubic kilometers, or about 327,672,000 cubic miles. This estimate includes the oceans, the mediterranean seas, the border seas, and the gulfs. This estimate of Kossinna is accepted here.

The density of sea water [34] of normal salinity (35 parts per thousand) at a temperature of 0° C. is 1.028. Grabau [35] assumes a density of 1.04 in order to take into account the increased density at the bottom. Dr. E. D. Williamson, of the Carnegie Geophysical Laboratory, who has calculated for us the change in density brought about by pressure and the compressibility of sea water, finds that the density at the bottom would be about 1.04, and estimates the density of average sea water as about 1.033. We may therefore accept a density of 1.03 as approximately correct.

By assuming 1,370,323,000 cubic kilometers for the total volume of the oceanic waters and 1.03 for the average density, we obtain 1,411.4 $\times 10^{15}$ metric tons as the total mass of the oceans and connected bodies of salt water.

Mass of the atmosphere.—The total mass of the atmosphere is readily calculated approximately according to Humphreys [36] "by the continued product of the world average height of the mercurial barometer in centimeters at the actual surface of the earth, the density of mercury, and the area of the earth in square centimeters." The mass as thus determined by several authorities [37] is 5 $\times 10^{15}$ metric tons, but the latest and most careful estimate is that of Humphreys, who gives as his final result 5.11 $\times 10^{15}$ metric tons.

Composition of the crustal mass.—When we combine the data given above, assuming a crust 10 miles thick, we obtain the following percentages:

Mass composition of the crust of the earth.

	Metric tons.	Per cent.
Lithosphere (10 miles)	19,002.7 $\times 10^{15}$	93.06
Hydrosphere	1,411.4 $\times 10^{15}$	6.91
Atmosphere	5.1 $\times 10^{15}$	.03
	20,419.2 $\times 10^{15}$	100.00

This estimate differs but slightly from the estimate obtained by Clarke and given by him in papers already published.

In short, we may regard the surface layer of the earth, to a depth of 10 miles, as consisting very nearly of 93 per cent of solid rock and 7 per cent of water holding salts in solution and may treat the atmosphere as a small correction to be applied as needed.

The figure assigned to the ocean includes the fresh waters of the globe and the water of the atmosphere, which are too small in amount to be estimable directly. Their insignificance may be inferred from the fact that a section of the

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[31] Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 22, 1920.

[32] Murray, Sir John, On the height of the land and the depth of the ocean: Scottish Geog. Mag., vol. 4, p. 39, 1888.

[33] Kossinna, E., Die Tiefen des Weltmeeres, pp. 24, 68, Berlin, 1921.

[34] Cf. Murray, Sir John, and Hjort, Johan, The depths of the ocean, p. 239, 1912.

[35] Grabau, A. W., Principles of stratigraphy, p. 3, 1913.

[36] Humphreys, W. J., The mass of the atmosphere and of each of its more important constituents: Monthly Weather Review, vol. 49, p. 341, 1921.

[37] Davis, W. M., Elementary meteorology, p. 10, 1894. Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 1, p. 5, 1904. Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 22, 1920.

earth's crust 10 miles thick having the surface area of the United States would represent only about 1.5 per cent of the entire mass of the earth's crust. A quantity of water equivalent to 1 per cent of the ocean, or 0.07 per cent of the 10-mile crust, would cover all the land of the globe to a depth of 290 feet. Even the mass of Lake Superior is thus negligible.

The 10-mile crust of the earth is composed largely of igneous rocks, a considerable part of which is overlain by a relatively thin covering of sedimentary rocks. For our purpose we must make an estimate of the relative amounts of igneous and sedimentary rocks. It is almost if not quite impossible to form an estimate of the amount or the composition of the metamorphic rocks; but inasmuch as they are either modified igneous or modified sedimentary rocks their average composition should be much like the mean of that of the other two classes. An average gneiss, for example, resembles a granite in chemical composition, and a slate or mica schist is a metamorphosed shale.

The data and the reasoning by which we may estimate approximately the relative amounts of the igneous and sedimentary rocks in the crust of the earth are presented elsewhere (see p. 32), but it may be stated here that the outer 10 miles of the crust contains about 95 per cent of igneous and about 5 per cent of sedimentary rocks. The 5 per cent of sedimentary rocks consists of 4 per cent of shale, 0.75 per cent of sandstone, and 0.25 per cent of limestone. Van Hise [38] assigns to the sedimentary rocks of the land portion of the earth an average thickness of 2 kilometers, or 3.67 per cent of the outer 10-mile crust by volume. The average thickness of the sedimentary shell, which completely envelops the globe, is here estimated at about one-half mile, or a little less than 1 kilometer.

A few words must be said regarding the thickness of the so-called crust and the composition of its deeper parts, as these have important bearing on various geologic and geogonic theories. In the present paper we consider only the rocks that are accessible to our observation, as we desire to confine our data and the averages derived from them to known facts and to disregard the unknown. The rocks which are thus considered are necessarily those that form the outermost layers of the globe.

In order to have a definite mass of matter under consideration, and for the purposes of certain computations in which the masses of the hydrosphere and the atmosphere are also considered, it has been necessary to assume a definite thickness for this outermost known part of the lithosphere, the part that is represented by the analyses used by us. A thickness of 10 miles has been assumed, chiefly because it corresponds approximately with the total thickness of known rocks of all kinds between the extremes of the maximum elevations above and depressions below sea level.[39] This depth of 10 miles is admittedly arbitrary, but any other assumed depth of material having the composition of the known surface rocks would also be arbitrary. Many estimates have been made of the thickness of the numerous sedimentary deposits that overlie the igneous crust in different parts of the earth. These estimates vary, but according to all of them the total thickness of the sedimentary beds is several times 10 miles.[40] As these sedimentary rocks have been derived from the upper parts of the outermost igneous crust, and as the average composition of the sedimentary rocks as a whole does not differ greatly from that of the igneous rocks, the assumption, for purposes of computation, of a 10-mile or even a 20-mile outer crust of approximately constant composition does not seem to be unreasonable.

If we reject the old idea, advocated by Fisher and others, of a thin solid crust overlying a molten, liquid interior, and regard the earth as solid, any exact limitation of the depth of the "crust," or even a definition of what constitutes the "crust," becomes very difficult, if not impossible. The theory of isostasy, based on gravity determinations and average rock densities,[41] indicates that the "depth of compensation" or "isopiestic level" is about 96 kilometers (Hayford and Bowie) or 60 kilometers (Washington) beneath the surface. Other evidence also indicates corresponding depths for a zone of change of some sort which

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[38] Van Hise, C. R., A treatise on metamorphism: U. S. Geol. Survey Mon. 47, p. 940, 1904.

[39] Clarke, F. W., The relative abundance of the chemical elements: Philos. Soc. Washington Bull., vol. 11, p. 131, 1889.

[40] See Pirsson, L. V., and Schuchert, Charles, A textbook of geology, Part II, Historical geology, 1915, passim. Schuchert gives an estimate of 53 miles in Lull, R. S., and others, The evolution of the earth and its inhabitants, p. 60, 1919.

[41] See Washington, H. S., Isostasy and rock density: Geol. Soc. America Bull., vol. 33, p. 375, 1922, and references to Hayford, Bowie, and others there given. See also Daly, R. A., The earth's crust and its stability: Am. Jour. Sci., 5th ser., vol. 5, p. 349, 1923.

is not sharp but rather gradual. However, on the assumption of a solid earth we seem to be forced to believe that there is no abrupt break in continuity of either chemical or physical conditions, above which is the "crust" and below which is the "interior," but rather that there is probably a continuous, progressive, and probably regular change, material and physical, as the center of the earth is approached.

As the density of the earth as a whole is about 5.52 and that of the exterior "crustal" rocks is about 2.79 the conclusion is obvious that the density of the rocks increases with depth. It is also known that the material which makes up the continents is lighter and that which forms the ocean floors is heavier than the average known rock. This topic has been discussed by many writers—Lord Kelvin, Sir George Darwin, Suess, Wiechert, Daly, and a host of others; indeed it is so well known to all students of the earth that it is unnecessary to discuss it here. Suffice it to say that the writers are at one with many others in the belief that the material of the "crust" and the material that lies beneath the "crust" increase in density with depth.

The gradient or rate of increase in density is unknown, and it is likewise unknown whether the increase is regular or not, or even whether there may not be a diminution in density in some zones or shells. Many factors enter into the problem, such as temperature, pressure, differences in chemical composition, strength of materials, flowage, presence of gases, and possibly radioactivity, none of which can be evaluated at present, especially for great depths. It is the opinion of the writers, therefore, that the time has not yet come for detailed discussion of the change in physical and chemical constitution of the "crust" associated with change in depth; our knowledge is inadequate for detailed treatment—it is barely sufficient for the consideration of the broader aspects.

The writers are in general agreement with Suess's concept of an outer shell of "sal," underlain by one of "sima," that by one of "nifesima," these overlying a nucleus (or at least a zone) of "nife"; and we are also in general accord with the similar views of Daly, Mennell, and others that a granitic shell overlies one of basalt, or more probably of gabbro, although we do not believe with Daly [42] in a limited miscibility between granitic and basaltic magmas. But even if one is perhaps justified in indulging in such general speculations one is not as yet, in our opinion, justified in making precise statements as to conditions in depth, such as "the average rock down to this depth [20 miles] probably corresponds to a gabbro, containing about 50 per cent of silica."[43] The Italians have a proverb that is apropos: "Chi va piano va sano."

Helmert [44] has calculated that the density of the matter at the center of the earth is about 11.2. If this be true it would follow that the real nucleus of the earth may be composed chiefly of the heavier metals, such as silver, gold, lead, thallium, and the metals of the platinum group, not combined with other elements, because the densest compound minerals known have densities considerably below 11.2, these being sperrylite, platinum arsenide (10.6); dyscrasite, silver antimonide (9.4–9.8); uraninite, uranium oxide (9.0–9.7); thorianite, thorium oxide (9.3); and calaverite, gold telluride (9.0). It is assumed here that the effect of pressure is negligible. The suggestion has been made by the junior author [45] that "the central core, the real nucleus of the earth, is composed of the metallogenic elements, that is, the elements or metals of highest atomic weight, either as native metals or possibly in the form of selenides, tellurides, arsenides, antimonides, bromides, and iodides. Above this would be the nickel-iron zone, and above this the silicate crust." This arrangement would accord with the principle of "gravitative adjustment," also with the great rarity of the metallogenic elements, the apparently intermediate character of the iron-cobalt-nickel triad, the magnetism of the earth, the low melting points of the metallogenic sulphides, arsenides, sulpho-salts, and other compounds, and other facts.

AVERAGE ELEMENTARY COMPOSITION OF IGNEOUS ROCKS.

GENERAL STATEMENT.

The general average chemical composition of igneous rocks given in Table 10 (p. 16) includes the constituents for which enough ana-

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[42] Daly, R. A., Igneous rocks and their origin, pp. 170, 226, 1914.

[43] Crook, Thomas, Nature, vol. 110, p. 255, 1922.

[44] Helmert, F. R., Theorien der höheren Geodesie, vol. 2, p. 475, Leipzig, 1884.

[45] Washington, H. S., The chemistry of the earth's crust: Franklin Inst. Jour., vol. 190, p. 787, 1920.

lytical determinations have been made to permit us to state an average, as well as a few others that have been determined quantitatively with sufficient accuracy to permit us to obtain an idea of their approximate relative amounts. Other constituents have been detected qualitatively, but most of them are found in amounts far too small to permit their easy or frequent quantitative determination. We can, however, form an estimate of the relative amounts of many of even these rarer elements through a knowledge of their associations and of the comparative rarity or abundance of the minerals in which they occur.

The average chemical composition of the igneous rocks, expressed in elements, is given in Table 11, which is based in part on Table 2 (p. 10) and Table 10 (p. 16), and in part on considerations regarding some of the rarer elements which will be brought out in the following pages. In Table 11 the elements are arranged in the order of their abundance, and the table is divided into two parts. The first part includes the abundant major elements and the common minor elements—those to which definite figures can be assigned from quantitative analytical data sufficient to permit us to form a reasonable estimate of their approximate amount. These minor constituents are stated in percentages to three decimal places, and although the figures in the third place mean little they serve to indicate the proper sequence of the elements in the table.

The second part includes the less common elements shown in the first part, from cerium-yttrium down to the end, which are repeated here because these are less accurately known than the more common elements and because it makes comparison of them with the rarer elements more easy. The second part also includes those rare elements whose percentages probably or certainly do not reach the third decimal place but as to whose position in the sequence we can form some idea. In the second part the order of the elements is not stated in percentages, because a long array of ciphers is confusing and is not readily intelligible. The elements are therefore stated exponentially, in parts of a gram per gram of rock. An "n" is used (in place of "x") to indicate the first significant though unknown integer. The positions assigned to these rarer elements are determined in part by the results of studies made by Vogt,[46] Vernadsky,[46a] De Launay,[47] Beyschlag,[48] Lindgren,[49] Clarke and Steiger,[50] Washington,[51] and others, and more recent studies of our own.

For comparison earlier estimates by Clarke, by Clarke and Washington, and by Vogt are given. The figures in Table 11 have been recalculated from the data in Table 10 and otherwise revised and corrected; they supersede a table prepared by us.[52]

TABLE 11.—*Average elementary composition of igneous rocks.*

Major and common elements.

	1	2	3	4
Oxygen	46.59	46.41	47.29	47.2
Silicon	27.72	27.58	28.02	28.0
Aluminum	8.13	8.08	7.96	8.0
Iron	5.01	5.08	4.56	4.5
Calcium	3.63	3.61	3.47	3.5
Sodium	2.85	2.83	2.50	2.5
Potassium	2.60	2.58	2.47	2.5
Magnesium	2.09	2.09	2.29	2.5
Titanium	.63	.720	.46	.33
Phosphorus	.13	.157	.13	.22
Hydrogen	.13	.129	.16	.17
Manganese	.10	.124	.078	.075
Sulphur	.052	.080	.10	.06
Barium	.050	.081	.093	.03
Chlorine	.048	.096	.063	.04–.025
Chromium	.037	.068	.034	.01
Carbon	.032	.051	.13	.22
Fluorine	.030	.030	.10	.04–.025
Zirconium	.026	.052	.017	.02–01
Nickel	.020	.031	.020	.005
Strontium	.019	.034	.034	.005
Vanadium	.017	.041	.017	.00n
Cerium, yttrium	.015	.020	....	.00nn
Copper	.010	.010	....	.000, n
Uranium	.008	.000,00n	....	.000, 00n
Tungsten	.005	.000.00n	....	.000, 00n
Lithium	.004	.005	.004	.004
Zinc	.004	.004	....	.000, n
Columbium, tantalum	.003	.000,00n	....	.000,000,n
Hafnium	.003	....	....	....
Thorium	.002	.000,00n	....	.000,000,n
Lead	002	.002	....	.000, n
Cobalt	.001	.003	....	.00n
Boron	.001	.001	....	.00n
Glucinum	.001	.001	....	.00n
	100.000	100.000	100.000	100.000

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[46] Vogt, J. H. L., Ueber die relative Verbreitung der Elemente, besonders der Schwermetalle: Zeitschr. prakt. Geologie, 1898, pp. 226, 315.

[46a] Vernadsky, V., The relative abundance of the elements: Ref. in Zeitschr. Kryst., vol. 55, p. 173, 1915. (Original in Russian.)

[47] De Launay, L., La science géologique, p. 637, 1905; Traité de métallogénie: Gîtes minéraux et métallifères, vol. 1, p. 26, 1913.

[48] Beyschlag, F., Vogt, J. H. L., and Krusch, P., The deposits of the useful minerals and rocks, their origin, form, and content (translated by S. J. Truscott), vol. 1, pp. 147–158, 1914.

[49] Lindgren, Waldemar, Mineral deposits, pp. 4–14, 1913.

[50] Clarke, F. W., and Steiger, George, The relative abundance of several metallic elements: Washington Acad. Sci. Jour., vol. 4, p. 58, 1914.

[51] Washington, H. S., The distribution of the elements in igneous rocks: Am. Inst. Mining Eng. Trans., 1908, p. 735; The chemistry of the earth's crust: Franklin Inst. Jour., vol. 190, p. 777, 1920.

[52] Clarke, F. W., and Washington, H. S., The average chemical composition of igneous rocks: Nat. Acad. Sci. Proc., vol. 8, pp. 112, 113, 114, 1922.

TABLE 11.—*Average elementary composition of igneous rock*—Continued.

Less common and rare elements.

	5	6	7
Cerium, yttrium	1.5×10^{-4}	2×10^{-4}	$n\times10^{-5}$
Copper	1×10^{-4}	1×10^{-4}	$n\times10^{-6}$
Uranium	8×10^{-5}	$n\times10^{-8}$	$n\times10^{-8}$
Tungsten	5×10^{-5}	$n\times10^{-8}$	$n\times10^{-8}$
Lithium	4×10^{-5}	4×10^{-5}	4×10^{-5}
Zinc	4×10^{-5}	4×10^{-5}	$n\times10^{-6}$
Columbium, tantalum	3×10^{-5}	$n\times10^{-8}$	$n\times10^{-9}$
Hafnium	3×10^{-5}	....	....
Thorium	2×10^{-5}	$n\times10^{-8}$	$n\times10^{-9}$
Lead	2×10^{-5}	2×10^{-5}	$n\times10^{-6}$
Cobalt	1×10^{-5}	3×10^{-5}	$n\times10^{-5}$
Boron	1×10^{-5}	1×10^{-5}	$n\times10^{-5}$
Glucinum	1×10^{-5}	1×10^{-5}	$n\times10^{-5}$
Molybdenum	$n\times10^{-6}$	$n\times10^{-6}$	$n\times10^{-7}$
Rubidium	$n\times10^{-6}$	$n\times10^{-6}$	$n\times10^{-5}$
Arsenic	$n\times10^{-6}$	$n\times10^{-6}$	$n\times10^{-5}$
Tin	$n\times10^{-6}$	$n\times10^{-6}$	$n\times10^{-5}$
Bromine	$n\times10^{-6}$	$n\times10^{-6}$	$n\times10^{-5}$
Caesium	$n\times10^{-7}$	$n\times10^{-7}$	$n\times10^{-8}$
Scandium	$n\times10^{-7}$	$n\times10^{-7}$	$n\times10^{-12}$
Antimony	$n\times10^{-7}$	$n\times10^{-7}$	$n\times10^{-5}$
Cadmium	$n\times10^{-7}$	$n\times10^{-7}$	$n\times10^{-8}$
Mercury	$n\times10^{-7}$	$n\times10^{-7}$	$n\times10^{-8}$
Iodine	$n\times10^{-7}$	$n\times10^{-7}$	$n\times10^{-5}$
Bismuth	$n\times10^{-8}$	$n\times10^{-8}$	$n\times10^{-9}$
Silver	$n\times10^{-8}$	$n\times10^{-8}$	$n\times10^{-9}$
Selenium	$n\times10^{-8}$	$n\times10^{-8}$	$n\times10^{-9}$
Platinum	$n\times10^{-9}$	$n\times10^{-9}$	$n\times10^{-10}$
Tellurium	$n\times10^{-9}$	$n\times10^{-9}$	$n\times10^{-10}$
Gold	$n\times10^{-9}$	$n\times10^{-9}$	$n\times10^{-10}$
Iridium	$n\times10^{-10}$	....	....
Osmium	$n\times10^{-10}$	....	....
Indium	$n\times10^{-11}$	$n\times10^{-11}$	$n\times10^{-11}$
Gallium	$n\times10^{-11}$	$n\times10^{-11}$	$n\times10^{-11}$
Thallium	$n\times10^{-10}$	$n\times10^{-10}$	$n\times10^{-11}$
Rhodium	$n\times10^{-11}$	....	....
Palladium	$n\times10^{-11}$	....	....
Ruthenium	$n\times10^{-11}$	....	....
Germanium	$n\times10^{-11}$	$n\times10^{-12}$	$n\times10^{-12}$
Radium	$n\times10^{-12}$	$n\times10^{-14}$	....

1. Igneous rocks, Clarke, F. W., and Washington, H. S., 1924.
2. Igneous rocks, Clarke, F. W., and Washington, H. S., The average chemical composition of igneous rocks: Nat. Acad. Sci. Proc., vol. 8, p. 112, 1922.
3. Igneous rocks, Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 28, 1920.
4. Igneous rocks, Vogt, J. H. L., Ueber die relative Verbreitung der Elemente, besonders der Schwermetalle: Zeitschr. prakt. Geologie, 1898, p. 324.
5. Clarke, F. W., and Washington, H. S., 1924.
6. Clarke, F. W., and Washington, H. S., op. cit., pp. 113, 114.
7. Vogt, J. H. L., op. cit., p. 324.

DATA CONSIDERED.

A statement of the grounds on which the less common and the rarer elements were assigned to their positions in the table may be of interest.

The figures given for the rarer elements are not of equal weight. Some of these figures (as those for copper, zinc, cadmium, cerium-yttrium, lead, and arsenic) are based on quantitative analytical data and may be regarded as approximately correct. Those for uranium, thorium, and radium are based on determinations by radioactive methods and may be provisionally accepted, although they appear to be at variance with the general experience of mineralogists as to the relative abundance of the minerals that contain these elements as essential constituents.

Other estimates are very rough; some are scarcely better than guesses based on the general known or supposed relative rarity or abundance of the minerals that contain the elements considered. Others are based on statistics of production and like data, and these may be subject to serious error. Data of these kinds are obviously imperfect and incomplete, so that they must be regarded as merely rough first approximations. They are, further, subject to great changes, many of which are caused by improvements in analytical methods or by changes or progress in the arts and industries. Thus, the invention of the Welsbach mantle and of certain special steels brought to our knowledge previously unknown or neglected deposits of thorium and the rare earths and of ores of vanadium, tungsten, and molybdenum and led to their development; and the search for radium has led to the discovery of large bodies of uranium minerals. Some of these changes may be seen by comparing the estimates made by Vogt in 1898 with ours, uranium being an example.

Notwithstanding all these uncertainties, the figures presented may give a rough idea of the general sequence or order of magnitude of the quantities of the rare elements in the earth's crust, but it should be understood that they are by no means highly accurate.

The figures for fluorine shown in Table 2 (p. 10), as determined by the second method of averaging (0.15) and by the third method (0.076), are unquestionably too high, whereas the figure given by the first method (0.006) is too low. Fluorine occurs in igneous rocks chiefly as a constituent of the ubiquitous apatite, $Ca_5(PO_4)_3F$, which contains also the phosphoric oxide given in Table 10. If the 0.30 per cent of P_2O_5 there given is all carried in apatite, then the corresponding percentage of fluorine is only 0.027, which may be rounded off to 0.030 in order to allow for small amounts of fluorine contained in a few minerals, such as hornblende and biotite. The figure 0.030

has been adopted in the final estimate of the composition of the lithosphere.

Many years ago Hillebrand[53] showed that vanadium is present in determinable quantities in many rocks, especially in the less silicic ones. The average percentage of V_2O_3 shown by 56 special determinations by Hillebrand was 0.025. Since Hillebrand called attention to the common presence of vanadium in rocks it has been determined rather frequently, mostly by chemists in the United States, Australia, and England.

The oxides of the rare-earth metals, those of the cerium and yttrium groups, were determined in only about 20 analyses given in Professional Paper 99, but analyses since published have increased the number somewhat. Their widespread occurrence in small amounts in certain minerals, such as acmite,[54] indicates that they are more common in determinable amounts than is usually supposed. The maximum amount of the rare earths reported, 1.79 per cent, was found in a monchiquite of Madras,[55] 0.59 was found in a Swedish nephelite syenite,[56] 0.37 in a peculiar granitic rock of the islet of Rockall,[57] 0.13 in a Swiss syenite,[58] and smaller percentages in alkalic rocks of Texas,[59] Wyoming,[60] Italy,[61] and other places.

The average for $(Ce, Y)_2O_3$ given by the 19 determinations in the superior analyses in Professional Paper 99 is 0.088 per cent. This includes two exceptionally high values, those for the rocks of Almunge and Rockall; if these are omitted from the reckoning the average is 0.042. This average is that for highly alkalic, mostly sodic rocks in which the rare earths are most abundant, and this average is therefore higher than that for all igneous rocks. On the other hand, there are very few determinations of the rare earths in rock analyses, the methods used for their determination tend to yield too low results, and there are some rocks in which the quantity of the rare earths is high. A general average of 0.20 may therefore be accepted as an approximation to the truth as close as we can arrive at from present data. The cerium metals appear to be more abundant than the yttrium metals, and recent chemical analyses of silicate minerals indicate that lanthanum is almost as abundant as cerium.

Small amounts of copper have been determined in many modern rock analyses, although the copper reported in some analyses was probably derived from the copper utensils used, or was really platinum derived from the crucibles or basins.[62] Some examples are given of unquestionable determinations of copper in igneous rocks. The "traps" of the Lake Superior region[63] and those of New Jersey[64] contain an average of about 0.02 per cent of copper, as do the traps of Wyoming[65] and the rocks of British Guiana,[66] and the average content of copper in the Butte granite was 0.006.[67] R. C. Wells found 0.03 in a basalt from Oregon;[68] Steiger found 0.0155 per cent of copper in a composite sample of 71 Hawaiian lavas[69] and 0.01167 per cent of CuO in a composite sample of 329 American rocks.[70] As Lindgren says,[71] "From this evidence the conclusion may be drawn that probably all igneous rocks contain appreciable amounts of copper and that acidic rocks contain less than basic rocks. The copper is

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[53] Hillebrand, W. F., Distribution and quantitative occurrence of vanadium and molybdenum in rocks of the United States: Am. Jour. Sci., 4th ser., vol. 6, p. 209, 1898; The analysis of silicate and carbonate rocks: U. S. Geol. Survey Bull. 700, p. 184, 1919.

[54] Unpublished studies by H. S. Washington and H. E. Merwin.

[55] Personal communication of J. W. Evans. See Washington, H. S., Chemical analyses of igneous rocks: U. S. Geol. Survey Prof. Paper 99, p. 1119, 1917. This analysis was, unfortunately, placed among the inferior analyses, because of its high summation, but it would be better placed, because of its interest, among the superior analyses.

[56] Quensel, Percy, The alkaline rocks of Almunge: Geol. Inst. Upsala Bull., vol. 12, p. 179, 1913.

[57] Washington, H. S., The composition of rockallite: Geol. Soc. London Quart. Jour., vol. 70, p. 297, 1914. Cf. Lacroix, A., Lá signification des granites alcalines très riche en soude: Compt. Rend., vol. 177, p. 417, 1923.

[58] Weber, F., Ueber den Kalisyenit des Piz Giuf und Umgebung: Beitr. geol. Karte Schweiz, Lief. 14, p. 43, 1904.

[59] Clarke, F. W., Analyses of rocks and minerals: U. S. Geol. Survey Bull. 591, pp. 60, 61, 1915.

[60] Cross, Whitman, Igneous rocks in Wyoming: Am. Jour. Sci., 4th ser., vol. 4, p. 130, 1897.

[61] Washington, H. S., The Roman comagmatic region: Carnegie Inst. Washington Pub. 57, p. 146, 1906.

[62] Hillebrand, W. F., Some principles and methods of analysis applied to silicate rocks: U. S. Geol. Survey Bull. 148, p. 42, 1897; The analysis of silicate and carbonate rocks: U. S. Geol. Survey Bull. 700, pp. 27, 136, 1919. Washington, H. S., Manual of the chemical analysis of rocks, 3d ed., p. 19, 1919.

[63] Lane, A. C., Mine waters: Lake Superior Min. Inst. Proc., 1908, p. 86. Grout, F. F., Keweenawan copper deposits: Econ. Geology, vol. 5, p. 471, 1910.

[64] Lewis, J. V., Copper deposits of the New Jersey Triassic: Econ. Geology, vol. 2, p. 242, 1907.

[65] Spencer, A. C., The copper deposits of the Encampment district: U. S. Geol. Survey Prof. Paper 25, p. 49, 1904.

[66] Harrison, J. B., The geology of the gold fields of British Guiana, pp. 60–62, 76–78, 95–96, 1908.

[67] Weed, W. H., Geology and ore deposits of the Butte district, Mont.: U. S. Geol. Survey Prof. Paper 74, p. 94, 1912.

[68] Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 632, 1920.

[69] Clarke, F. W., idem, p. 632.

[70] Clarke, F. W., and Steiger, George, The relative abundance of several metallic elements: Washington Acad. Sci. Jour., vol. 4, p. 60, 1914.

[71] Lindgren, Waldemar, Mineral deposits, p. 9, 1915.

largely associated with the ferromagnesian silicates and in the lavas at least it appears to be present as a silicate."

Zinc and lead have been found in igneous rocks by several chemists. Hillebrand[72] found an average of 0.002 per cent of lead oxide in porphyries from Leadville, Colo., and two samples contained, respectively, 0.008 and 0.004 per cent of zinc oxide, the samples being taken from points distant from the ore bodies. Robertson[73] found an average of 0.004 per cent of lead, 0.009 per cent of zinc, and 0.006 per cent of copper in igneous rocks of Missouri. Becker[74] detected arsenic, antimony, copper, and lead in fresh granites of Steamboat Springs, Nev. Warren[75] found 0.71 per cent of zinc in the cumberlandite of Rhode Island. Zinc has been found in the granite of Laurion, in Attica, Greece,[76] one specimen containing 2.14 per cent of zinc; and zinc is stated to be common in the eurites of the district. Lead was looked for but was not found. Harrison[77] found small amounts (up to 0.02 per cent) of lead oxide in diabase, syenite, and schist of British Guiana. Clarke and Steiger[78] examined large composite samples of deep-sea clays, river silts, and igneous rocks, and found copper, zinc, lead, nickel, and arsenic in all of them. The percentages of metals in 90 gram samples of the composite of 329 igneous rocks of the United States were: CuO, 0.01167; ZnO, 0.00638; PbO, 0.00081; NiO, 0.00655; As_2O_5, 0.00074.

The wide distribution and general presence of uranium, thorium, and radium in most rocks and many minerals has been established by the work of many students of radioactivity.[79]

The amounts of thorium and radium were determined by their radioactivity, and the amount of uranium was determined by the equilibrium ratio of radium to uranium; the latest and probably the best of several concordant determinations of this ratio is 3.40×10^{-7}. A great variety of rocks—igneous, metamorphic, and sedimentary—as well as soils, oceanic and spring and river waters, and the atmosphere have been examined for thorium and radium, with fairly concordant results. As stated by Holmes:[80] "We may conclude that in general radium shows a marked preference for alkaline and acid rocks, and to a less extent for volcanic, as compared with plutonic rocks. * * * Although the evidence in the case of thorium is less abundant than for radium, it tends to show that similar statements are equally true of that element." Igneous rocks contain in general more radium than sedimentary rocks. Joly[81] arrives at the average values of 2.5×10^{-12} gram of radium per gram of igneous rock, and 1.5×10^{-12} gram of radium per gram of sedimentary rock. He gives[82] the following average values for different classes of rocks, the figures to be multiplied by 10^{-12}: Acid rocks, 3.01; intermediate rocks, 2.57; basic rocks, 1.28; 7 lavas from Vesuvius, 12.6. This last high value for rocks rich in potash is noteworthy. The average amount of uranium in igneous rocks is calculated to be 8.5×10^{-5} gram per gram of rock by using the radium-uranium ratio 3.40×10^{-7} and the radium value 2.5×10^{-12}. The amount of thorium is estimated

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[72] Hillebrand, W. F., Geology and mining industry of Leadville, Colo.: U. S. Geol. Survey Mon. 12, pp. 591–594, 1886.

[73] Robertson, J. D., Lead and zinc deposits in Missouri: Missouri Geol. Survey, vol. 7, p. 479, 1894.

[74] Becker, G. F., Geology of the quicksilver deposits of the Pacific slope: U. S. Geol. Survey Mon. 13, p. 350, 1888.

[75] Warren, C. H., Contributions to the geology of Rhode Island: The petrography and mineralogy of Iron Mine Hill, Cumberland: Am. Jour. Sci., 4th ser., vol. 25, p. 24, 1908.

[76] Lepsius, R., Geologie von Attika, p. 93, Berlin, 1893.

[77] Harrison, J. B., The geology of the gold fields of British Guiana, pp. 61, 77, 95, 1908.

[78] Clarke, F. W., and Steiger, George, The relative abundance of several metallic elements: Washington Acad. Sci. Jour., vol. 4, p. 58, 1914.

[79] The literature is rather extensive; some of the more important papers are cited here. Eve, A. S., and McIntosh, Douglas, Amount of radium present in typical rocks in the immediate neighborhood of Montreal: Philos. Mag., vol. 14, p. 231, 1907. Joly, John, On the radioactivity of certain lavas: Idem, vol. 18, p. 577, 1909; On the distribution of thorium in the earth's surface materials: Idem, vol. 17, p. 760, 1909, and vol. 18, p. 140, 1909. Blanc, G. A., On the distribution of thorium in the earth's surface materials: Idem, vol. 18, p. 146, 1909. Joly, John, On a method of investigating the quantity of radium in rocks and minerals: Idem, vol. 22, p. 134, 1911; Radioactivity of the rocks of the St. Gothard Tunnel: Idem, vol. 23, p. 201, 1912. The radioactivity of terrestrial surface materials: Idem, vol. 24, p. 694, 1912. Holmes, Arthur, Radium and the evolution of the earth's crust: Nature, vol. 91, p. 398, 1912; The terrestrial distribution of the radioelements: Nature, vol. 91, p. 582, 1912; The terrestrial distribution of radium: Sci. Progress, vol. 9. p. 12, 1915. Watson, H. E., and Pal, G., On the radioactivity of the rocks of the Kolar gold field: Philos. Mag., vol. 28, p. 44, 1914. Smith, W. F., and Watson, H. E., The radioactivity of Archean rocks of Mysore State, South India: Idem, vol. 35, p. 206, 1918. Poole, J. H. J., Radium content of the rocks of the Loetschberg Tunnel: Idem, vol. 40, p. 466, 1920. Lind, S. C., and Roberts, L. D., New determination of the absolute value of the radium-uranium ratio: Am. Chem. Soc. Jour., vol. 42, p. 1170, 1920. The following more general works may also be consulted: Joly, John, Radioactivity and geology, an account of the influence of radioactive energy on terrestrial history, London, 1909. Gockel, A., Die Radioactivität von Boden und Quellen, Braunschweig, 1914.

[80] Holmes, Arthur, The terrestrial distribution of radium: Sci. Progress, vol. 9, p. 19, 1915.

[81] Joly, John, The radioactivity of terrestrial surface materials: Philos. Mag., vol. 24, p. 703, 1912.

[82] Idem, p. 697.

by Holmes[83] to be 2×10^{-5} gram per gram of rock. These quantities, expressed in percentages, are uranium, 0.0085; thorium, 0.002; radium, 0.000,000,000,25.

It would thus appear that in general uranium is nearly as abundant as copper, and thorium is as abundant as lead and nearly as abundant as zinc. To a mineralogist these results appear very remarkable in view of the facts that the copper, zinc, and lead minerals, especially the sulphides, are very common and are widely spread over the earth and form enormous ore bodies. The uranium and thorium minerals, on the other hand, are all rare or very rare, are localized in their occurrence, and do not form very extensive ore bodies. The figures for uranium and thorium given above can scarcely be doubted, because of the general concordance between the determinations by the many expert physicists who made them; but we may be permitted to call attention to the apparent discrepancy between the values arrived at by radioactive methods and the apparent relative abundance based on experience in the occurrence of the minerals containing the radioactive elements mentioned above. If the average amounts of uranium and thorium are really as high as the physicists would have us believe they should be readily determinable in many rocks by quantitative chemical analysis if large portions (say 10 to 20 grams) are used. The matter seems to be worthy of investigation.

The position of hafnium,[84] or celtium, the recently discovered element No. 72, may be considered, although any statement concerning it must be regarded at present as highly tentative. According to Coster and Hevesy, its possible discoverers, hafnium occurs in zirconium minerals, especially in zircon, and they variously estimate its average amount as from 5 to 10 per cent of many zirconium minerals (chiefly zircon) and as "more than 1 part in 100,000" in the earth's crust. We have therefore provisionally assumed its percentage as 0.003, that is, one-tenth of that of zirconium, and place it in the table immediately after columbium-tantalum and preceding thorium. The previously calculated percentage figure for zirconium, 0.029, must therefore be corrected to 0.026.

To tungsten, columbium, and tantalum have been tentatively assigned average values between those of uranium and thorium. These assignments are based on our judgment of what appear to be the relative abundance and numbers of occurrences of the minerals that contain these elements. There are no known determinations of tungsten in igneous rocks. Christensen found 0.30 and 0.45 per cent of Cb_2O_5 in igneous rocks of the Ilimausak district in Greenland,[85] and small amounts of what is supposed to be largely columbic and tantalic oxides (called "X") have been found by several analysts[86] in igneous rocks of the Kaiserstuhl, Monte Amiata, Magnet Cove, and Castle Mountains (Montana).

The place of cobalt was determined by the results of an investigation of the chemistry of meteorites by Merrill,[87] which included many excellent analyses by Whitfield. A series of 40 selected analyses of stony meteorites gave the ratio Ni : Co :: 15.90 : 1, and 16 analyses (by Whitfield) of iron meteorites and the metallic parts of stony ones gave Ni : Co :: 15.79 : 1—a remarkably close agreement. The average of these results is Ni : Co :: 15.85 : 1. As Beyschlag[88] arrives at a closely similar ratio (8–20 : 1) from 75 analyses of terrestrial and meteoric nickel-iron, corroborated by analyses of olivine, the quantitative relation of nickel to cobalt may be considered as fairly well established at about 15 : 1.

There are practically no quantitative data for the determination of the positions of boron and glucinum, but we have tentatively estimated their average percentages at 0.001, placing them after cobalt at the end of the

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[83] Holmes, Arthur, The terrestrial distribution of radium: Sci. Progress, vol. 9, p. 20, 1915.

[84] Coster, D., and Hevesy, G., On the new element hafnium: Nature, vol. 111, pp. 182, 252, 1923.

[85] Ussing, N. V., Geology of the country around Julianehaab, Greenland: Meddelser om Groenland, vol. 38, pp. 175, 182, 1911.

[86] Knopf, Adolph, Ueber die Augite des Kaiserstuhlgebirges in Breisgau (Grossherzogthum Baden): Zeitschr. Kryst., vol. 10, p. 73, 1885. Williams, J. F., Ueber den Monte Amiata in Toscana und seine Gesteine: Neues Jahrb., Beilage Band 5, p. 404, 1887. Williams, J. F., The igneous rocks of Arkansas (Magnet Cove): Arkansas Geol. Survey Ann. Rept. for 1890, vol. 2, p. 226, 1891. Pirsson, L. V., Geology of the Castle Mountain mining district, Mont. (Castle Mountains): U. S. Geol. Survey Bull. 139, p. 130, 1896. Compare Schoeller, W. R., and Powell, A. R., The analysis of minerals and ores of the rarer elements for analytical chemists, metallurgists, and advanced students, pp. 130, 137, London, 1919.

[87] Merrill, G. P., Report on researches on the chemical and mineralogical composition of meteorites, with special reference to their minor constituents: Nat. Acad. Sci. Mem., vol. 14, Mem. 1, 1916.

[88] Beyschlag, F., Vogt, J. H. L., and Krusch, P., The deposits of the useful minerals and rocks, their origin, form, and content, vol. 1, p. 153, 1914.

column in the first part of Table 11. Boron is widespread and must be a common element, as it occurs in tourmaline, which is rather common in granitic rocks, and in datolite, which is frequently present as a secondary mineral in basalt and diabase. Boron is also of rather common occurrence in volcanic emanations and in hot springs. Glucinum is the basic element in beryl, a mineral which is very common and abundant in pegmatites. It is probable that boron is somewhat more abundant than glucinum.

A rough but satisfactory estimate of the order of abundance of molybdenum is furnished by the work of Hillebrand,[89] who showed quantitatively the presence of this element in some igneous rocks, especially the more silicic. Ferguson[90] also found molybdenum in basalts of Kilauea. The amounts found by these chemists were "traces"—that is to say, 0.01 per cent or less—but the determination of the occurrence of molybdenum may be used to illustrate a fairly safe principle to follow in making such estimates, namely, that if an element can be determined as present by quantitative analytical methods it may be considered common or at least not very rare.

Rubidium is assigned to a high position in the order of abundance among the rare elements because of its presence in many specimens of some common minerals, especially feldspars,[91] micas,[92] beryl,[93] and leucite.[94] It is undoubtedly more abundant than caesium, although caesium is present in some beryl,[95] and we have provisionally assumed the ratio Rb : Cs :: 10 : 1.

The position of arsenic in the table is fairly well established by the work of Clarke and Steiger,[96] who found 0.00074 per cent of As_2O_5 in a composite sample of 329 rocks from the United States. The value $n \times 10^{-6}$ may therefore be considered as a close approximation to the truth.

Tin has been detected by several chemists in orthoclase, mica, and possibly other silicate minerals.[97] Cassiterite, the chief tin ore, is almost invariably associated with granite, and Ferguson and Bateman[98] have thought that in general the tin-bearing granites are "more potassic than the average granite." We believe that tin is associated with sodic granites. Its position in the table is tentative.

Dittmar's analyses of oceanic salts showed in them a ratio of chlorine to bromine of about 300 to 1, which we have adopted, although there is grave doubt whether this ratio will apply to the solid igneous crust, in which the relative quantity of bromine is probably less. Iodine is less abundant than bromine and its quantity may be tentatively put at one-tenth of that of bromine; there seem to be no satisfactory data on which to base an even approximately correct estimate.

Scandium has been detected spectroscopically by Crookes[99] and by Eberhard[1] in many common rocks and minerals. As the spectroscopic method used by Eberhard is "capable of detecting one part of scandia in twenty thousand," and as both Crookes and Eberhard found it widely distributed, a rough idea of its approximate relative abundance may be had. Vernadsky[2] concludes from Eberhard's observations that scandium occurs mostly in the minerals of granitic and syenitic pegmatites.

Antimony has seldom been determined in igneous rocks. Mingaye[3] found 0.03 and a

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[89] Hillebrand, W. F., Distribution and quantitative occurrence of vanadium and molybdenum in rocks of the United States: Am. Jour. Sci., 4th ser., vol. 6, p. 209, 1898.

[90] Ferguson, J. B., The occurrence of molybdenum in rocks, with special reference to those of Hawaii: Am. Jour. Sci., 4th ser., vol. 37, p. 399, 1914.

[91] Vernadsky, W., Sur le microcline à rubidium: Soc. franç. minéralogie Bull., vol. 36, p. 258, 1913; Notes sur la distribution des éléments chimiques dans l'écorce terrestre: Acad. Sci. Petrograd Bull., 6th ser., vol. 8, p. 951, 1914. This last paper is in Russian.

[92] Clarke, F. W., Researches on the lithia micas: Am. Jour. Sci., 3d ser., vol. 32, p. 357, 1886.

[93] Duparc, L., Wunder, M., and Sabot, R., Note complémentaire sur le beryl de Madagascar: Soc. franç. minéralogie Bull., vol. 34, p. 241, 1911.

[94] Vernadsky, W. J., Ueber Worobiewit und die chemische Zusammensetzung der Berylle: Mus. Pierre le Grand près Acad. Imp. Sci. St.-Pétersbourg Trav., vol. 2, p. 81, 1908.

[95] Penfield, S. L., On the occurrence of alkalies in beryl: Am. Jour. Sci., 3d ser., vol. 28, p. 25, 1884. Penfield, S. L., and Sperry, E. S., Mineralogical notes, 1, Beryl: Am. Jour. Sci., 3d ser., vol. 36, p. 317, 1888. Lacroix, Alfred, Nouvelles observations sur les minéraux des pegmatites de Madagascar: Soc. franç. minéralogie Bull., 33, p. 46, 1910. Ford, W. E., The effect of the presence of alkalies in beryl upon its optical properties: Am. Jour. Sci., 4th ser., vol. 30, p. 128, 1910. Lacroix, Alfred, Minéralogie de la France, vol. 4, p. 809, 1910; Minéralogie de Madagascar, vol. 1, p. 546, 1922.

[96] Clarke, F. W., and Steiger, George, The relative abundance of several metallic elements: Washington Acad. Sci. Jour., vol. 4, p. 60, 1914.

[97] Compare Beyschlag, F., Vogt, J. H. L., and Krusch, P., op. cit., p. 154.

[98] Ferguson, H. G., and Bateman, A. M., Geologic features of tin deposits: Econ. Geology, vol. 7, p. 209, 1912.

[99] Crookes, Sir William, On scandium: Roy. Soc. London Philos. Trans., ser. A, vol. 209, p. 15, 1908, and ser. A, vol. 210, p. 359, 1910.

[1] Eberhard, G., Ueber die weite Verbreitung des Scandiums auf der Erde: K.-preuss. Akad. Wiss. Sitzungsber., 1908, p. 851. See also Levy, S. I., The rare earths, their occurrence, chemistry, and technology, pp. 3, 213, 1915; and Spencer, J. F., The metals of the rare earths, pp. 20, 128, 1919.

[2] Vernadsky, W., Zur Frage ueber die Verbreitung des Scandiums: Acad. imp. sci. St.-Pétersbourg Bull., vol. 2, p. 1273, 1908. Referate in Zeitschr. Kryst., vol. 50, p. 69, 1912.

[3] Andrews, E. C., The geology of the New England plateau, with special reference to the granites of northern New England: New South Wales Geol. Survey Rec., vol. 8, pp. 217, 218, 1907.

"trace" of Sb_2O_3 in two granites of New South Wales, and 0.14 per cent is reported in a Mexican rhyolite.[4] Its rather common occurrence as an accessory in many ore bodies indicates that it is fairly widespread. The position assigned it here must be regarded as tentative.

The place of cadmium is fairly well fixed by the studies by Clarke and Steiger[5] of a large number of technical determinations of cadmium in zinc ores, leading to the approximate ratio Zn : Cd :: 200 : 1. According to Vogt[6] the ratio for most occurrences ranges from 600 : 1 to 1,000 : 1.

The position of mercury is difficult to fix, because the deposits of this metal are peculiar in many ways, and mercury is seldom accompanied by large amounts of other metals, so that a basis for estimation of its comparative abundance is lacking.[7] Mercury has never been found in any igneous rock, so far as we know, a fact probably due to its ready volatility. The position assigned it here is tentative. Iodine has been mentioned in connection with bromine, its relative amount being placed tentatively at about one-tenth of that of the latter. Bismuth is unquestionably less abundant than antimony, but there appear to be no data from which to form a just estimate of its relative abundance. It is assumed that bismuth is about one-tenth as abundant as antimony, but the ratio is probably less than this.

Several attempts have been made to estimate the order of abundance of the precious metals—silver, gold, and platinum[8]—but because of the natural concentration of gold and platinum in placers, the rarity of the primary occurrence of these metals in igneous rocks, and their nondetermination in most rock analyses, the results are not very satisfactory. Primary gold and silver have been reported in a considerable number of igneous rocks, but the truly primary nature of the metals in some of them is doubtful. Silver and gold have been found in very small amounts in igneous rocks of Nevada and Colorado[9] and of British Guiana,[10] in places where their derivation from ore bodies seems to have been impossible. Mallet found silver to the extent of 1 part in about 100,000 in the volcanic ash of Cotopaxi and of Tunguragua.[11] Lincoln decides that although "the data concerning the primary gold and silver content of igneous rocks are insufficient to warrant drawing definite conclusions, the evidence, such as it is, tends to show that the igneous rocks contain minute amounts of gold and silver, distributed in an extremely irregular manner, * * * and that the gold favors neither acid nor basic rocks, while the silver manifests a slight partiality for basic rocks." Harrison, on the other hand, inclines toward the belief that in British Guiana the two metals are associated with basic rocks, especially gabbro and diabase, while Beyschlag and Vogt think that they show no decided preference or that "at least no regular rule formulating such preference can be drafted."

Silver is undoubtedly much more abundant than gold, but it is somewhat difficult to arrive at an exact ratio. Vogt estimates the ratio at Ag : Au :: 25–100 : 1, while Lindgren[12] is of the opinion that "silver may constitute 0.000,01 per cent of the crust and gold 0.000,000,5 per cent—that is, in about the ratio Ag: Au :: 20: 1. Wagoner[13] obtained the ratio Ag : Au :: 16 : 1 from a long series of assays of various igneous rocks. For our purpose, then, the relative positions of silver and gold may be expressed by putting gold one decimal place below silver. We differ with Lindgren, however, in placing both of them one decimal place lower in the table than he does.

Platinum and the other metals of the platinum group[14] occur mostly as native metals, the products of magmatic segregation, in olivine rocks (dunite, peridotite) and in pyroxenite,

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[4] Farrington, O. C., Observations on the geography and geology of western Mexico, including an account of the Cerro Mercado: Field Columbian Mus. Pub. 89, Geol. Ser., vol. 2, No. 5, p. 224, 1904.

[5] Clarke, F. W., and Steiger, George, The relative abundance of several metallic elements: Washington Acad. Sci. Jour., vol. 4, p. 61, 1914.

[6] Vogt, J. H. L., Ueber die relative Verbreitung der Elemente, besonders der Schwermetalle: Zeitschr. prakt. Geologie, 1898, p. 386. Compare Beyschlag, F., Vogt., J. H. L., and Krusch, P., op. cit., p. 162.

[7] Compare Lindgren, Waldemar, Mineral deposits, pp. 458, 472, 1913.

[8] Compare Vogt, J. H. L., Ueber die relative Verbreitung der Elemente, besonders der Schwermetalle: Zeitschr. prakt. Geologie, 1898, pp. 322, 388. Beyschlag, F., Vogt, J. H. L., and Krusch, P., The deposits of the useful minerals and rocks, vol. 1, p. 155, 1914. Lindgren, Waldemar, Mineral deposits, p. 10, 1913. For gold, see Lincoln, F. C., Certain natural associations of gold: Econ. Geology, vol. 6, p. 250, 1911.

[9] Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 631, 1920.

[10] Harrison, J. G., The geology of the gold fields of British Guiana, pp. 63, 78, 96, 204, London, 1908.

[11] Mallet, J. W., On the occurrence of silver in volcanic ash from the eruption of Cotopaxi of July 22 and 23, 1885: Roy. Soc. London Proc., vol. 42, p. 1, 1886.

[12] Lindgren, Waldemar, Mineral deposits, p. 14, 1913.

[13] Wagoner, Luther, The detection and estimation of small amounts of gold and silver: Am. Inst. Min. Eng. Trans., vol. 31, p. 798, 1901. Compare Lindgren, Waldemar, op. cit., p. 11.

[14] For the occurrence of platinum, see Kemp, J. F., Geological relations and distribution of platinum and associated metals: U. S. Geol. Survey Bull. 193, 1902; Beyschlag, F., Vogt, J. H. L., and Krusch, P., op. cit., p. 342; Lindgren, Waldemar, op. cit., p. 744; Duparc, Louis, and Tikonowich, M. N., Le platine et les gîtes platinifères, Genève, 1920.

and rarely in less basic ones. The platinum arsenide (sperrylite) occurs with copper ores in Ontario and Wyoming, and ruthenium sulphide (laurite) is known. Studies by Vogt[15] on the occurrence of gold and platinum in magmatic nickel pyrrhotite deposits in gabbro in Norway and at Sudbury show that small quantities of these metals are normally present in these gabbros and their basic differentiates, and that the amount of platinum is considerably greater than that of gold, but the difference is probably not great enough to justify their separation by a decimal place in the list.

Duparc and Tikonowich[16] have estimated the amount of platinum per cubic meter of dunite in two of the mining districts of the Ural Mountains, their calculations being based on the total volume of rock excavated and the amounts of metal extracted and stolen and remaining. Their figures are 0.1700 and 0.0115 gram of platinum per ton of rock, which correspond to 5×10^{-8} and 4×10^{-9} gram of platinum per gram of rock. It would appear, from the many analyses of platinum that they give and from other sources, that the relative order of abundance of the metals of the platinum group is as follows: Pt, Ir, Os, Pd, Rh, Ru. Platinum is by far the most abundant, about ten to twenty times as abundant as iridium, which seems to be rather more so than osmium. These are about five to ten times more abundant than palladium, which is a little more abundant than rhodium, while ruthenium is the rarest of all. The order of abundance is inverse to that of their atomic weights.

Selenium and tellurium are both among the rarer elements, but selenium is much less rare than tellurium. "In minute quantities selenium is present in many deposits, particularly in the pyritic copper deposits, and it is recovered on a rather large scale during the electrolytic refining of copper."[17] Selenium occurs also very generally with sulphur, so that "it is found almost regularly in the lead chambers of sulphuric acid works. In amount, however, it falls far behind sulphur, the relation between the two being as 1 to 100,000."[18] Tellurium occurs for the most part in combination with gold, and these tellurides generally contain much more tellurium than gold. For this reason, in spite of the relative abundance of free gold, concentrated in placer deposits through its high density, tellurium has been placed above gold in the table. Selenium has been assigned the value relative to sulphur given it by Beyschlag, so that it is probably ten times more abundant than tellurium.

Traces of gallium, indium, and thallium are found in rocks and minerals much more often than was formerly thought, as is shown especially by the studies of Vernadsky[19] and of Hartley and Ramage,[20] the last named having also detected gallium in a meteorite.[21] Hartley and Ramage found gallium (spectroscopically) in nearly all hematite and limonite ores, but seldom indium and thallium; indium, but not gallium or thallium in siderite; gallium in bauxite and kaolin; gallium in nearly all zinc blende, indium frequently, and thallium occasionally; indium in all tin ores; gallium and thallium in manganese ores; indium and thallium in many pyrites, but gallium in only one; no gallium, indium, or thallium in galena.

Gallium (alloyed with some indium) has been obtained from spelter of Missouri.[22] It is said that 12,000 pounds of spelter contained "a few grams of gallium," and that 8 grams of gallium were obtained from 100 pounds of zinc oxide, the source of which is not stated. The quantity of indium in the Missouri spelter appears to be less than one-tenth of that of the gallium. A little germanium occurs with the gallium in the zinc oxide. Thallium is widespread in small amounts in iron pyrites and other minerals, which, as Moissan says,[23] is doubtless the cause of its presence in many industrial products.

It is somewhat difficult to determine the order of abundance of these three elements, as the difference between them does not appear to be great. Vogt[24] places them in the order

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[15] Vogt, J. H. L., Platingehalt in norwegischem Nickelerz: Zeitschr. prakt. Geologie, 1902, p. 258.

[16] Duparc, Louis, and Tikonowich, M. N., op. cit., p. 210.

[17] Lindgren, Waldemar, op. cit., p. 493.

[18] Beyschlag, F., Vogt, J. H. L., and Krusch, P., op. cit., p. 151.

[19] See references in recent volumes of Chemical Abstracts. The papers by Vernadsky are in the Russian language.

[20] Hartley, W. N., and Ramage, H., The wide dissemination of some of the rarer elements and the mode of their association in common ores and minerals: Chem. Soc. London Jour., vol. 71, p. 533, 1897.

[21] Ramage, H., Gallium, its wide distribution, etc.: Chem. News, vol. 13, p. 280, 1913.

[22] Hillebrand, W. F., and Scherrer, J. A., Recovery of gallium from spelter in the United States: Jour. Ind. Eng. Chemistry, vol. 8, p. 225, 1916. Fogg, H. C., and James, C., Extraction of gallium and germanium from zinc oxide: Am. Chem. Soc. Jour., vol. 41, p. 947, 1919.

[23] Moissan, Henri, Traité de chimie minérale, vol. 4, p. 910, 1905.

[24] Vogt, J. H. L., Platingehalt in norwegischem Nickelerz: Zeitschr. prakt. Geologie, 1902, p. 325.

thallium, indium, gallium; Beyschlag[25] states that a blende rich in indium gave the ratio In : Zn :: 1 : 1,000, and that two other blendes, rich in gallium, gave the ratio Ga : Zn :: 1 : 30,000. In the Missouri zinc mentioned above the content of indium is much less than that of gallium. Thallium appears to be less abundant than the other two. We tentatively place them in the order indium, gallium, thallium, but with the same decimal place or exponent.

Germanium is undoubtedly less widely diffused and less abundant than any of the preceding elements. It forms an essential constituent of only two very rare minerals, but is present in very small amount in many zinc blendes.[26] It is known to occur in notable amount in only two districts, Bolivia and Saxony. Urbain, who studied its distribution, obtained 5 grams of the metal from 550 kilograms of Mexican blende.[27] It is stated that the germanium produced at the Freiberg mine amounts to about 30 kilograms, which was extracted from 325 kilograms of argyrodite.[28] We have tentatively assigned to germanium a position in the table below thallium, with one more decimal place.

The position of radium has been briefly mentioned above (p. 24) in discussing the positions of uranium and thorium. It seems to be clear that the radioactive determinations of the amounts of radium in many igneous rocks establish its average amount as $n \times 10^{-12}$ gram per gram of rock, "n" being probably about 2.5. This places it at the end of the second part of Table 11. According to Moore and Kithill[29] the total production of radium from uranium ores (either extracted or present in the ores) in 1912 was, in the United States about 6.6 grams, and in Austria and other countries about 3 grams, making a total actual or potential production of about 10 grams of radium in 1912.

It may be of interest to quote the figures expressing approximately the relative abundance of the various elements arrived a by Beyschlag, Vogt, and Krusch.[30] They are:

500 oxygen:1 sulphur; 10,000–100,000 sulphur:1 selenium; 500 sodium:480 potassium; 1 lithium:½ rubidium; 5 chlorine:1 fluorine; 2 chlorine:1 fluorine, in the solid crust; 150 chlorine:1 bromine; $\frac{1}{10}$ iodine: 400 calcium; 1 barium:⅓ strontium; 500 magnesium:1 glucinum [beryllium]; 1,000 aluminum:1 barium; 10,000 aluminum:1 cerium, 1 yttrium; 65 silicon:1 titanium; 25 titanium:1 zirconium; 25,000 silicon:1 tin; 60 iron:1 manganese; 300 iron:1 chromium; 500 iron:1 nickel; 10–15 nickel:1cobalt; 500–2,000 lead or copper:1 silver; 25–100 silver:1 gold; 500–1,000 zinc:1 cadmium.

One very striking fact appears on a survey of the two parts of Table 11, namely, the very sharp division into abundant and common petrogenic elements and rare metallogenic elements. From oxygen down to and including rubidium the elements listed in the order of their abundance are petrogenic, with the three exceptions of copper, zinc, and lead, the iron-cobalt-nickel triad being considered petrogenic. On the other hand, from arsenic down to the end of the list the elements are metallogenic, again with three exceptions, caesium, scandium, and radium, the platinum metals being considered metallogenic. This is in striking confirmation of our division of the periodic table of the elements into the two groups shown on page 76.

The exceptions of copper, zinc, lead, and radium seem to be real, as their positions in the table are based on data of such character that they can not be far wrong. It may be that future investigation and further knowledge may prove the exceptional positions of caesium and scandium to be incorrect, and that they really should be placed farther up, among the other petrogenic elements. If we leave these few exceptions aside this sharp division of the table justifies confidence in the belief that there is some fundamental difference between the two groups of elements.

AVERAGE COMPOSITION OF SEDIMENTARY ROCKS.

We have some good material to show the composition of the sedimentary rocks, but it is not comparable in quantity with that from which we have computed the composition of the igneous rocks. The sedimentary rocks represent, however, material that was originally igneous but that has been differentiated

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[25] Beyschlag, F., Vogt, J. H. L., and Krusch, P., op. cit., p. 163.

[26] Urbain, Georges, L'analyse spectrographique de la blende: Compt. Rend., vol. 149, p. 602, 1909. Buchanan, G. H., The occurrence of germanium in zinc materials: Jour. Ind. Eng. Chem., vol. 8, p. 585, 1916.

[27] Urbain, G., Blondel, M., and Obiedof; L'extraction de germanium des blendes: Compt. Rend., vol. 150, p. 1758, 1910.

[28] Moissan, Henri, Traité de chimie minérale, vol. 2, p. 560, 1905.

[29] Moore, R. B., and Kithill, K. L., A preliminary report on uranium, radium, and vanadium: U. S. Bur. Mines Bull. 70, p. 56, 1913.

[30] Beyschlag, F., Vogt, J. H. L., and Krusch, P., op. cit., p. 157.

into many forms by natural processes. From this material salts have been leached into the ocean, and to it oxygen, water, and carbon dioxide have been added, mainly from the atmosphere. Corrections can be made for these changes, but their effect is very small.

For the present purposes sedimentary rocks may be divided into shale, sandstone, and limestone. Few analyses of shale and sandstone are available, and the method of averaging adopted for the igneous rocks is not applicable to the sedimentary rocks. A different procedure has therefore been adopted—that of analyzing composite samples made up of many specimens. Average mixtures of a large number of parts of representative samples of shale, sandstone, and limestone were prepared, and an analysis was made of each mixture.[31] The results appear in the following table, in which the original figures are recalculated to 100 per cent.

TABLE 12.—*Average composition of sedimentary rocks.*

	1	2	3	4	5
SiO_2	58.11	78.31	5.19	58.53	62.20
Al_2O_3	15.40	4.76	.81	13.07	14.38
Fe_2O_3	4.02	1.08	.54	3.37	3.73
FeO	2.45	.30		2.00	2.24
MgO	2.44	1.16	7.89	2.51	2.85
CaO	3.10	5.50	42.57	5.44	6.33
Na_2O	1.30	.45	.05	1.10	1.22
K_2O	3.24	1.32	.33	2.81	3.07
H_2O+	3.66	[a] 1.32	[a] .56	3.16	3.47
H_2O-	1.33	.31	.21	1.12	....
CO_2	2.63	5.04	41.54	4.94	5.78
TiO_2	.65	.25	.06	.56	.62
P_2O_5	.17	.08	.04	.15	.15
SO_3	.65	.07	.05	.54	.58
S	....	....	.09	....	....
Cl	....	Trace.	.02	Trace.	....
BaO	.05	.05	.00	.05	....
SrO	.00	.00	.00	None.	....
MnO	Trace.	Trace.	.05	Trace.	....
Li_2O	Trace.	Trace.	Trace.	Trace.	....
C (organic)	.80	....	....	.65	.72
	100.00	100.00	100.00	100.00	107.34

[a] Includes organic matter.

1. Composite analysis of 78 shales.
2. Composite analysis of 253 sandstones.
3. Composite analysis of 345 limestones.
4. Average composition of sedimentary rocks. (Clarke and Washington.)
5. Average composition of sedimentary rocks, Leith, C. K., and Mead, W. J., Metamorphic geology, a text book, Table 13, p. 80, New York, 1915. No explanation is given of the high total.

In column 4 is given the average composition of all sedimentary rocks, based on the figures in the three preceding columns, the classes of sedimentary rocks having been weighted as follows: Shale 80 per cent, sandstone 15 per cent, limestone 5 per cent. The average sedimentary rock shows some resemblances to, as well as some significant differences from, the average igneous rock as given in Table 10. In the average for sedimentary rocks, silica, ferric oxide, lime, and potash are about the same as in the average for igneous rocks; alumina, ferrous oxide, magnesia and soda are notably less; and water (combined and hygroscopic) and carbon dioxide are much more. Titanium and phosphoric oxides are less in the sedimentary rocks, while the amount of sulphur has increased.

The results of our calculations as to the changes brought about by weathering and other processes in the production of sedimentary rocks from igneous rocks differ in some respects from those of Leith and Mead,[32] yet the two are in accord as to the most salient changes, at least in direction. In both comparisons ferric oxide has increased and ferrous oxide has decreased in the sedimentary rocks; there is little change in silica, alumina, and potash; soda has greatly decreased in both; magnesia has decreased and lime increased. The decrease in magnesia and especially in soda may be attributed to solution and the consequent presence of salts of sodium and magnesium in the oceanic waters. Leith and Mead attribute the retention of lime, one of the most soluble constituents, to "inaccuracies in the average analyses employed;" it seems, however, more reasonable to attribute it to the redeposition of dissolved lime as limestone through organic agencies, especially animal agencies. The retention of potash seems to be rightly attributed to its entry into relatively stable hydrated minerals, such as sericite, and to the ready retention of potassium salts by clays and other colloids, a feature that is in marked contrast with the behavior of sodium salts. The great increase in the percentages of water and carbon dioxide in the sedimentary rocks shown by both comparisons is readily

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[31] The mixtures were made under the direction of G. K. Gilbert, and the samples were analyzed by H. N. Stokes. See Clarke, F. W., Analyses of rocks and minerals from the laboratory of the United States Geological Survey, 1880-1914: U. S. Geol. Survey Bull. 591, p. 23, 1915.

[32] Leith, C. K., and Mead, W. J., Metamorphic geology, a textbook. pp. 79-88 and Table 13, New York, 1915. Their relative amounts of shale, sandstone, and limestone differ somewhat from ours.

understandable, as hydration and carbonation are the principal processes in the production of sedimentary rocks from igneous rocks.

AVERAGE COMPOSITION OF THE LITHOSPHERE.

In attempting to compare these analyses with those showing the average composition of the igneous rocks we must remember that they do not represent well-defined varieties of rock, but mixtures that shade into one another. Most limestones contain some clay and sand; most shales contain some calcium carbonate. Furthermore, the samples analyzed do not include all the products of the decomposition of the original rock, and they do not represent the great masses of sediment on the floor of the ocean; nor do they contain the salts and the other materials that have been dissolved and removed from the rocks.

Partly on these accounts and partly because the sedimentary rocks contain water and carbon dioxide, which have been added to the original igneous material, the composite analyses can not be so recombined as to show exactly the composition of the original rock. To do this it would be necessary to allow for the oceanic salts, which represent, in part at least, losses from the land. That factor in the problem, however, is perhaps the least embarrassing, for its magnitude can easily be estimated, and the estimate gives a measure of the extent to which the igneous rocks have been decomposed.

If all the sodium in the ocean was leached from the primitive rocks and if the average composition of those rocks as stated is correct, the quantity of sodium in the hydrosphere—the ocean—is very nearly one-thirtieth of that in the 10-mile lithosphere. That is, a shell of igneous rock one-third of a mile thick, completely enveloping the globe, would yield on complete decomposition all the sodium now in the ocean. Some sodium, however, is retained in the sediments, and the analyses show that it is about one-third of the total original amount in the igneous rocks from which the sediments were derived. That is, the oceanic sodium represents two-thirds of that produced by the decomposition of the rocks, and the estimate must accordingly be increased one-half. Therefore, a rock shell half a mile thick, completely enveloping the globe, would yield slightly more sodium than that in the sea and the sediments.

In order to make this estimate more precise let us consider the data upon which it is based. The maximum allowance for sodium in the ocean is 1.14 per cent, as shown by Dittmar's analyses made for the *Challenger* expedition. The maximum is taken rather than the average, in order to allow for the beds of salt in the earth's crust. This maximum is fully adequate, for if all the saline matter of the ocean could be collected into one solid block its volume would be more than 4,800,000 cubic miles, enough to cover the entire United States to a depth of about 1.6 miles. In comparison with a quantity so great in a calculation such as ours the known beds of salt in the crust of the earth become negligible.

The quantity of sodium in the igneous rocks, as shown in our final average, amounts to 2.85 per cent. Now, assuming that the hydrosphere—the ocean—represents 6.9 per cent and the lithosphere 93.1 per cent of the 10-mile crust, we find that the ratio between oceanic sodium and rock sodium is about 1:35. Hence, the sodium in the ocean is equivalent to that contained in one thirty-fifth of all the igneous rocks of the earth's crust to a depth of 10 miles, or to 46,500,000 cubic miles of the average igneous rock.

The amount of sodium left in the sedimentary rocks can be determined from their composite analyses. This sodium is found chiefly but not entirely in the shales, and it amounts to less than 1 per cent of the rocks—probably about 0.90 per cent. This percentage is about 32 per cent of the total sodium in the igneous rocks, so that the oceanic sodium, which represents the quantity removed from the rocks by leaching, amounts to 68 per cent of the total sodium originally in the rocks. From this percentage and the equivalent volume of igneous rock given above we may derive the following ratio: 68:100: :46,500,000:68,400,000. That is, 68,400,000 cubic miles of igneous rock has undergone decomposition to yield the sodium in the ocean and that in the sedimentary rocks. An allowance of 10 per cent, which is perhaps excessive, may be made for the increase in the volume of the sedimentary rocks by oxidation, carbonation, and absorption of water. This allowance will raise the volume assignable to the sedimentary rocks to 75,200,000 cubic miles. Assuming a thickness of 10 miles of rock below sea level and including all elevations on the continents, we may say that the volume of the lithosphere is 1,633,000,000 cubic miles. Of this volume, then, a little less than 5 per cent represents the sedimentary rocks.

The figures thus given differ considerably from those found in earlier estimates.[33] The difference is due entirely to the higher percentage of sodium as given in our final average for the composition of the igneous rocks. That increase, from 2.50 to 2.85 per cent, lowers the amount of rock needed to supply the sodium of the ocean and so reduces the thickness assigned to the sedimentary beds. It is conceivable that other changes in the fundamental data may modify our conclusions. If the ocean contained primitive sodium, not derived from the rocks, the half-mile thickness must be regarded as a maximum. If the primeval rocks were richer in sodium than those of to-day a smaller mass of them would suffice to account for the salt in the sea; if they were poorer more would be needed. Of these two possibilities the former is the more likely, but neither need be considered. If we assume that our igneous rocks are not altogether primary, but that some of them are re-fused or metamorphosed sediments, we must conclude that they have been partly leached and have therefore lost sodium. That is, the original matter was richer in sodium, and our half-mile estimate is consequently too large.

One other uncertainty in our present calculations must not be ignored. These calculations are based upon an estimated volume for the ocean of 302,000,000 cubic miles, having an average salinity of 3.5 per cent and a specific gravity of 1.03. But other estimates of the volume are larger, one of them being as much as 327,000,000 cubic miles, an increase of about 8 per cent. This is an extremely high estimate, but any increase at all implies that a larger quantity of sodium must be considered and therefore that a larger volume of rock has been decomposed. Even with this highest estimate the thickness of a sedimentary shell enveloping the entire globe would still be less than half a mile, the figure that will be retained in our future calculations. To modify this figure to any extent would be to strain after unattainable precision. We are dealing with quantities that are not mathematically exact but that are subject to various errors. These errors, however, do not all tend in one direction; in part at least they are compensatory.

The relative proportions of the different sedimentary rocks in the half-mile shell can be estimated only approximately. Such an estimate can be best made by studying the average igneous rock and determining the way in which it can break down. A statistical examination of about 700 igneous rocks, which have been described petrographically, leads to the following rough estimate of their mean mineral composition:

Average composition of the igneous rocks.

Quartz	12. 0
Feldspars	59. 5
Pyroxene and hornblende	16. 8
Mica	3. 8
Accessory minerals	7. 9
	100. 0

The average limestone contains 76 per cent of calcium carbonate, and the composite analyses of shales and sandstones correspond to the subjoined percentages of the component minerals:

Average composition of shale and sandstone.

	Shale.	Sandstone.
Quartz [a]	22. 3	66. 8
Feldspar	30. 0	11. 5
Clay [b]	25. 0	6. 6
Limonite	5. 6	1. 8
Carbonates	5. 7	11. 1
Other minerals	11. 4	2. 2
	100. 0	100. 0

[a] The total percentage of free silica.

[b] Probably sericite in part. In that case the percentage of feldspar becomes lower.

If, now, we assume that all the igneous quartz (12 per cent) has become sandstone it will yield 18 per cent of that rock, which is evidently a maximum, for some quartz has remained in the shales. One hundred parts of the average igneous rock will form on decomposition less than 18 per cent of sandstone.

The igneous rocks contain 5.10 per cent of lime, mostly in the feldspars and pyroxene shown in the table given above. This lime would form 9.10 per cent of calcium carbonate or, reckoned as an average limestone, 10.9 per

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[33] See Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, pp. 30, 31, 1920.

cent of the crust. But at least half the lime has remained in sediments other than limestone, so that its true proportion can not reach 6 per cent, or one-third the proportion in the sandstones. The remainder of the igneous material, plus some water and minus the oceanic sodium, has formed the siliceous residues that are grouped under the vague title of shale.

Broadly, then, we may estimate that the lithosphere, within the limits of 10 miles here assumed, contains 95 per cent of igneous rock and 5 per cent of sedimentary rock. If we assign 4 per cent of the sedimentary rocks to the shales, 0.75 per cent to the sandstones, and 0.25 per cent to the limestones, we shall come as near the truth as we can with our present data. According to this estimate the sedimentary rocks should consist of 80 per cent of shale, 15 per cent of sandstone, and 5 per cent of limestone. Van Hise [34] divides the sedimentary rocks into 65 per cent shales, 30 per cent sandstones, and 5 per cent limestones. Mead,[35] by a graphic process, divides the sedimentary rocks into 80 per cent shales, 11 per cent sandstones, and 9 per cent limestones. In a later paper Mead [36] modifies this estimate somewhat.

The average composition of the lithosphere, according to the estimate here made, may be summed up as shown in the following table. The analyses used have all been recalculated to 100 per cent.

TABLE 13.—*Average composition of the lithosphere.*

	1	2	3	4	5
SiO_2	59.12	58.11	78.31	5.19	59.07
Al_2O_3	15.34	15.40	4.76	.81	15.22
Fe_2O_3	3.08	4.02	1.08	.54	3.10
FeO	3.80	2.45	.30		3.71
MgO	3.49	2.44	1.16	7.89	3.45
CaO	5.08	3.10	5.50	42.57	5.10
Na_2O	3.84	1.30	.45	.05	3.71
K_2O	3.13	3.24	1.32	.33	3.11
H_2O	1.15	4.99	1.63	.77	1.30
CO_2	.10	2.63	5.04	41.54	.35
TiO_2	1.05	.65	.25	.06	1.03
ZrO_2	.04				.04
P_2O_5	.30	.17	.08	.04	.30
Cl	.05		Trace.	.02	.05
F	.03				.03
SO_3		.65	.07	.05	
S	.05			.09	.06
$(Ce,Y)_2O_3$	.02				.02
Cr_2O_3	.06				.05
V_2O_3	.03				.03
MnO	.12	Trace.	Trace.	.05	.11
NiO	.03				.03
BaO	.05	.05	.05	.00	.05
SrO	.02	.00	.00	.00	.02
Li_2O	.01	Trace.	Trace.	Trace.	.01
Cu	.01				.01
C	.00	.80			.04
	100.00	100.00	100.00	100.00	100.00

1. Average igneous rock (95 per cent).
2. Average shale (4 per cent).
3. Average sandstone (0.75 per cent).
4. Average limestone (0.25 per cent).
5. Weighted average lithosphere (10 miles).

The final average is closely similar to that of the igneous rocks alone, differing from it only within the limits of uncertainty due to experimental errors and to the assumptions made as to the relative proportions of the sedimentary rocks.

In the preceding table the combined water of the rocks is taken into account, but so far the underground waters, which also belong to the lithosphere, have been neglected. Extravagant estimates of their quantity have been made, based upon the fact that all rocks are more or less porous.[37] Van Hise, however, contends that the pore spaces below a depth of 6 miles are probably closed by the pressure of the superincumbent strata, a probability that must be considered. He estimates the volume of the underground waters to a depth of 10,000 meters as equal to that of a sheet covering the continental areas to a depth of 69 meters or 226 feet. Fuller, whose estimate is more complete, involving a consideration of the relative quantities and average porosities of the sedimentary and igneous rocks, concludes that the volume

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[34] Van Hise, C. R., A treatise on metamorphism: U. S. Geol. Survey Mon. 47, p. 940, 1904.

[35] Mead, W. J., Redistribution of elements in the formation of sedimentary rocks: Jour. Geology, vol. 15, p. 238, 1907.

[36] Mead, W. J., The average igneous rock: Jour. Geology, vol. 22, p. 772. 1914.

[37] See Delesse, A., Recherches sur l'eau dans l'intérieur de la terre: Soc. géol. France Bull., 2d ser., vol. 19, p. 64, 1861; Dana, J. D., Manual of geology, 4th ed., p. 209, 1895; Greenlee, W. B., The amount of water in the earth's crust: Am. Geologist, vol. 18, p. 33, 1896; Keller, O., Saturation hygrométrique de l'écorce du globe: Annales des mines, 9th ser., vol. 12, p. 32, 1897; Slichter, C. S., The motions of underground waters: U. S. Geol. Survey Water-Supply Paper 67, p. 14, 1902; Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 1, p. 209, 1904; Van Hise, C. R., A treatise on metamorphism: U. S. Geol. Survey Mon. 47, p. 129, 1904. Fuller, M. L., Total amount of free water in the earth's crust: U. S. Geol. Survey Water-Supply Paper 160, p. 59, 1906; Adams, F. D., An experimental contribution to the question of the depth of the zone of flow in the earth's crust: Jour. Geology, vol. 20, p. 97, 1912. See also an address by J. F. Kemp (The ground waters: Am. Inst. Min. Eng. Trans., vol. 45, p. 3, 1914).

of subterranean water is about one one-hundredth of that of the ocean. These conclusions reached by Van Hise and others evidently require some modification, for F. D. Adams, by experiments made in the compression of granite, has shown that porosity may exist in rocks at a depth of at least as much as 11 miles. No matter what may be the depth of porosity, however, the quantity of underground water is so small relatively that it is negligible, for, if added to the volume of the hydrosphere it would not appreciably affect the final computation, as it would increase the proportion of water in known terrestrial matter by less than 0.1 per cent.

AVERAGE COMPOSITION OF THE HYDROSPHERE.

The composition of the ocean can easily be determined from data given by Dittmar.[38] The maximum salinity observed by him amounted to 37.37 grams of salts in a kilogram of water, and by taking this figure instead of a lower average we make allowance for saline masses in the solid crust of the earth, the amount of which would otherwise not be included in the final estimates. Table 14, below, shows the composition of the oceanic salts, expressed in the conventional combinations. By combining the figure given by Dittmar to show the maximum salinity of the ocean with his figures showing the average composition of the oceanic salts we get Table 15, below, showing the elements found in the water of the ocean. Sea water contains some other elements, but only in traces so minute that they need not be considered here; no one of them would reach 0.001 per cent of the grand total.

TABLE 14.—*Composition of the oceanic salts.*

$NaCl$	77.76
$MgCl_2$	10.88
$MgSO_4$	4.74
$CaSO_4$	3.60
K_2SO_4	2.46
$MgBr_2$	.22
$CaCO_3$	.34
	100.00

TABLE 15.—*Composition of the ocean.*

Oxygen	85.79
Hydrogen	10.67
Chlorine	2.07
Sodium	1.14
Magnesium	.14
Calcium	.05
Potassium	.04
Sulphur	.09
Bromine	.008
Carbon	.002
	100.00

AVERAGE COMPOSITION OF THE ATMOSPHERE.[39]

The composition of the atmosphere is practically constant, except for variations in the amount of water vapor it contains, and is almost uniform over the whole surface of the earth. This constancy, however, persists vertically, through mixture by convection, to a height of only about 11 kilometers. Above this layer (the troposphere) lies the isothermal region, the stratosphere, in which there is almost no vertical convection and the gases lie in strata determined by their molecular weights. The part of the atmosphere that lies below a height of 11 kilometers, however, constitutes about 77 per cent of the whole, and as the composition changes but little up to a height of 20 kilometers, below which lies about 95 per cent of the atmosphere, no appreciable error can be made by assuming that the composition of the atmosphere is that of its surface portion. Indeed, in comparison with the 10-mile crust the relative mass of the whole atmosphere is so small (0.03 per cent) that we may regard it as composed entirely of nitrogen, an exaggeration that allows for the traces of nitrogen found in rocks. The figures given in Table 16, below, for other elements than nitrogen and oxygen are inserted chiefly to make the table complete.

TABLE 16.—*Volumetric composition of the atmosphere.*

[Calculations made by Dr. W. J. Humphreys.]

	Per cent.	Kilograms.
Nitrogen	78.03	$38,722,986.0\times10^{11}$
Oxygen	20.99	$11,596,239.0\times10^{11}$
Argon	.94	$623,925.0\times10^{11}$
Water vapor	....	$132,600.0\times10^{11}$
Carbon dioxide	.03	$21,658.0\times10^{11}$
Hydrogen	.01	$1,291.0\times10^{11}$
Neon	.00123	471.0×10^{11}
Helium	.0004	63.0×10^{11}
Krypton	.00005	64.0×10^{11}
Xenon	.000006	11.6×10^{11}
		$51,100,000.0\times10^{11}$

AVERAGE COMPOSITION OF THE EARTH'S CRUST.

We now have the data requisite for the calculation of the average composition of the known outer part of the earth—that is, the 10-mile crust, the hydrosphere, and the atmos-

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[38] Dittmar, W., *Challenger* Rept., Physics and chemistry, vol 1, 1884.

[39] For the data given under this heading we are indebted to Dr. W. J. Humphreys, Physics of the air, 1920, and The mass of the atmosphere and of each of its more important constituents: Monthly Weather Review, vol. 49, p. 341, 1921.

phere—in terms of its constituent elements. The percentages of the masses involved are as follows:

Lithosphere	93
Hydrosphere	7
Atmosphere	0. 03

The lithosphere is assumed to be made up as follows:

Igneous rocks	95. 00
Shale	4. 00
Sandstone	0. 75
Limestone	0. 25

The results of the calculation are given in Table 17, below. This table shows also the calculated composition of a crust 20 miles thick and the composition of the hydrosphere and the atmosphere.

TABLE 17.—*Elements in the lithosphere, the hydrosphere, and the atmosphere.*

	1	2	3	4
Oxygen	49. 52	48. 08	46. 71	46. 59
Silicon	25. 75	26. 72	27. 69	27. 72
Aluminum	7. 51	7. 79	8. 07	8. 13
Iron	4. 70	4. 87	5. 05	5. 01
Calcium	3. 39	3. 52	3. 65	3. 63
Sodium	2. 64	2. 69	2. 75	2. 85
Potassium	2. 40	2. 49	2. 58	2. 60
Magnesium	1. 94	2. 01	2. 08	2. 09
Hydrogen	. 88	. 51	. 14	. 13
Titanium	. 58	. 60	. 62	. 63
Chlorine	. 188	. 101	. 045	. 048
Phosphorus	. 12	. 13	. 13	. 13
Carbon	. 087	. 091	. 094	. 032
Manganese	. 08	. 09	. 09	. 10
Sulphur	. 048	. 050	. 052	. 052
Barium	. 047	. 048	. 050	. 050
Chromium	. 033	. 034	. 035	. 037
Nitrogen	. 030	. 016	....	....
Fluorine	. 027	. 028	. 029	. 030
Zirconium	. 023	. 024	. 025	. 026
Nickel	. 018	. 018	. 019	. 020
Strontium	. 017	. 017	. 018	. 019
Vanadium	. 016	. 016	. 016	. 017
Cerium, Yttrium	. 014	. 014	. 014	. 015
Copper	. 010	. 010	. 010	. 010
Inclusive	. 032	. 033	. 033	. 034
	100. 000	100. 000	100. 000	100. 000

1. Average composition 10-mile crust, hydrosphere, and atmosphere.
2. Average composition 20-mile crust, hydrosphere, and atmosphere.
3. Average composition 10-mile crust, igneous rocks, and sedimentary rocks.
4. Average composition 10-mile crust, igneous rocks.

The average composition of the combined igneous and sedimentary rocks (in a 10-mile crust) and of the igneous rocks alone are repeated for convenience of reference. The order of statement of the constituent elements is that found in the combination of the 10-mile crust with the hydrosphere and the atmosphere. Under "Inclusive" are put all the less common elements from uranium to glucinum as listed in Table 11, page 20.

The averages in all four of the columns are much alike, but there are some marked differences and there is a gradual transition from the first to the last as the influence of the composition of the hydrosphere, and above all its water content, diminishes. It is needless to point out these and other details here; a careful comparison of the columns will make them sufficiently evident.

AVERAGE COMPOSITION OF STONY METEORITES.

Merrill was the first to attempt to determine the average composition of meteorites. In his estimate,[40] made in 1909, he used 99 analyses of stony meteorites. Farrington,[41] in 1911, published estimates of the composition of both stone and iron meteorites. He used 125 analyses of stone and 318 of iron meteorites, and combined the two to get a general average. In 1916 Merrill[42] published another estimate of the average for stony meteorites, using 53 selected analyses, among them 16 analyses made by Whitfield especially for the investigation. In computing the averages, Merrill adopted the second method already mentioned (p. 11)—that of dividing the sum of the percentages by the number of determinations; whereas Farrington used the first method—that of dividing the sum of the percentages of each constituent by the whole number of analyses considered.

Harkins[43] also has calculated the "atomic percentage" of both stone and iron meteorites, using Farrington's data and weighting the analyses of the two kinds according to the ratio of stone to iron meteorites shown by the observed falls—340 stone to 10 iron.[44] This

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[40] Merrill, G. P., The composition of stony meteorites compared with that of terrestrial igneous rocks and considered with reference to their efficacy in world-making: Am. Jour. Sci., 4th ser., vol. 27, p. 471, 1909.

[41] Farrington, O. C., Analyses of stone meteorites: Field Mus. Nat. Hist. Pub., Geol. ser., vol. 3, No. 9, pp. 211-213, 1911.

[42] Merrill, G. P., Report on researches on the chemical and mineralogical composition of meteorites, with especial reference to their minor constituents: Nat. Acad. Sci. Mem., vol. 14, Mem. 1, p. 28, 1916.

[43] Harkins, W. D., The evolution of the elements and the stability of complex atoms: Am. Chem. Soc. Jour., vol. 39, p. 864, 1917.

[44] Farrington, O. C., Meteorites, their structure, composition, and terrestrial relations, p. 4, 1915.

plan is a distinct improvement on that of averaging indiscriminately all satisfactory analyses of stone and iron meteorites, because, as both Merrill and Farrington have pointed out, iron meteorites preponderate largely among the meteorites found, chiefly because their weight, density, and metallic appearance call attention to them, whereas the meteoric stones are overlooked as ordinary rocks and are more likely to decay and disintegrate by weathering. A more just method would be to estimate, on observed falls, the average of good analyses of both stone and iron meteorites, and to weight each analysis according to the weight of the meteoric fall it represents.

Table 18 shows, in column 4, the average of the superior analyses of igneous rocks that belong to the dofemane and perfemane classes as tabulated by the junior author.[44a]

TABLE 18.—*Average analyses of stony meteorites.*

	1	2	3	4
SiO_2	38.68	38.732	39.12	37.01
Al_2O_3	2.88	2.733	2.62	7.20
Fe_2O_3	....	.835	.38	8.97
FeO	14.58	16.435	16.13	11.99
MgO	22.67	22.884	22.42	16.64
CaO	2.42	1.758	2.31	9.73
Na_2O	.87	.943	.81	1.01
K_2O	.21	.328	.20	.74
H_2O	.75	....	.20	1.19
CO_2	(?)	....	....	.17
TiO_2	.18	....	.02	3.83
ZrO_2	None.	....	....	.006
SnO_2	None.	....	.02	....
P_2O_5	.26	....	.03	.76
S	1.80	1.839	1.98	.13
Cl	.08	....	....	.08
F	(?)	....	....	.12
P	....	.109	.04	....
Cr_2O_3	.47	(*a*)	.41	....
V_2O_3	Trace.	....	....	.14
MnO	.29	.556	.18	.26
NiO	.54	....	.21	.10
BaO	None.	....	....	.05
SrO	None.	....	....	.05
Li_2O	Trace.	....	....	.01
Fe	11.98	11.536	11.46	None.
Ni	1.15	....	1.15	None.
Co	.07	1.312	.05	None.
Cu	.014	....	.02	(?)
C	.15	....	.06	None.
	100.044	100.000	99.82	100.186

[a] In Fe_2O_3. [b] Includes "Ni, Mn, Cu, Sn."

1. Merrill, G. P., Report on researches on the chemical and mineralogical composition of meteorites, with especial reference to their minor constituents: Nat. Acad. Sci. Mem., vol. 14, Mem. 1, 1916; 53 analyses.

2. Merrill, G. P., The composition of stony meteorites compared with that of terrestrial igneous rocks and considered with reference to their efficacy in world-making: Am. Jour. Sci., 4th ser., vol. 27, pp. 469–474, 1909.

3. Farrington, O. C., Analyses of stone meteorites: Field Mus. Nat. Hist., Geol. ser., vol. 3, No. 9, 1911; 125 analyses.

4. Washington, H. S., Chemical analyses of igneous rocks: U. S. Geol. Survey Prof. Paper 99, 1917. Average of dofemane and perfemane rocks; 57 analyses.

Of the three averages of stony meteorites the latest, by Merrill (in column 1 of the table), may be accepted as the best, as it is based only on analyses of good quality and the averages of the several constituents are determined by the second method. The differences between the three, however, are slight.

The average analysis of the terrestrial femic rocks shows some features that present a striking contrast to those of the stony meteorites. The presence of about 13 per cent of metallic iron and nickel in the meteorites is the most obvious one. Allowance for this would bring the percentage of silica in the stony meteorites considerably above that in the femic igneous rocks, a fact that lends weight to Farrington's suggestion that analyses of stony meteorites that are practically free from metallic iron should be used for comparison with analyses of terrestrial rocks. The much lower alumina and titanic oxide and the higher sulphur of the meteorites are also marked and significant. There seems to be comparatively little difference in the figures for phosphorus, manganese, chromium, and other elements.

ACCURACY OF THE ANALYSES.

QUESTIONS TO BE CONSIDERED.

In judging the probable accuracy of the data on which the rock averages here presented are based we should consider the analytical processes employed, the possible errors made, the probable character or trend of the errors, and the magnitude of the errors as to each constituent. As we are dealing here with averages obtained by many analyses, not by single analyses, we must consider the general influence of the analytical processes on the accuracy of the results. We must ask, for each constituent: Are the average results reasonably correct, or, keeping clearly in mind our knowledge of the analytical methods used and the possible errors made, are we to think that the averages for various constituents are

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[44a] Washington, H. S., Chemical analyses of igneous rocks: U. S. Geol. Survey Prof. Paper 99, 1917.

probably too high or too low, and if so by about what amount? In view of the complexity of these problems, the variety of methods that have been used by chemists of many nationalities, and the paucity of our knowledge as to most of the minor constituents, it is impossible to make an even approximately accurate quantitative estimate of the possible or probable departures from the truth due to analytical errors; but we can at least get an idea, more or less justified by experience, as to the trend or direction of the probable errors so far as they may affect each constituent, and we may be able to make a rough estimate of their magnitude. Some aspects and details of these problems have been discussed elsewhere.[45] These problems differ somewhat from those discussed in the papers just cited, for we are now considering the general results obtained, not the effects of possible sources of error in any particular analysis. In the following matter the phrase "minus error" denotes that the figure furnished by the analysis is lower than the truth, and "plus error" that it is higher.

PROBABLE ERRORS IN THE DETERMINATION OF THE MAJOR CONSTITUENTS.

Silica.—The analytical errors incident to the determination of silica, which is by far the most abundant constituent of igneous rocks, are of small magnitude and of relatively small importance. Though there may be a slight tendency to small minus errors, it has been found, in appraising several thousand analyses of rocks, that the determinations of silica and of lime are the ones in which the most confidence may be placed, even in analyses of inferior quality. Therefore the errors to which its determination are liable are negligible; the figures shown by the averages determined from the analyses may be regarded as closely approximating to the truth.

A general source of error that applies to many rocks is the inevitable though slight loss of dust[46] that occurs while the rock is being pulverized for analysis. If the rock is a practically homogeneous glass, an obsidian, say, or is very fine grained and aphanitic, though crystalline, as are most basalts, the dust will be all of one kind, so that the loss of any part of it will not affect the composition of the powder to be analyzed.

Minerals differ much in toughness, however, and the brittle ones yield more powder than those that are tough. The powder lost during pulverization will therefore consist in greater part of the brittle minerals than of the tough ones. The powder of medium-grained to coarse-grained or porphyritic rocks will therefore contain somewhat less of the brittle quartz, feldspar, nephelite, or leucite and somewhat more of the tough pyroxene, amphibole, and biotite than the rock itself. This error is aggravated by the fact that the more brittle minerals are of lower density than the tough ones. As a consequence, most rock analyses show slightly too low figures for silica, alumina, soda, and potash, and slightly too high figures for the iron oxides, magnesia, titanium, and possibly lime. The actual error from this source is very small, affecting no one constituent more than a few hundredths of 1 per cent, but it is a real error, though it is one to which little attention has been paid.

The analysis of the femic and subsilicic rocks involves greater complexities and difficulties than the analysis of the more silicic and feldspathic rocks, and many of the analyses of rocks of the kind first named are therefore poor. We have accordingly omitted from our data a large number of these poor analyses. Moreover, as the femic and subsilicic rocks have a greater tendency to alteration, many analyses of them may not represent the original unaltered rock. This discrimination between good and poor analyses, unfortunate but unavoidable, would seem to give figures for silica that are somewhat too high. On the other hand, however, large areas and masses of the more silicic rocks, such as the granites, are no doubt inadequately represented in the analyses, a fact that would make the figures for silica rather low. It is difficult, if not impossible, however, to determine accurately the relative effect of errors arising from these two sources, but the inadequate representation of the silicic and feldspathic rocks is probably a source of more serious error than the exclusion of the

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[45] Washington, H. S., Chemical analyses of igneous rocks: U. S. Geol. Survey Prof. Paper 99, pp. 13-21, 1917; Manual of the chemical analysis of rocks, 3d ed., pp. 120-124, 139-220, 1919.

[46] Cf. Washington, H. S., Chemical analyses of igneous rocks: U. S. Geol. Survey Prof. Paper 99, p. 12, 1917; Manual of the chemical analysis of rocks, pp. 66-67, 71, 1919; also Zaleski, Stanislaus, Ueber den Kieselsäure- und Quarzgehalt mancher Granite: Min. pet. Mitt., vol. 14, p. 350, 1895.

many poor analyses of the femic and subsilicic rocks. On the whole, therefore, it may be said that the average figures for silica should be higher than those given here by 1 per cent of the whole rock. This qualification applies especially to analyses of rocks from the continental masses. In the analyses of rocks from the oceanic islands, on the other hand, the figures given for silica are probably too high, possibly also by about 1 per cent. The result as regards the average for the whole earth would be that the percentage of silica given is somewhat too low; it should probably be about one-half of 1 per cent higher.

Alumina.—The determination of alumina is more subject to error, in both variety and magnitude, than that of any other constituent, partly because we have no simple and direct method for separating and weighing it individually, for a number of other constituents are precipitated and weighed with it. These constituents are TiO_2, ZrO_2, P_2O_5, Fe_2O_3, Cr_2O_3, V_2O_3, $(Ce, Y)_2O_3$, and a little SiO_2 and MnO, each of which is or should be determined separately, and their total weight deducted from the weight of the sample analyzed. The alumina is thus determined by difference, and any errors incident to the determination of the other constituents fall on it. Also the nondetermination of any of these constituents increases by its amount the apparent percentage of alumina, an error that may be serious in incomplete analyses, especially and most often because of the nondetermination of TiO_2 and P_2O_5. Many analyses that are otherwise good show that amounts up to as much as 5 per cent of TiO_2, or several tenths of 1 per cent of P_2O_5, have not been determined, thus raising by a corresponding amount the percentage of alumina stated. Although we have endeavored to exclude all such seriously defective analyses from our tables, it was impracticable to avoid the inclusion of some in which small amounts of TiO_2 or P_2O_5 had not been determined, so that the stated average percentages for Al_2O_3 must be regarded as a little too high. It is difficult to estimate the amount of this plus error, which is slightly counterbalanced by the probably too small representation of the granitic and granodioritic rocks just mentioned under the heading "Silica." At a venture, however, we might say that in all or nearly all the averages given here the Al_2O_3 is too high by possibly as much as 0.5 per cent of the rock.

A second serious error to which the determination of alumina is liable, especially at the hands of beginners and incompetent analysts, is that caused by the precipitation of magnesia with it. Such coprecipitation will occur unless the conditions are carefully adjusted and unless precipitation is repeated once or twice. The apparent percentage of alumina would thus be too high and that of magnesia too low by the same amount. This might be and in many inferior analyses is indeed a very serious plus error, but it is one that is likely to occur only with poor analysts. It is furthermore one that may be detected in most analyses, and it is also very likely to be connected with other serious and obvious analytical errors, such as incorrect summation. We believe that we have excluded from our data practically all analyses in which this plus error for alumina is large, so that this source of error may be neglected.

Ferric oxide.—In the determination of ferric oxide there are several sources of error, partly chemical and partly mechanical, the results of which tend to produce a slight minus error. On the other hand, there is tendency toward a minus error in the determination of ferrous oxide, and as the percentage of ferric oxide determined is dependent upon that of ferrous oxide this tendency would be likely to produce a corresponding plus error in that of ferric oxide. This error is less serious in modern analyses than in those made twenty or more years ago. It is very difficult properly to balance these two opposing tendencies, but in view of the high standard of analytical work we have fixed for our data the average error for Fe_2O_3 should not be serious. We may therefore assume that, in the averages of superior analyses we have used, analyses made by careful analysts and in which the ferrous oxide has been correctly determined, the average figures for Fe_2O_3 may be regarded as fairly reliable, including probably a minus error of, say, 0.05 to 0.10 per cent of the rock.

Ferrous oxide.—In the earlier days of rock analysis the determination of ferrous oxide was that which was most fraught with difficulty—at least of an obvious kind—because of the ready oxidizability of ferrous iron and the difficulty of decomposing the very stable, refractory compounds into which it enters in silicates without such oxidation during the process as seriously to invalidate the results of the determination. More recently, however, a very simple, rapid, and reliable method for the determination of ferrous oxide has come into use which, in the hands of careful workers, is capable of yielding very accurate results, as we have found by many years of analytical work. At the same time, however, the tendency to oxidation is still a very real danger to a careless analyst, and a number of analyses that are otherwise good and that are included among our data because of the difficulty of detecting their possible error as to FeO are open to suspicion in this respect. They are not numerous, however, nor does their inclusion seriously invalidate the final averages. As has been said above, this tendency to a minus error in FeO leads to a plus error in Fe_2O_3. Balancing up the probabilities roughly, it may be said that in the averages the probable percentage for FeO should be about 0.1 more than that given here.

Lime.—To a careful analyst the determination of lime involves little if any serious error. The nondetermination of strontia (which is weighed with lime) is negligible, as this constituent is nearly always found in practically insignificant amount. Even in otherwise inferior analyses the figures for lime and for silica are those in which we can place most confidence. In the averages, therefore, the percentages of CaO may be regarded as free from analytical error.

Magnesia.—The fact that magnesia is likely to be precipitated with alumina, except in the presence of sufficient ammonium salts, has already been mentioned as affecting not only the apparent percentage of magnesia but that of alumina. It is believed, however, that this source of error has here been eliminated by the selection of superior analyses. Apart from this possible error those incident to the determination of magnesia are few and of small magnitude, and as they tend to be either plus or minus, the figures for magnesia given in the averages are no doubt closely approximate to the truth.

Soda and potash.—With such proper care as is assumed to have been taken in making the analyses here used for soda and potash, especially as since the Lawrence Smith method is now generally employed, there is little liability to error in their determination, so that, so far as the analyses are concerned, we may consider the averages for them very trustworthy.

Water.—The old method for the determination of water by "ignition" is generally considered unreliable, for it is one that generally gives too low percentages, because of the oxidation, partial or complete, of the ferrous oxide in the rock analyzed. A method by which the water is collected and weighed, such as the simple, rapid, and accurate one devised by Penfield, is now always used in superior work. Although the method of ignition was employed in a large number of the analyses we used to obtain our averages, yet the error can not be considered serious in view of the comparative unimportance of this constituent. As a consequence of our inclusion of such earlier analyses, however, the average percentages for water given here are no doubt a trifle too low. If the water had been determined by ignition in all the analyses used and if all the ferrous oxide in each rock had been fully oxidized the maximum possible error would be about 0.4 per cent. Neither of these suppositions is true, and the water averages here given are probably too low by about 0.1 per cent of the rock.

It is unnecessary here to go into the question of the determination of "combined" and "hygroscopic" water, that is, the water which is given off above and below about 110°. This question has been discussed by Hillebrand,[47] and one of us.[48] In our averages we have considered only the "combined" water, as this is essentially that which is an integral constituent of the rock.

Titanium dioxide.—It is now well known, chiefly because of the examples set by the chemists of the United States Geological Survey in making complete rock analyses, that titanium is one of the most abundant elements of igneous rocks—the ninth in abundance. Unfortunately it was not determined in many of the older analyses and is not stated even in some of the modern ones, especially those made in Europe. As has been explained above, its nondetermination makes the apparent percentage of alumina too high by the amount of TiO_2 in the rock analyzed. In many of the older analyses the amount of TiO_2 is reported as a

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[47] Hillebrand, W. F., The analysis of silicate and carbonate rocks: U. S. Geol. Survey Bull. 700, p. 72, 1919.

[48] Washington, H. S., Manual of the chemical analysis of rocks, pp. 12, 208, 1919.

"trace," a very misleading term, because in many such analyses, especially those of the femic or less silicic rocks, we may be sure that the so-called "trace" of TiO_2 is really a very considerable percentage, as much as 1 or 2 per cent, or, in some analyses, even 4 or 5 per cent. We have excluded many such analyses from our data, but we have been obliged to include a very considerable number in which this error occurs, especially analyses of the more silicic and feldspathic rocks. Fortunately the amounts of TiO_2 in such rocks are never very large. It is, however, quite certain that the average figures for TiO_2, which have been obtained by dividing the total titanium dioxide by the number of analyses, are slightly too low. It is difficult to estimate accurately the amount of this minus error, but it probably ranges from 0.1 to 0.2 per cent of the total rock. The analytical error in the determination of titanium may be regarded as negligible.

Phosphorus pentoxide.—In dealing with phosphorus we meet the same difficulty that we met with in dealing with titanium, namely, that its nondetermination will affect the apparent percentage of alumina. Although the consequent error is very much less than that with titanium, yet it must be considered. A rough estimate would indicate that the average figures for P_2O_5 here given should be increased by at least one-tenth of their amount, or, roughly, by 0.03 per cent of the total rock. The analytical errors in the determination of phosphorus are negligible.

Manganese oxide.—The nondetermination of manganese oxide in many rock analyses, or its statement as a "trace," involves a slight minus error. This error is offset to some extent by the inclusion in our data of some earlier analyses in which the amount of MnO is undoubtedly too high because of the common and probable error incident to its gravimetric determination by the basic acetate method, in which a little alumina may be precipitated and weighed with the manganese. The average errors arising from these two sources—errors that tend in opposite directions—are not great absolutely, but may be considerable relatively. It is difficult to determine their respective magnitudes, but we may say that, on the whole, they involve an increase of the average figures for MnO by about one-tenth.

PROBABLE ERRORS IN THE DETERMINATION OF THE MINOR CONSTITUENTS.

We have been considering the 12 chemical constituents of igneous rocks that should be and are assumed to be determined in every superior analysis, so that their averages are obtained by dividing their total amounts by the number of analyses made. We have to consider now the minor constituents, which are determined in but few analyses and only in those of the highest class, especially in those made by American, British, Canadian, and Australian chemists. In analyses made to determine these constituents the methods employed are generally rather complicated, but as they deal with only small quantities the errors made, although absolutely small, may be relatively great. As Hillebrand has said, it is more important to know whether one of these minor constituents is or is not present than to know the exact percentage.

The average for each of these minor constituents has been determined by taking the mean between the quotient obtained by dividing the sum of the percentages for the constituent by the number of analyses in which it was determined and the quotient obtained by dividing the sum of the percentages by the total number of analyses made. From our general knowledge of the chemistry of igneous rocks, however, and from the tendency of certain elements to be associated with others or with rock magmas of certain kinds, we may form a fairly correct idea of the direction if not of the magnitude of the corrections that should be applied to the average figures that we derived from the imperfect data at our command.

Zirconia.—The oxide of zirconium occurs as a constituent of silicate minerals in igneous rocks much more frequently than is generally thought, and it is not determined as often as it should be. It is found chiefly in the more sodic rocks, such as nephelite syenite, phonolite, and tinguaite, but it occurs also as zircon in many granites. Furthermore, the older methods for its determination are likely to yield percentages that are too low. On the other hand, the rocks in which zirconia is most abundant are comparatively rare. Balancing the several considerations, we may say that the average figures for zirconia are undoubtedly slightly low and that they should be increased by probably one-fifth of the amount here stated. As this amount is small, however, only about 0.04 per cent of the rock, the difference is not very great, nor does it affect seriously the average figure for the much more abundant alumina, which is changed in a plus direction by the nondetermination of zirconia.

Rare earths.—Ceria and the other rare earths are determined in rock analyses even less often than zirconia, yet we know, from the occurrence of minerals containing them, such as allanite and monazite, that ceria, lanthana, and yttria occur in many rocks, especially the more sodic rocks, in small but readily determinable amounts. Indeed, several analyses show quantities of ceria and yttria amounting to 0.10 to 0.60 per cent. We have therefore good reason to believe that the igneous rocks may contain greater quantities of the rare earths than those indicated by the few determinations now available.

Sulphur.—Although sulphur occurs in igneous rocks both as sulphate and sulphide, it is not generally determined; yet it is determined more frequently than zirconia and other minor constituents. The sulphide sulphur is often stated as SO_3. The average figures for sulphur are no doubt fairly correct, although they are a trifle low, for we know that sulphur and its oxides are among the most common constituents of volcanic emanations.

Chlorine.—Hydrogen chloride, like sulphur, is one of the most common constituents of volcanic gases, and chlorine is found in some igneous rocks, although it is not determined as often as it should be. The average figures for chlorine are probably too low, although this deficiency is in part counterbalanced by its presence in rocks which have been collected near the sea and which have derived it from sea water. Chlorine is also found in a few silicates, such as the scapolites and sodalite.

Fluorine.—The analytical determination of fluorine, especially in the extremely small amounts in which it occurs in igneous rocks, is difficult, and the results are not very accurate. The fluorine found is in large part a constituent of the almost ever-present apatite, although it occurs in small amounts in other minerals, especially in the micas and hornblendes. A fair estimate of the amount of fluorine in a rock, or at least an estimate showing its minimum amount, may be made by considering the amount of phosphoric oxide found, for most of the apatite in igneous rocks is fluorapatite. The average fluorine should be about one-tenth that of the phosphoric oxide. Although this percentage is somewhat higher than that found in normal apatite, the slight excess will cover the small amount of fluorine in the other minerals just mentioned. The percentage of fluorine shown in the averages is therefore almost certainly too high—perhaps double its correct amount. It has been corrected in the final average for the earth.

Chromium sesquioxide.—Many igneous rocks, especially the more magnesic and less silicic rocks, contain a small amount of chromium, but it is seldom determined. For these small amounts the colorimetric method gives very accurate results, more so than gravimetric methods. As chromium is most abundant in the peridotites and other olivine-bearing rocks, which are especially liable to alteration to serpentine, etc., many analyses of such rocks are not represented among our data. The average figures for it are no doubt too low; they should be increased possibly by 50 or 100 per cent.

Vanadium sesquioxide.—The determination of vanadium, because of analytical difficulties and the very small amounts dealt with, is attempted less often than that of chromium, although Hillebrand and others have shown that it is common in very small amounts in the more femic igneous rocks. It has recently been reported as present in quantities amounting to several hundredths of 1 per cent in a series of basalts from the Arctic.[49] On the other hand, it seems to be absent from the more silicic and feldspathic rocks.

Nickel oxide.—Nickel, like chromium and vanadium, occurs most commonly in the more femic rocks, especially those high in iron, but its determination is complex and is seldom attempted. It has been reported, in quantities amounting to a few hundredths of 1 per cent in a number of rocks from Western States that were analyzed many years ago by a chemist then connected with the Geological Survey, but his reported "nickel" was probably platinum derived from the basins and crucibles used in the analyses. Nickel is no doubt widely distributed among femic igneous rocks, but it has not been determined as frequently as it should be; yet because of the errors made in its rela-

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[49] Holmes, Arthur, The basaltic rocks of the Arctic region: Mineralog. Mag., vol. 18, p. 180, 1918.

tively numerous determinations the average figure deduced by us from the data at hand is probably too high.

Baria.[50]—Barium is regularly determined in analyses of igneous rocks only by the chemists of the United States, Canada, and Australia, by Harrison in British Guiana, and (in recent years) by chemists in England. Its distribution is undoubtedly much wider than that indicated by its nondetermination in analyses made by the chemists of other countries. The average figure for baria is doubtless fairly correct, as its determination involves no serious sources of error.

Strontia.—Strontia is less often determined than baria, being rarely recorded except in the analyses made by the chemists of the countries just mentioned. The few determinations made indicate that it, like several other minor constituents, is more widely diffused than is generally supposed. The average given by us is probably nearly correct.

Lithia.—Although the spectroscope and mineral occurrences show that lithia is widely distributed in igneous rocks, particularly in the more alkalic and especially sodic varieties, it occurs in amounts so small, and the analytical difficulties in its determination are so great, that it is seldom recorded in analyses except as a "trace," determined with the spectroscope. The amount stated in our average may be slightly too high, although the absolute percentage is so small that the difference is insignificant.

Copper.—Small amounts of copper occur in igneous rocks, especially the more femic ones, but some of the figures reported for it, like those reported for nickel, are due to copper taken up in the course of analysis or to platinum derived from the utensils employed. All things considered, the figure for copper given in our tables of average composition is no doubt approximately correct.

GEOGRAPHIC RÉSUMÉ AND CHARACTERIZATION OF THE DATA.

ORDER OF PRESENTATION.

To understand the value of the data from which the averages for the areas here considered have been calculated, and especially to determine the extent to which the averages are really representative, we shall state briefly the degree to which the analytical data represent the whole complex of igneous rocks of the areas whose averages have been calculated. We shall not consider here generally the quality of the analyses; we have already said that we have used in our computations only good or excellent, fairly complete analyses ("superior" analyses) of unaltered rocks.

Most of the smaller regions or areas for which averages are here given are political divisions whose limits are determined by State or national lines rather than truly comagmatic regions, determined by the cognate petrologic character of their rocks.

We shall here take up each area for which the average has been calculated, indicate the prominent chemical features of the average, and show briefly how far the average is determined or affected by some special attention that may have been paid by petrologists to certain parts of it and the consequently greater number of analyses of rocks from those parts. We may thus determine the degree to which each region—large or small—is represented by its analyses and their average and shall discover which areas may be regarded as well known and which may especially require further study.

The continental and oceanic divisions will be considered in the following order: North America, South America, Europe, Africa, the Atlantic Islands, Asia, Australasia, the Pacific Islands, and the Antarctic Continent and islands. Within each of these major areas we shall consider first the averages for the smaller areal units, next the averages for the continent or oceanic basin to which the smaller units belong, and finally the average for the whole earth. Most of the smaller areas will be considered in the order in which the junior author has already considered them elsewhere.[51]

The authorities cited will include only authors who have published many analyses for a given area or those who have made notable studies of certain districts.

NORTH AMERICA.

The average for North America is derived from 1,709 analyses, which represent rocks distributed as shown below.

Greenland.—The average for Greenland, which includes Ellesmere Land, is character-

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[50] The name baria is here used for BaO, instead of baryta, the usual name, because it is analogous to the names of other oxides, such as ceria, strontia, thoria, and zirconia.

[51] Washington, H. S., Chemical analyses of igneous rocks: U. S. Geol. Survey Prof. Paper 99, p. 29, 1917.

ized chemically by rather low silica but especially by high iron oxides, very high soda, high zirconia and titanic oxide, and low magnesia and lime. The total soda and alkalies are the maxima among all the averages. The relations of silica and the alkalies are clearly shown by the presence in the norm of about 4 per cent of nephelite, a noteworthy amount, as only two other areal averages show normative nephelite and both show less than the average for Greenland. Nearly all the others show normative quartz—that is, an excess of silica.

Average and norm for rocks of Greenland (41 analyses).

Average.		Norm.	
SiO_2	57.14	Or	19.46
Al_2O_3	15.48	Ab	51.35
Fe_2O_3	3.93	An	1.11
FeO	4.73	Ne	4.26
MgO	1.54	Di	12.80
CaO	3.51	Ol	.66
Na_2O	6.99	Mt	5.57
K_2O	3.25	Il	2.89
H_2O	1.12	Ap	.34
TiO_2	1.49		
ZrO_2	.12	Symbol, II.5.1.4.	
P_2O_5	.19		
MnO	.21		
Inclusive	.30		
	100.00		

Greenland and Ellesmere Land are covered almost entirely with ice, so that their igneous rocks are accessible only along the narrow coastal zone. Few of the specimens of igneous rocks brought back by Arctic explorers have been studied petrographically or analysed.

The district of Julianehaab, in the extreme southwest corner of Greenland, is the best known and has been fully described by Ussing, who gives 29 excellent analyses, almost three-fourths of the whole number available for the Greenland average. This small district has therefore a decidedly preponderating influence on the character of the average; and as most of the rocks of Julianehaab are very high in soda, iron and titanic oxides, and zirconia and are low in silica, magnesia, and lime, the peculiarities of the average for Greenland must be attributed in great part to them.

Ordinary granitic, dioritic, and basaltic rocks, of which we have only a few analyses, occur farther north, on both the east and west coasts of Greenland and on Ellesmere Land, and it would seem, from the scanty information available, that such rocks are common in Greenland. There are especially several large areas of plateau basalts, some of which contain native iron. On the other hand, we have evidence, such as that afforded by the cryolite deposits of Ivigtut and the sodic hornblende kaersutite on the Nugsuaks Peninsula, that highly sodic rocks occur along the west coast elsewhere than at Julianehaab. So small a proportion of the igneous rocks of Greenland are accessible, and they have been so little studied, that our present knowledge of the character of the whole is largely conjectural.

The average for Greenland, then, is probably too high in soda, iron and titanic oxides, and zirconia and too low in magnesia and lime and possibly in silica, but it doubtless shows the general tendency of the average for the area as contrasted with most of the other averages.

East Canada. — The area here called East Canada includes Ontario, Quebec, New Brunswick, Nova Scotia, Newfoundland, and Labrador. The average is very low in silica, the averages for only the Atlantic and Pacific Islands showing lower percentages of this constituent and that for the Antarctic Continent being but slightly more. Soda is rather high, but not sufficiently so to yield nephelite in the norm, in spite of the low silicity. Alumina is somewhat above the average. An interesting minor feature is presented by the very high figures for chlorine (0.20), sulphur (0.16), nickel oxide (0.13), baria (0.06), and strontia (0.03), among the minor constituents.

Average and norm for rocks of East Canada (99 analyses.)

Average.		Norm.	
SiO_2	52.74	Or	16.12
Al_2O_3	16.40	Ab	41.39
Fe_2O_3	4.59	An	14.73
FeO	5.84	Di	7.82
MgO	3.27	Hy	3.99
CaO	5.30	Ol	2.81
Na_2O	4.89	Mt	6.73
K_2O	2.65	Il	4.26
H_2O	1.09	Ap	.67
TiO_2	2.20		
P_2O_5	.21	Symbol, II.5.2″.4.	
MnO	.17		
Inclusive	.65		
	100.00		

The chief areas that should go to make up this average are the following: The areas of anorthosite in Labrador, Newfoundland, Chibougamau, Saguenay, Morin, and elsewhere; the areas of granite and gneiss, with diabase dikes, in the vast expanse in the north around Hudson Bay and in New Brunswick and Nova Scotia; small areas of dominantly sodic rocks in Quebec, as at Montreal and in the Monteregian Hills; areas of alkalic (generally sodic) rocks, some of them corundum-bearing, in Ontario, as in the Haliburton-Bancroft district; the norite-granite area of Sudbury; and areas composed chiefly of diabase, as at Rainy Lake and Cobalt, which, with Sudbury, might be included in the Algonkian area. There are some others, but we have either few or no analyses of their rocks, and for the present they must be disregarded.

Of the general areas enumerated, that of the granitic rocks around Hudson Bay is by far the largest; but these rocks are almost unstudied and are wholly unrepresented by analyses. There are but few analyses of the rocks of the Maritime Provinces, Newfoundland, or Labrador, and these are not very satisfactory. The areas of anorthosite would probably come next in extent to those of granite, but analyses of anorthosite are woefully few. The Sudbury, Cobalt, and Rainy Lake areas are much better known through a very considerable number of good analyses; the alkalic areas in Quebec and Ontario are best represented by the largest number of analyses. The average is influenced most by the Monteregian Hills and the Haliburton-Bancroft district; and Sudbury, Rainy Lake, and Cobalt, together, are of almost equal weight with them, the scattering analyses of the other localities being almost negligible. The areally most abundant granitic and anorthosite masses are almost unrepresented. The present average is probably rather too low in silica and lime and too high in soda. In view of the vast extent of petrographically unknown country in the north the state of our knowledge of the chemistry of the igneous rocks of East Canada can not be regarded as satisfactory.

Alaska.—The Yukon should be included with Alaska, but we have no analyses of its rocks; yet they would presumably resemble those of the adjacent United States territory. The average for Alaska is characterized chiefly by its high silica and rather low alkalies, by soda dominant over potash, and relatively high lime. As is seen from the norm the average falls almost in persalane and the high lime makes it alkalicalcic. In general it much resembles the averages for the California and New Mexico-Arizona areas. There is 0.04 per cent of baria.

Average and norm for rocks of Alaska (24 analyses.)

Average.		Norm.	
SiO_2	63.31	Q	16.98
Al_2O_3	16.13	Or	16.68
Fe_2O_3	2.18	Ab	32.49
FeO	2.46	An	18.35
MgO	2.25	Di	4.64
CaO	5.05	Hy	4.86
Na_2O	3.85	Mt	3.25
K_2O	2.82	Il	1.52
H_2O	.78	Ap	.34
TiO_2	.77		
P_2O_5	.18		
MnO	.10		
Inclusive	.12		
	100.00		

Symbol, (I)II.4″.″3.″4.

There are not many analyses of Alaskan rocks, and most of those analyzed are volcanic lavas, chiefly rhyolites and andesites—very few plutonic rocks. No analyses of such femic rocks as the basalt or diabase of Alaska have been published, but the average is doubtless closely approximate to the truth.

British Columbia.—The area of British Columbia that has been studied from the data available covers only the southern part of the Province, including Vancouver Island. The northern half, toward the Yukon, is almost unknown chemically. Analyses of rocks from southern Alberta are included. For petrologic and comagmatic reasons the area might be separated into an eastern and a western division, but this is scarcely practicable at present.

The average presents no specially peculiar features; it resembles rather closely the averages for Washington-Oregon and the United States, as well as that for the North American areas, which are normal. The ratio of potash to soda is closer to unity in British Columbia than in the Washington-Oregon average. The very high figures for baria (0.11) and strontia (0.06) should be noted, as they are exceptional and are surpassed only by those for the Montana area.

Average and norm for rocks of British Columbia (60 analyses).

Average.		Norm.	
SiO_2	58.34	Q	7.44
Al_2O_3	15.79	Or	18.90
Fe_2O_3	2.21	Ab	29.34
FeO	3.99	An	18.07
MgO	4.57	Di	6.48
CaO	5.66	Hy	12.90
Na_2O	3.54	Mt	3.25
K_2O	3.18	Il	1.37
H_2O	1.14	Ap	.67
TiO_2	.69		
P_2O_5	.33		
MnO	.14		
BaO	.11		
Inclusive	.31		
	100.00		

Symbol, II. (4)5.″3.3 (4).

The average for British Columbia is made up of a large number of analyses of rocks that occur along the international boundary, described by Daly; analyses of rocks from Vancouver Island; and a rather large number of analyses of rocks from scattered mining districts. The analyses are good, are numerous for the extent of territory covered, and are fairly well distributed, so that the average for southern British Columbia may be considered as representative of the area. Study of the analyses in connection with the distribution of the rocks and their relations to those of the areas immediately to the south points to the conclusion that there are two or parts of two comagmatic regions in southern British Columbia, one at the southwest, which closely resembles the Washington-Oregon area to the south, and the other at the southeast, which is very like the Montana area.

Canada.—The average for Canada here given includes the average for Alaska and the averages for East Canada and British Columbia. Its only noteworthy difference from the Canadian average given in Table 3 is that this average, which includes Alaska, has about 1 per cent more silica. The average resembles that for East Canada, except that the silica is about 3 per cent higher and the iron oxides and the alkalies are a little lower.

Average and norm for rocks of Canada (188 analyses).

Average.		Norm.	
SiO_2	56.29	Q	3.06
Al_2O_3	16.67	Or	17.79
Fe_2O_3	3.31	Ab	37.20
FeO	4.65	An	16.96
MgO	3.39	Di	6.96
CaO	5.34	Hy	9.10
Na_2O	4.40	Mt	4.87
K_2O	3.00	Il	2.43
H_2O	1.08	Ap	.34
TiO_2	1.25		
P_2O_5	.19		
MnO	.13		
BaO	.04		
Inclusive	.26		
	100.00		

Symbol, II.5.2(3).4.

The analyses of rocks from Alaska are so small in number that their influence is almost unegligible, although they do raise the percentage of silica a trifle. The large number of analyses of rocks from East Canada gives that area a somewhat greater influence than British Columbia; as between the two the average represents more nearly East Canada. Because of our ignorance of the vast expanse of country north of the areas whose rocks are known, the average is not representative of the northern half of North America and is of little significance as a whole, although the averages of its component areas are of considerable interest.

New England-New York.—The average for the New England-New York area is almost a duplicate of that for the whole United States, and it resembles also closely that of the earth, although the average of the small area is slightly higher in silica. The average therefore presents no features that call for comment except that, in contrast with some other areas, the very small amount of baria (0.01) may be noted.

Average and norm for rocks of New England-New York (213 analyses).

Average.		Norm.	
SiO_2	61.41	Q	11.10
Al_2O_3	15.20	Or	19.46
Fe_2O_3	2.47	Ab	33.54
FeO	4.21	An	13.90
MgO	3.01	Di	6.09
CaO	4.46	Hy	8.90
Na_2O	3.94	Mt	3.48
K_2O	3.30	Il	1.67
H_2O	.74	Ap	.34
TiO_2	.91		
P_2O_5	.11		
MnO	.09		
Inclusive	.15		
	100.00		

Symbol, II.4(5).2″.(3)4.

The average of the New England-New York area is made up chiefly of analyses of rocks from four petrologically distinct districts—extensive areas of granitic rocks; the Triassic trap areas; several small, sporadic areas of decidedly alkalic (sodic) rocks in Maine, New Hampshire, and Massachusetts; the granosyenite-anorthosite area of the Adirondacks. There are other smaller areas, some of them of rocks of much petrologic interest, such as the cortlandtite areas of New York and Connecticut, the cumberlandite area in Rhode Island, and many peculiar scattered dikes, but few analyses of these rocks are available.

The total extent of the granitic areas is unquestionably the largest, and these are represented by the largest number of analyses. The next area in size is that of the Triassic traps, and although there are comparatively few analyses of these, their scarcity is compensated for by some analyses of diabasic dikes that accompany the granites. The alkalic areas, although small individually, are of much petrologic importance, and their analyses are rather numerous but probably not inordinately so. The Adirondack anorthosite area is probably not so well represented quantitatively as it should be; but the cortlandtite and other such small areas are probably fairly well represented. The distribution of the analyses over the whole area is probably equitable, although the rocks of Maine have been somewhat neglected. On the whole, it is reasonable to suppose that the average given here is a close approximation to the truth.

Appalachia.—The designation Appalachia is used here for the row of States—or rather for the piedmont and mountainous parts of them—that extend along the Atlantic seaboard from Pennsylvania to Georgia, inclusive. The more northerly part of this region has been included in the New England-New York area. The Appalachian average is decidedly high in silica and, in view of this fact, is rather high in lime. It tends to be sodic rather than potassic. These features have a bearing on the composition of the waters of the area, discussed by the senior author elsewhere.[52] The average resembles that for Alaska in a general way, though it is somewhat more femic.

Average and norm for rocks of Appalachia (188 analyses).

Average.		Norm.	
SiO_2	62.98	Q	16.68
Al_2O_3	14.73	Or	17.79
Fe_2O_3	1.86	Ab	27.77
FeO	3.69	An	16.40
MgO	3.70	Di	4.91
CaO	4.69	Hy	10.77
Na_2O	3.31	Mt	2.78
K_2O	2.97	Il	1.67
H_2O	.82	Ap	.34
TiO_2	.89		
P_2O_5	.20	Symbol, II.4.''3.3(4).	
MnO	.08		
Inclusive	.08		
	100.00		

Two factors dominate the Appalachian average—the many masses of granite, which extend along the whole zone but which seem to be most abundant toward the southern end, and the areas of Triassic traps and diabase dikes, which seem to be most abundant toward the northern end of the zone. There are a few small areas of alkalic rocks in New Jersey, Virginia, and North Carolina, and Virginia has a few bodies of very unusual rocks, but the analyses that represent them have a very slight effect on the average. The analyses of the granites are by far the most numerous, especially those of the granites of Georgia, described by Watson, and of South Carolina, though there are not so many analyses of the granites of this State. These analyses are, indeed, so numerous that they must represent very well the general characters of the granites of the whole area. Analyses of the basaltic rocks, most of them of the sheets and flows of New Jersey, described by Lewis, are not so numerous as the analyses of the granites, but they are probably sufficient in number to be representative, in view of the smaller areas and lesser thickness of the sheets of femic rock. On the whole, it may be said that the Appalachian average represents the area fairly well.

Algonkian region.—The Algonkian region includes the States of Michigan, Wisconsin, and Minnesota. The average is decidedly low in silica, lower than that for any other area in either North or South America, Greenland, and East Canada. The most striking feature of the average is the very high percentage of the total iron oxides, which surpasses that of all the other averages, even of the salfemic (basaltic) averages of the Atlantic and Pacific islands. The figures for the other constituents require no special comment, though attention should be called to the high figures for chromium (0.05) and vanadium (0.06) oxides. In view of the general character of the magma the percentage of titania seems low.

Average and norm for rocks of the Algonkian region (66 analyses).

Average.		Norm.	
SiO_2	57.81	Q	11.28
Al_2O_3	15.43	Or	13.34
Fe_2O_3	4.60	Ab	30.39
FeO	5.98	An	19.18
MgO	3.52	Di	2.51
CaO	4.64	Hy	13.78
Na_2O	3.60	Mt	6.73
K_2O	2.31	Il	1.37
H_2O	.98	Ap	.34
TiO_2	.73		
P_2O_5	.08	Symbol, II.4(5).3.4.	
MnO	.16		
Inclusive	.16		
	100.00		

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[52] Clarke, F. W., The composition of the river and lake waters of the United States: U. S. Geol. Survey Prof. Paper 135, 1924.

The controlling factor in this average is the great abundance of salfemic rocks, chiefly gabbro, diabase, and basalt, which are associated with the iron ores of the region. The exceptionally high figures for iron oxides are interesting and significant. There are some granitic rocks in the area, but not many analyses of them have been made and they are not sufficiently represented. The few small areas of rather alkalic syenites are insignificant in the average.

The Algonkian region, then, as the average indicates, is composed largely of gabbro, diabase, and basalt, though the presence of considerable quartz in the norm may be somewhat unexpected. It is now becoming recognized, however, that many such salfemic rocks carry small amounts of modal quartz. The data from which the average has been computed are not wholly satisfactory. In view of the general uniformity of the rocks of the region, the comparatively small number of analyses is not a very serious fault except for the paucity of analyses of granitic rocks, but many of the rocks about Lake Superior are more or less altered, and the analyses of these were not included among those used in obtaining the average. Furthermore, a very considerable proportion of the analyses of the rocks of this region are so poor that they were rejected, even some that represented fresh rocks. The omission of these analyses has perhaps not seriously affected the average, yet if all the analyses available had been well made and represented fresh, unaltered material the true average would probably be more femic and would show less silica and more ferrous oxide, magnesia, and lime. But the change would not be great, and the average may be regarded as approximately correct.

Arkansas-Texas.—The Arkansas-Texas region contains bodies of igneous rocks in Missouri, Arkansas, Oklahoma, and Texas. No analyses of igneous rocks from Louisiana are known.

This average is rather lower in silica than the average for the United States, and it is also low in magnesia and lime. Its most striking peculiarity is the large amount of alkalies, as it shows the maximum for both total alkalies and for potash. The averages for Greenland and Finland are the only ones that approach it in total alkalies, and it surpasses in potash even the average for Italy, with its many leucitic rocks. As a consequence of these high alkalies the average is almost peralkalic, and there is but a very small amount of excess silica. Apart from these features the average is not especially noteworthy except that the amount of baria, though small, is greater than that in the averages for the States east of the Mississippi.

Average and norm for rocks of the Arkansas-Texas region (50 analyses).

Average.		Norm.	
SiO_2	58.53	Q	0.06
Al_2O_3	16.36	Or	27.80
Fe_2O_3	3.74	Ab	45.06
FeO	2.36	An	6.67
MgO	2.54	Di	9.87
CaO	4.11	Hy	1.90
Na_2O	5.35	Mt	5.34
K_2O	4.69	Il	1.37
H_2O	1.04	Ap	.34
TiO_2	.76		
P_2O_5	.19	Symbol, II.5.(1)2.(3)4.	
MnO	.10		
BaO	.02		
Inclusive	.21		
	100.00		

This area is not very clearly defined and the exposures of igneous rocks in it are sporadic and most of them are small, the greater part of the area being covered by thick sedimentary beds. The rocks, too, are heterogeneous, and their heterogeneity seems to imply the absence of close genetic relations between many of them.

Small and widely scattered exposures of granitic rocks in Missouri and Oklahoma, even though they are few, indicate the presence of much granite at great depths. The best known districts of igneous rocks are in Arkansas, where exposures of sodic syenite, nephelite syenite, and accompanying dikes have been studied by J. F. Williams, who gives many good analyses. Analyses of the generally sodic rocks of the trans-Pecos and Uvalde districts in Texas are rather numerous. There are few analyses of rocks of the area outside of these Arkansas and Texas districts, the granites being represented by only about 10 analyses.

The average for the area is therefore determined almost entirely by the analyses of the Arkansas and Texas rocks already mentioned, which make it appear highly alkalic. If it were possible to study more of the deep-lying granites of the area the average would undoubtedly be considerably higher in silica, but the few analyses of the granites that are at hand indicate that there would probably be but little change in the relative amounts of the other constituents. The granites of Missouri resemble those of Appalachia and are probably comagmatic, but the more alkalic rocks of Arkansas and Texas evidently belong to a distinct region.

Montana-Idaho.—It is doubtful whether the rocks of Idaho should be included with those of Montana, as they probably belong to a different comagmatic region and are more likely connected with those of Washington and Oregon. The number of analyses of rocks from Idaho is, however, so few (only 11) that their influence on the average is negligible.

The Montana average resembles that of the whole United States in its percentage of silica and of most of the other constituents, except that potash is notably higher and the average is more decidedly alkalic. The Montana average is remarkable for its high percentage of baria (0.15), the highest known; in this respect it resembles the average for west Canada, as we have seen. The strontia also is high (0.04).

Average and norm for rocks of Montana and Idaho (133 analyses).

Average.		**Norm.**	
SiO_2	60.36	Q	8.58
Al_2O_3	15.26	Or	23.91
Fe_2O_3	2.53	Ab	31.96
FeO	3.07	An	12.51
MgO	3.77	Di	7.66
CaO	4.81	Hy	8.45
Na_2O	3.82	Mt	3.71
K_2O	3.99	Il	1.06
H_2O	1.03	Ap	.67
TiO_2	.58	Symbol, II.(4)5.2:3″.	
P_2O_5	.32		
MnO	.10		
BaO	.15		
SrO	.04		
Inclusive	.17		
	100.00		

The rocks of this region that are of most interest petrologically are those of what Pirsson called the Central Montana province, which were described by him and Weed in a long series of classic papers. With these are to be classed the rocks of the Crazy Mountains, many of which have been analyzed but which are not yet described. These rocks include both plutonic and effusive kinds, and their 80 analyses comprise about two-thirds of all the analyses of rocks from Montana. Chemically they are distinctly alkalic, but they contain about as much potash as soda, the potash even dominating the soda in the less silicic rocks. There are also a considerable number of rocks of more ordinary characters from mining centers, such as Butte and Marysville, and a few from other places. The influence of the rocks from central Montana on the average for the region is marked, but the average as here given is no doubt fairly representative of the rocks of Montana.

Wyoming-South Dakota.—The average for the rocks of the Wyoming-South Dakota region, which includes the Yellowstone National Park, is very similar to that of Montana; the alumina and soda are a trifle higher, and the ferrous oxide is slightly lower, but there is no other significant difference. The rocks of this area contain an unusually large percentage of baria (0.08), approaching that of the rocks in the Montana and west Canada areas, north of it. They contain also some strontia (0.02 per cent).

Average and norm for rocks of Wyoming-South Dakota (134 analyses).

Average.		**Norm.**	
SiO_2	60.00	Q	8.82
Al_2O_3	16.17	Or	22.24
Fe_2O_3	2.92	Ab	34.58
FeO	2.44	An	14.73
MgO	3.26	Di	4.18
CaO	4.50	Hy	7.32
Na_2O	4.08	Mt	4.18
K_2O	3.81	Il	1.22
H_2O	1.49	Ap	.67
TiO_2	.64	Symbol, ″II.(4)5.2″.3(4).	
P_2O_5	.30		
MnO	.06		
BaO	.08		
Inclusive	.25		
	100.00		

This average is essentially that of the Yellowstone Park, as the data affording it include only 14 analyses of rocks from Wyoming outside of the park and only 6 analyses of rocks from South Dakota, nearly all from the Black Hills. The analyses of the rocks from Yellowstone Park, which have been described chiefly by Iddings, are so numerous and cover so many varieties that the average given may be regarded as fully representative of this region. The occurrence of the very peculiar, highly potassic rocks of the Leucite Hills, which lie farther south in Wyoming, and that of phonolitic rocks in the Black Hills area indicate that the Yellowstone Park is surrounded by decidedly alkalic rocks, but in the aggregate these rocks would probably have much less relative effect in influencing the average than those of the park, so that the average given for Wyoming may be considered reasonably representative.

Colorado.—The average for Colorado resembles the two preceding ones, although it shows a little more normative quartz (excess silica). It is somewhat unusual in the ratio of potash to soda, for the percentage of potash slightly exceeds that of soda, so that the average is sodipotassic. The percentage of baria (0.07), is almost the same as that of Wyoming. Hillebrand [53] pointed out years ago that the igneous rocks along the east slope of the Rocky Mountains are exceptionally high in barium. The averages here given indicate that the northern part of this zone is highest in barium, and that there is a steady and fairly regular decrease in this element as we go south from west Canada and Montana through Wyoming to Colorado and beyond into New Mexico and Arizona.

Average and norm for rocks of Colorado (171 analyses).

Average.		Norm.	
SiO_2	60.07	Q	10.38
Al_2O_3	15.94	Or	22.80
Fe_2O_3	3.41	Ab	33.01
FeO	2.86	An	14.46
MgO	2.34	Di	5.88
CaO	4.85	Hy	4.59
Na_2O	3.87	Mt	4.87
K_2O	3.91	Il	1.67
H_2O	1.12	Ap	.67
TiO_2	.88		
P_2O_5	.34		
MnO	.12		
BaO	.07		
Inclusive	.22		
	100.00		

Symbol, ″II.4(5).2″.3″.

The analyses of rocks from Colorado, for the study of most of which we are indebted to Whitman Cross, are numerous, and they cover the State very well. From their number and quality, and from the distribution of the rocks analyzed, we may say that the Colorado average is exceptionally good and that it is satisfactorily representative of the area.

Utah-Nevada.—The average for Utah and Nevada is unusual in its high percentage of silica—the highest average for any region in the United States and exceeded in all the world only by that of the Balkan Peninsula. It is also unusual in showing a very high ratio of potash to soda, being surpassed in this respect only by the average of Italy. The amount of baria is small but appreciable. The Utah-Nevada and Balkan rocks are the only ones that fall in the persalane class.

Average and norm for rocks of Utah-Nevada (79 analyses).

Average.		Norm.	
SiO_2	65.78	Q	20.76
Al_2O_3	15.52	Or	24.46
Fe_2O_3	2.17	Ab	29.34
FeO	1.60	An	14.46
MgO	1.52	Di	1.51
CaO	3.44	Hy	3.23
Na_2O	3.50	Mt	3.25
K_2O	4.09	Il	1.06
H_2O	1.41	Ap	.34
TiO_2	.55		
P_2O_5	.13		
MnO	.04		
BaO	.05		
Inclusive	.20		
	100.00		

Symbol, I(II).4.2″.3.

The analyses that represent the rocks of Utah-Nevada are not very numerous, but the rocks analyzed are fairly well scattered over the region. It would appear, however, that the average is subject to a decidedly serious error, for the rocks analyzed are nearly all from mining districts, in which the more salic and silicic varieties are common, and include very few basalts and other more femic rocks, although extensive sheets and other occurrences of so-called basalt are very common in the region. If we could make proper correction for these the average would be distinctly more femic—that is, it would be lower in silica and alkalies (especially potash), and higher in iron oxides, magnesia, and lime. The change, however, would probably not be great, but it would make the average more femic than that of Colorado.

New Mexico-Arizona.—The average for the New Mexico-Arizona region resembles closely that of Colorado but it is slightly higher in silica and lower in potash. The percentage of baria (0.04) is a little below that for Colorado and that for Utah-Nevada.

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[53] Hillebrand, W. F., Some principles and methods of rock analysis: U. S. Geol. Survey Bull. 176, p. 17, 1900.

Average and norm for rocks of New Mexico-Arizona (79 analyses).

Average.		Norm.	
SiO_2	61. 39	Q	11. 82
Al_2O_3	16. 24	Or	17. 79
Fe_2O_3	2. 84	Ab	35. 63
FeO	2. 85	An	16. 40
MgO	2. 74	Di	5. 31
CaO	4. 81	Hy	6. 35
Na_2O	4. 18	Mt	4. 18
K_2O	3. 04	Il	1. 37
H_2O	. 69	Ap	. 67
TiO_2	. 72		
P_2O_5	. 31		
MnO	. 11		
BaO	. 04		
Inclusive	. 04		
	100. 00		

Symbol, II.4(5).2(3).4.

The number of analyses is so small that the average may not represent the area satisfactorily. Most of the rocks from Arizona were obtained from mining districts; most of those from New Mexico were more widely scattered. The numerous basaltic rocks of the area are probably not sufficiently represented, so that the average given is somewhat too high in silica and generally too salic but perhaps by small amounts.

Washington-Oregon.—When we reach the Washington-Oregon area, on the Pacific coast, we come upon a decided change in the character of the averages. The percentage of silica remains about the same as in the averages for the Rocky Mountain States, but there is a decided increase in the amounts of iron oxides, magnesia, and lime, and a diminution in the percentage of potash, that of soda remaining almost unchanged. The average is thus distinctly more femic, falling centrally in dosalane, and it is also alkalicalcic and dosodic. We may note again here the presence of a small but perceptible amount of baria.

Average and norm for rocks of Washington-Oregon (51 analyses).

Average.		Norm.	
SiO_2	59. 97	Q	12. 36
Al_2O_3	15. 90	Or	9. 45
Fe_2O_3	2. 11	Ab	31. 44
FeO	4. 13	An	21. 96
MgO	4. 38	Di	6. 05
CaO	6. 11	Hy	12. 96
Na_2O	3. 71	Mt	3. 02
K_2O	1. 55	Il	1. 22
H_2O	1. 11	Ap	. 34
TiO_2	. 66		
P_2O_5	. 17		
MnO	. 06		
BaO	. 05		
Inclusive	. 09		
	100. 00		

Symbol, II.4″.3.4.

The average for the area is probably not quite satisfactory, for the analyses are too few and represent rocks that are not widely scattered over the area, which needs much further study.

Of the 35 analyses of the rocks of Oregon made in the laboratory of the Geological Survey, 15 are analyses of lavas of Crater Lake described by Diller. The extensive flows of the plateau basalts of Columbia and Snake rivers are represented by only two analyses, and these are of somewhat abnormal types, exceptionally high in silica. On the other hand, part of the Washington-Oregon area may be regarded as a continuation of that of California, which is higher in silica. It may be said that the Washington-Oregon average is based on too few analyses, and that it should be somewhat more femic and lower in silica, so that it is not very satisfactory.

California.—The average for California resembles in general that for Washington-Oregon, immediately to the north, though it is slightly higher in silica. It falls centrally in tonalose (II.4.3.4). The small content of titanic oxide and of baria may be noted as minor characters.

Average and norm for rocks of California (175 analyses).

Average.		Norm.	
SiO_2	62. 49	Q	16. 74
Al_2O_3	15. 71	Or	11. 68
Fe_2O_3	1. 97	Ab	30. 39
FeO	3. 01	An	20. 85
MgO	3. 67	Di	5. 13
CaO	5. 67	Hy	9. 91
Na_2O	3. 57	Mt	3. 02
K_2O	2. 03	Il	. 91
H_2O	1. 05	Ap	. 34
TiO_2	. 45		
P_2O_5	. 15		
MnO	. 09		
BaO	. 05		
Inclusive	. 09		
	100. 00		

Symbol, II.4.3.4.

Although the area of California is large, the analyses are numerous and are well distributed over the State. The rocks analyzed come not only or chiefly from mining districts but many of them from volcanic cones, lava flows, and intrusive bodies. Indeed, the volcanoes of Lassen Peak and Shasta, not yet fully described, but concerning which Diller gives some brief notes, are exceptionally well represented. The average for California, like that for Colorado, is no doubt thoroughly representative, and it is probably one of the most satisfactory and truly representative areal averages among all those considered in this paper.

United States.—The average for the United States is an almost exact duplicate of that for the earth as a whole. The slight difference shown by the higher silica for the United States is insignificant, and the agreement between the two as regards the other constituents is remarkably close. We may note here the presence in the general average of 0.05 per cent of baria and of 0.02 per cent of strontia.

Average and norm for rocks of the United States (1,351 analyses).

Average.		Norm.	
SiO_2	60.77	Q	12.66
Al_2O_3	15.44	Or	18.90
Fe_2O_3	2.77	Ab	31.96
FeO	3.46	An	15.57
MgO	3.15	Di	5.10
CaO	4.82	Hy	7.85
Na_2O	3.78	Mt	4.18
K_2O	3.23	Il	1.98
H_2O	1.01	Ap	.67
TiO_2	1.01		
P_2O_5	.29	Symbol, II.4″.2(3).(3)4.	
MnO	.10		
BaO	.05		
SrO	.02		
Inclusive	.10		
	100.00		

The average for the United States is determined from a large number of analyses, most of them extremely good, and the rocks analyzed are well distributed over the area, so that the average may be considered thoroughly representative. Areas here and there may need some correction, but probably none of great magnitude, and they unquestionably tend to compensate one another, so that they may be regarded as negligible.

The average is probably not notably dominated or determined by any one or by several sets of the analyses used. We may assume that the number of analyses for each area should be roughly proportional to the size or extent of the area, and although this assumption is not strictly justifiable, it may afford a rough measure for want of a better. On comparing the percentages of numbers of analyses with the sizes of the areas they represent we find that the proportions are closely alike only for Appalachia and for the Montana and New Mexico-Arizona areas. The number of analyses is proportionately much greater than the relative areal extent for the New England-New York, Wyoming, Colorado, and California areas, and it is less for the Lake Superior, Missouri-Texas, Utah-Nevada, and Washington-Oregon areas. The greatest discrepancies are in the New England-New York area, where the ratio of analyses to areal extent is 3 to 1; and in the Arkansas-Texas area, where the percentage of areal extent is about five times that of the number of analyses. Taken as a whole, however, the several ratios so compensate each other that we are justified in thinking that the general average for the United States is fairly representative.

Mexico-Central America.—The average for Mexico-Central America, a small but interesting area, closely resembles that of California and especially that of Washington-Oregon. The percentage of silica is almost exactly that of the Washington-Oregon area, and although the alkalies in the average for Mexico and Central America are slightly higher, all three averages are alkalicalcic and dosodic.

Average and norm for rocks of Mexico-Central America (47 analyses).

Average.		Norm.	
SiO_2	59.11	Q	10.14
Al_2O_3	16.58	Or	13.34
Fe_2O_3	2.88	Ab	34.58
FeO	4.11	An	20.29
MgO	3.07	Di	5.01
CaO	5.73	Hy	9.34
Na_2O	4.10	Mt	4.18
K_2O	2.32	Il	1.37
H_2O	1.04	Ap	.67
TiO_2	.63		
P_2O_5	.25	Symbol, II.(4)5.3.4.	
MnO	.06		
Inclusive	.12		
	100.00		

The number of analyses that represent this area is small, and only six of them represent Central America. Most of the rocks analyzed are volcanic lavas, chiefly rhyolites and basalts; there are only about six analyses of plutonic rocks—granodiorite, nephelite syenite, and tinguaite. The two highly sodic rocks last named are doubtless disproportionately represented. In spite of the small number of analyses, however, this area is perhaps fairly well represented.

West Indies.—The average for the West Indies is exceptional in several respects. It resembles the earth average and that of the United States in the percentages of silica, the iron oxides, magnesia, and soda, but it shows the maximum percentage for alumina among all the averages and much the highest percentage of lime among rocks having so high a content of silica, being exceeded in lime only by the averages for Antarctica and the Atlantic and Pacific islands, the percentages of silica for which are much lower. It also shows the minimum figure for potash. Because of these features it is the only average that is docalcic, and the only one which contains so little potash that it shows a decided tendency to be persodic, the ratio of soda to potash being the maximum. A rather large proportion of Japanese lavas are chemically much like those of the West Indies, although the average for all the Japanese rocks is more normal in being less calcic and less sodic.

Average and norm for rocks of the West Indies (82 analyses).

Average.		Norm.	
SiO_2	58.70	Q	2.58
Al_2O_3	18.30	Or	6.12
Fe_2O_3	2.85	Ab	26.72
FeO	4.20	An	32.80
MgO	3.36	Di	2.04
CaO	7.08	Hy	11.89
Na_2O	3.15	Mt	4.18
K_2O	.99	Il	.91
H_2O	.79		
TiO_2	.45		
P_2O_5	.08		
MnO	.02		
Inclusive	.03		
	100.00		

Symbol, II.4″.(3)4.4″.

The West Indies average is determined very largely by analyses of the lavas from Martinique (most of them from Mont Pelée), which number 49, and of 10 from St. Vincent and 5 from Guadeloupe. Most of these lavas have been described by Lacroix. There are 4 from Grenada, and the rest are scattered; some of them represent plutonic rocks, and some of these are not very good.

Although the average is thus largely controlled by analyses that represent but one volcano, yet study of the rocks from elsewhere in the area indicates that the general character of the West Indian lavas is probably fairly represented by the average given, with the minor exception that the percentage of manganous oxide should be about 0.17 instead of 0.02, as it appears in the stated average.

Average for North America.—The average for the whole of North America, including Greenland and the West Indies, is an almost exact duplicate of the average for the United States, and both of them closely resemble the general earth average, though this last is a trifle lower in silica and otherwise very slightly more femic.

Average and norm for the rocks of North America (1,709 analyses).

Average.		Norm.	
SiO_2	60.19	Q	11.34
Al_2O_3	15.76	Or	18.35
Fe_2O_3	2.88	Ab	33.01
FeO	3.67	An	16.40
MgO	3.16	Di	4.45
CaO	4.81	Hy	8.54
Na_2O	3.90	Mt	4.18
K_2O	3.07	Il	1.98
H_2O	1.01	Ap	.67
TiO_2	1.01		
P_2O_5	.26		
MnO	.10		
BaO	.04		
Inclusive	.14		
	100.00		

Symbol, II.4(5).(2)3.″4.

The average of North America is dominated by that for the United States, almost to the exclusion of the averages for other areas of the continent, as the analyses of rocks of the United States (excluding Alaska) make up 79 per cent of the total. The others tend to compensate each other in various ways. Thus the highly alkalic character of the Greenland average is offset by the calcic character of that of the West Indies. The analyses that represent Canada and Mexico-Central America are so few and so compensatory that they are of little influence on the average. As we have seen, the Canadian average should be more silicic, so that the average for North America may be considered a close approximation to the truth.

SOUTH AMERICA.

The average for South America is derived from 138 analyses, which represent rocks distributed as shown below.

British Guiana.—There are so few analyses of South American rocks that it is practicable at present to consider the averages of only three separate areas. We may begin with that of British Guiana, the most northerly. This average presents no specially remarkable features. On the whole it is much like those of

Washington-Oregon and of California but also shows some affinities with that of Appalachia. The presence of a notable amount of baria (0.09), and that of a distinct trace of copper, among the minor constituents, may be mentioned as of interest.

Average and norm for rocks of British Guiana (45 analyses).

Average.		Norm.	
SiO_2	61.06	Q	15.24
Al_2O_3	15.17	Or	10.01
Fe_2O_3	2.42	Ab	27.77
FeO	4.07	An	21.68
MgO	4.65	Di	6.05
CaO	5.91	Hy	13.82
Na_2O	3.29	Mt	3.48
K_2O	1.74	Il	.91
H_2O	.73		
TiO_2	.49	Symbol, II.4.3.4.	
P_2O_5	.07		
MnO	.18		
BaO	.09		
Inclusive	.13		
	100.00		

This average is based entirely on a series of excellent analyses by J. B. Harrison, to whom we are indebted for almost the only knowledge that we possess of the petrology of this part of northern South America. The variety of rocks represented is not great, but the average is of interest on that account. Quartz porphyries and granitic rocks, with basal gneisses, are most abundant, with some quartz diorite and diorite, a little syenite, and considerable gabbro and diabase. The general character of the area seems to be very uniform within these limits, and apparently highly alkalic rocks are absent. Although most of the specimens analyzed were necessarily collected along the rivers they are fairly well distributed, so far as the country is known, and the analyses are sufficiently numerous and concordant. The average of British Guiana may therefore be regarded as very satisfactory.

The Andes.—The average for the Andes includes the analyses of only the volcanic rocks, but none of the plutonic pedestal on which the volcanoes stand. It resembles those of Washington-Oregon and California and rather more closely that of Mexico, although the lime in the Andean average is a little lower. This correspondence indicates, as is evident from other considerations, that the line of the Andean volcanoes is a continuation of the volcanic zone farther north, in Mexico and along the Cordilleras in the western United States. It thus confirms the observation to the same general effect made 30 years ago by Iddings,[54] who pointed out the resemblance between the rocks of the Andes and those of the Great Basin and the Cordilleras.

Average and norm for rocks of the Andes (56 analyses).

Average.		Norm.	
SiO_2	61.85	Q	12.66
Al_2O_3	16.51	Or	16.12
Fe_2O_3	3.03	Ab	38.25
FeO	2.28	An	16.68
MgO	2.29	Di	3.09
CaO	4.55	Hy	6.16
Na_2O	4.47	Mt	4.41
K_2O	2.69	Il	1.37
H_2O	1.11	Ap	.67
TiO_2	.75		
P_2O_5	.25	Symbol, (I)II.4″.3.4.	
MnO	.22		
	100.00		

The number of analyses of Andean lavas is small—probably too small to be truly representative of this long line of gigantic volcanoes. Most of the analyses, indeed nearly all, are those published by Küch, Belowsky, and others who studied the large collections made by Reiss and Stübel many years ago. Those published by them are nearly all analyses of rocks from the north end of the volcanic zone, in Colombia and Ecuador, but they had at their command about 18,000 specimens from localities extending from Colombia into Chile. Our knowledge of the lavas of the more southerly volcanoes and of the few analyses of them that are available leads us to believe that the average is quite representative of the whole line of the Andean volcanoes. It would be of great interest to have chemical analyses of the rocks of the pedestal ridge on which the Andean volcanoes stand. These rocks are probably mostly granite, but they include some quartz diorite and diorite, and their average would probably not differ much from that of the volcanic lavas.

East Brazil.—The area called East Brazil (Bahia, São Paulo, and Rio Janeiro) includes Paraguay and East Argentina. The rocks are imperfectly known and the analyses are few, but a brief consideration of them in connection with the averages for other areas may be of interest.

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[54] Iddings, J. P., The volcanic rocks of the Andes: Jour. Geology, vol. 1, p. 164, 1893.

The average is much lower in silica than nearly all the averages that we have been considering, and it is especially notable for the high content of alkalies, both soda and potash. Indeed, the alkalies are so high that, in combination with the rather low silica, a little nephelite appears in the norm. This average is strikingly similar to those of Greenland and East Canada, for the rocks of East Canada contain about 4 per cent of normative nephelite. This occurrence of three similar highly alkalic areas along the eastern coast of the Americas is of great interest.

Average and norm for rocks of East Brazil (20 analyses).

Average.		**Norm.**	
SiO_2	54.94	Or	21.13
Al_2O_3	16.29	Ab	39.82
Fe_2O_3	4.05	An	11.12
FeO	3.52	Ne	1.70
MgO	4.33	Di	11.45
CaO	5.28	Ol	5.67
Na_2O	5.11	Mt	5.80
K_2O	3.57	Il	1.67
H_2O	1.55	Ap	.34
TiO_2	.88		
P_2O_5	.11		
MnO	.37		
	100.00		

Symbol, II.5.2.″4.

A consideration of the rocks of the area and of the kinds of rocks analyzed shows that the analyses were mostly confined to "interesting" distinctly alkalic rocks and therefore do not fairly represent the whole region. Furthermore, they are too few to be fully representative. On the whole, however, the average is of interest as showing that there is a distinct sodic tendency in the rocks along the east coast of South America, which is superposed, so to speak, on the tendency or trend of the probably more prevalent granitic, dioritic, and gabbroic rocks, which show relations here analogous to those of eastern North America. The average can not be considered as indicative of more than this regional tendency and is very unsatisfactory.

Average for South America.—The average for South America resembles that for North America in its general features, but it is notable in showing the highest silica found in all the continental averages. It has also the highest ratio of soda to potash, and, except for the Antarctic Continent, the lowest percentage of potash among the continental averages. In these two respects the averages of only the Pacific and Atlantic islands surpass it. The low figures for titanic and phosphoric oxides may probably be ascribed to the incompleteness of most of the analyses of South American rocks, particularly those of the Andes, as regards the minor constituents.

Average and norm for rocks of South America (138 analyses).

Average.		**Norm.**	
SiO_2	61.36	Q	12.30
Al_2O_3	15.20	Or	16.12
Fe_2O_3	3.03	Ab	34.58
FeO	3.30	An	15.01
MgO	3.47	Di	6.89
CaO	4.88	Hy	8.31
Na_2O	4.08	Mt	4.41
K_2O	2.69	Il	1.06
H_2O	1.04	Ap	.34
TiO_2	.56		
P_2O_5	.11		
MnO	.12		
Inclusive	.16		
	100.00		

Symbol, II.4″.2(3).4.

The average for South America is made up almost wholly of analyses of rocks from three areas—the Andes (56 analyses), British Guiana (42 analyses), and the East Brazil area (20 analyses), in all 118 analyses. The other rocks are from scattered localities—Madeira River, western Argentina, and southwestern Patagonia. These analyses are so few that they have but a negligible effect on the general average. The averages for the Andes and Guiana therefore practically determine the whole average. It is seen that we know the chemistry of the South American rocks only from the coastal districts; we are practically ignorant of those of the vast expanse of the interior. From such slight information of a general character as is vouchsafed us by the remarks of travelers and some geologic studies,[55] we gather, however, that granitic rocks predominate in the interior of the continent. We therefore seem to be justified in believing that the average for South America here given is approximately correct, at least in its main features, in spite of the small number of analyses and the paucity of our knowledge.

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[55] Compare Branner, J. C., Outlines of the geology of Brazil to accompany the geologic map of Brazil: Geol. Soc. America Bull., vol. 30, pp. 189-338, 1919; Stelzner, A., Beiträge zur Geologie und Palaeontologie der argentinischen Republik, vol. 1, 1885.

EUROPE.

The analyses of rocks from Europe number 1,985, and the rocks are distributed as shown below.

Great Britain and Ireland.—The average for Great Britain and Ireland is somewhat different from most of those that we have been examining. The silica is distinctly lower, as are the alumina and the alkalies; the iron oxides, magnesia, and lime are somewhat higher than in the general earth average, in that of the United States, or in that of Europe. The last may be regarded as the standard of comparison for the European averages. The British average is therefore distinctly femic.

Averages and norm for rocks of Great Britain and Ireland (171 analyses).

Average.			Norm.	
	1.	2.	Q	10.56
SiO_2	59.12	59.18	Or	16.12
Al_2O_3	13.81	15.46	Ab	29.87
Fe_2O_3	3.13	4.80	An	13.62
FeO	4.56	2.71	Di	8.93
MgO	4.80	3.72	Hy	12.33
CaO	5.41	4.85	Mt	4.41
Na_2O	3.54	3.19	Il	1.82
K_2O	2.68	2.77	Ap	.67
H_2O	1.44	2.18		
TiO_2	.97	.52	Symbol, II.(4)5.2(3).″4.	
P_2O_5	.22	.21		
MnO	.14	.41		
Inclusive	.18	......		
	100.00	100.00		

1. Clarke and Washington.
2. Harker.

The igneous rocks of this area have been described by so many petrologists and the localities represented are so well distributed that no particular area greatly dominates the average, although it would appear that there are rather more analyses of Scotch rocks than of English and that the rocks of Ireland are somewhat inadequately represented. There are more analyses of volcanic than of plutonic rocks. The abundance of basaltic lavas, however, would indicate that the number of analyses of them is not unduly large. Analyses of the peculiar alkalic rocks of Sutherland in Scotland, of Wales, and of other places, are rather numerous, but although the areas occupied by these rocks are small the employment of their analyses probably does not introduce any serious error. Any possible error due to this source and to the probably rather too small number of analyses of granitic rocks is compensated by the fact that there are among our data few or no analyses of the basalts of the outlying Orkney, Shetland, and Faroe Islands. The British average, then, may be regarded as probably approximately correct and as subject to only minor changes in the future.

It is of interest to compare this recently calculated average of the rocks of Great Britain and Ireland with that calculated by Harker some years ago.[56] The figures for silica, total iron oxides, lime, soda, and potash are much alike. In the older average, however, alumina is decidedly higher, and magnesia is lower by about the same amount, which leads to the thought that in many of these earlier analyses the common analytical error of weighing some magnesia with the alumina has been committed, and that it has been avoided by better work and better methods in the recent analyses. The inverse relations of the iron oxides also makes one suspect that the earlier determinations of ferrous oxide were not so accurate as the more recent ones. Titanium dioxide was not determined as frequently in the older analyses as now, and the older figure for manganese oxide looks suspiciously high.

France.—The Island of Corsica is included with France. Except that the silica is higher by about 3 per cent (of the total rock), the French average corresponds very well with that of Europe. It is higher in silica than any other European average, except the Balkan. The very low figure for manganese is to be attributed to the fact that this minor constituent is seldom determined in French rock analyses, a remark that applies also to the other minor constituents, except titanic and phosphoric oxides.

Average and norm for the rocks of France (163 analyses).

Average.		Norm.	
SiO_2	62.38	Q	14.52
Al_2O_3	15.15	Or	18.90
Fe_2O_3	2.41	Ab	31.44
FeO	3.04	An	15.01
MgO	3.79	Di	2.87
CaO	3.92	Hy	10.51
Na_2O	3.70	Mt	3.49
K_2O	3.24	Il	1.37
H_2O	1.46	Ap	.34
TiO_2	.75		
P_2O_5	.12	Symbol, II.4″.2(3).(3)4.	
MnO	.01		
Inclusive	.03		
	100.00		

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[56] Harker, Alfred, On the average composition of British igneous rocks: Geol. Mag., new ser., decade 4, vol. 6, p. 220, 1899; The Tertiary igneous rocks of Skye, p. 416, 1904.

The average for France is made up chiefly of analyses of rocks from the Auvergne (described by Fouqué and Lacroix), Brittany (described by Vandernotte), the Pyrenees (Lacroix), and Corsica (Deprat), of somewhat fewer analyses of rocks from Dauphiny (Termier), Esterel (Michel-Lévy), La Creuse (De Launay), Lyonnais (Michel-Lévy), and the Vosges and of some from other scattered localities. The principal areas of igneous rock in France would seem to be fairly well represented, but the analyses of the Corsican rocks, which are not quite satisfactory, are rather too prominent. As most of these rocks are decidedly sodic, we might be inclined to consider the whole average a trifle too sodic; but we must take into account a very considerable number of analyses of rocks from Auvergne that have been published recently by Lacroix and that are not included in our estimate. As these rocks are distinctly sodic, their omission tends to counterbalance the possibly undue prominence of the Corsican rocks. The fairly abundant basalts of Languedoc and Provence, in southern France, are perhaps worthy of larger recognition than they have received. The very femic rocks of the Pyrenees area appear to be of small total amount, less than would seem to justify the number of analyses of them that are included in our data. But, on the whole, it would appear that the average for France (from which the rocks of Corsica should be excluded) is satisfactorily representative.

Spain-Portugal.—The average for the Iberian Peninsula is remarkable among the European averages. It is the lowest in silica, except the average for Russia, and the highest in total alkalies, except the average for Finland. It also has the distinction of being the highest in both titanic and phosphoric oxides. The combination of low silica and high alkalies gives it a norm in which a little olivine appears; so that it is the only European areal average in which there is a deficiency in silica, all the others showing more or less normative quartz. Apart from the amount of silica and the alkalies, with their normative consequences, the amounts of the other constituents are about normal—that is, they are about the same as in the whole European average.

Average and norm for rocks of Spain and Portugal (33 analyses).

Average.		Norm.	
SiO_2	56. 88	Or	26. 69
Al_2O_3	15. 55	Ab	38. 77
Fe_2O_3	2. 69	An	8. 34
FeO	3. 57	Di	9. 23
MgO	4. 57	Hy	6. 02
CaO	4. 43	Ol	2. 23
Na_2O	4. 56	Mt	3. 94
K_2O	4. 47	Il	2. 58
H_2O	1. 19	Ap	. 67
TiO_2	1. 34		
P_2O_5	. 34		
MnO	. 07		
Inclusive	. 34		
	100. 00		

Symbol, II.5.2.3(4).

It is obvious at a glance that the number of analyses is inadequate to represent the large and somewhat complex Iberian Peninsula. Furthermore, the analyses are all of rocks from localities near or on the coast; none represent the interior. The average is made up practically of but three subareas—that of the basanitic volcanoes near Olot, in Catalonia, described by the junior author; the highly sodic and potassic rocks of Almeria and Murcia, in southeastern Spain, described by Osann; and the sodic rocks of southern Portugal. Apart from these but three scattered areas are represented. The peculiar features of the average obviously arise from the peculiarities of the few data available. We know from the publications of Calderón and Navarro that granites and quartz porphyries, apparently sodic rather than potassic, as well as dikes of diabase of ordinary types, are very abundant throughout the interior plateau of Spain and are perhaps the prevailing igneous rocks, there being few syenites, nephelite syenites, or diorites. There seems to be but one (a Spanish) analysis of these granites, and that is not included among our data.

From the above discussion it is clear that the average represents only the coastal fringe of alkalic and generally sodic rocks, whereas the much greater mass of ordinary granitic and fewer basaltic rocks of the interior is not represented. The average for Spain and Portugal must, therefore, be regarded as quite unrepresentative of the area.

Norway.—The analyses of rocks from Bornholm and Iceland are included in the average for Norway, but they are so few that the average is essentially that of Norway alone. The average resembles that of Europe in general but differs from it notably in having higher soda and lower lime, so that it is almost in persalane, and is distinctly more alkalic and more sodic relative to potash. Titanic oxide is considerably higher. If more of the analyses were complete the average might show a little zirconia and possibly some baria.

Average and norm for Norway (107 analyses).

Average.		Norm.	
SiO_2	59.83	Q	7.50
Al_2O_3	16.08	Or	20.57
Fe_2O_3	3.65	Ab	42.97
FeO	3.21	An	10.84
MgO	2.26	Di	4.97
CaO	3.64	Hy	3.43
Na_2O	5.10	Mt	5.34
K_2O	3.52	Il	3.19
H_2O	.75	Ap	.34
TiO_2	1.64	Symbol, ″II.(4)5.2.4.	
P_2O_5	.12		
MnO	.10		
Inclusive	.10		
	100.00		

In considering the factors that make up the average for Norway we may eliminate the analyses of rocks from Denmark and Iceland. The analyses for Bornholm Island (the only Danish locality) number but six, and all are analyses of granite. Only four analyses of rocks from Iceland were considered sufficiently good to use; three were analyses of rhyolites and one an analysis of a basalt. The lavas of Iceland are overwhelmingly basaltic, yet the number of analyses of rhyolitic rocks of the island so far published greatly outnumber those of basalts.

The average for Norway is made up almost entirely of analyses of rocks from but two districts, that of Christiania, described by Brögger, and that of Bergen, described by Kolderup. There are a few analyses of rocks from the Lofoten Islands and scattered localities, but they are of little influence. The analyses of the rocks of the Christiania district far outnumber those of Bergen; they are also much more varied in character, although their common dominant characteristic is high soda. The rocks of Bergen, on the other hand, are highly calcic. The Norway average, then, may be regarded as essentially that of the dominantly sodic Christiania district slightly modified by the calcic Bergen district. A considerable number of poor analyses of rocks from Norway have not been used in our computations. A study of the general petrographic character of the Scandinavian Peninsula, especially as exemplified in the average for Sweden, makes it quite certain that the abundant granites of Norway are inadequately represented in the average, which must be regarded as subject to future revision.

Sweden.—A few analyses of rocks from Spitzbergen are included with those of rocks from Sweden. The average for Sweden is very high in silica, being exceeded in this respect only by the averages for Utah-Nevada and the Balkans. It is decidedly alkalic, and the percentage of potash slightly exceeds that of soda, so that it is almost sodipotassic. Among all the European averages it has the lowest percentage of lime and next to the lowest percentage of magnesia. In these two points also it resembles the averages for Utah-Nevada and the Balkans.

Average and norm for the rocks of Sweden (206 analyses).

Average.		Norm.	
SiO_2	64.04	Q	18.84
Al_2O_3	14.24	Or	22.24
Fe_2O_3	3.65	Ab	31.44
FeO	3.41	An	10.84
MgO	1.82	Di	2.69
CaO	3.25	Hy	5.55
Na_2O	3.70	Mt	5.34
K_2O	3.82	Il	1.37
H_2O	.84	Ap	.67
TiO_2	.73	Symbol, ″I.4.2.3(4).	
P_2O_5	.25		
MnO	.15		
Inclusive	.10		
	100.00		

Most of the Swedish rocks analyzed are granitic. They are described by Holmquist and others and are fairly well distributed, although they represent best the southern part of Sweden. The districts of Smaland and Nordingra, in the granitic areas, are represented by the most analyses, and the somewhat sodic syenitic Kiruna district is also well represented. As there seems to be little difference between the southern and the northern granitic rocks of Sweden, the predominance of analyses from southern localities is of small consequence. The few analyses of highly sodic rocks, as those of Alnö and

Almunge, have no appreciable influence on the average. Our data include only nine analyses of rocks from Spitzbergen, so that their influence is negligible, even though most of them are analyses of basalts. The average for Sweden is among the few that are based largely on many analyses of the most common rocks; they represent few of the most "interesting" and uncommon kinds, and the average may be considered as highly representative of the character of the area.

Finland.—The igneous areas of the Kola Peninsula are included with Finland, because the rocks there seem to belong to the same general comagmatic region and are quite distinct from most of the other rocks of Russia. Tectonically, also, the Kola massif appears to be connected with Finland. The average for Finland, although it shows about the normal percentage of silica and slightly low percentages of most other constituents, is very high in soda, being surpassed in this respect only by the average for Greenland. The minor constituents, except titanium, phosphorus, and manganese oxides, were not determined, unfortunately, in the analyses for Finland and Kola, but it is almost certain that, were the analyses complete, the average would have shown very appreciable, though small, amounts of zirconia, baria, and other constituents.

Average and norm for rocks of Finland (59 analyses).

Average.		Norm.	
SiO_2	60.58	Q	1.38
Al_2O_3	16.43	Or	23.35
Fe_2O_3	2.75	Ab	51.35
FeO	2.88	An	5.84
MgO	2.16	Di	7.17
CaO	3.35	Hy	4.45
Na_2O	6.11	Mt	3.94
K_2O	3.96	Il	1.06
H_2O	.71	Ap	.67
TiO_2	.56		
P_2O_5	.27		
MnO	.19		
Inclusive	.05		
	100.00		

Symbol, "II.5.(1)2."4.

The analyses show that the rocks of Finland consist mostly of somewhat sodic granite but include some quartz diorite, syenite, gabbro, and diabase. They outnumber slightly the analyses of the rocks of the Kola Peninsula, which are mainly highly sodic rocks, rich in nephelite. Most of these rocks have been described by Ramsay and Hackmann. The analyses are confined mostly to rocks of southern Finland, the more northern granitic areas being almost unrepresented, and the comparatively small sodic igneous area of the Kola Peninsula is represented by what seems to be a disproportionate number of analyses, so that the average for Finland is somewhat too alkalic and especially too sodic and too low in silica.

Fennoscandia.—As the Scandinavian Peninsula, Finland, Kola, and Russian Karelia form parts of one connected tectonic mass, to which the name Fennoscandia was given first by Ramsay, its average has been calculated from the data obtained for its separate parts. It is higher in silica and both alkalies and lower in magnesia and lime than the average for Europe, and it has about the same percentages of alumina and iron oxides.

Average and norm for rocks of Fennoscandia (372 analyses).

Average.		Norm.	
SiO_2	62.31	Q	11.94
Al_2O_3	15.10	Or	22.24
Fe_2O_3	3.50	Ab	38.25
FeO	3.26	An	12.51
MgO	2.00	Di	2.00
CaO	3.37	Hy	5.49
Na_2O	4.48	Mt	5.10
K_2O	3.78	Il	1.82
H_2O	.79	Ap	.67
TiO_2	.96		
P_2O_5	.22		
MnO	.14		
Inclusive	.09		
	100.00		

Symbol, (I)II.4(5).2.(3) 4.

This average is no doubt fairly representative of the Fennoscandian area, although the abundant granitic rocks are possibly too little represented and the interesting alkalic rocks are somewhat overemphasized. The departures from the truth that these criticisms involve, however, are probably not serious, so that the average may be accepted as satisfactory.

Germany.—The average for Germany resembles that for the whole of Europe except that it is decidedly more femic, as is shown in the lower silica and alkalies and the higher iron oxides, magnesia, and lime. It is also brought out clearly in the larger proportion of femic minerals shown in the norm. If the German analyses generally were of better quality the average would be much more distinctly femic.

Average and norm for rocks of Germany (474 analyses).

Average.		Norm.	
SiO_2	58.84	Q	10.20
Al_2O_3	14.44	Or	17.79
Fe_2O_3	3.35	Ab	29.34
FeO	3.91	An	14.73
MgO	4.63	Di	8.65
CaO	5.56	Hy	10.41
Na_2O	3.45	Mt	4.87
K_2O	3.04	Il	1.67
H_2O	1.40	Ap	.67
TiO_2	.87		
P_2O_5	.29		
MnO	.04		
Inclusive	.18		
	100.00		

Symbol, II.(4)5.(2)3.(3)4.

The average for Germany is not very satisfactory. It represents a large number of analyses and many kinds of rocks, which are pretty well distributed over the country, so that it should be representative, but the quality of many of the analyses is so poor that they yield correspondingly untrustworthy figures for the average.

Most of the German analyses that we have been able to use are of mediocre quality and are rated as "fair" and "good." Very few of them are "excellent," and a very large proportion of all of them, say 30 per cent, must be rated as "poor" or "bad." The minor constituents, except titanium and phosphorus, are seldom determined, even manganese being mostly omitted; and such minor constituents as zirconia, baria, strontia, chromium, and nickel are determined only very exceptionally. This is the more unfortunate because most of the igneous rocks of Germany are decidedly femic and there is a considerable proportion of somewhat alkalic rocks. The femic rocks should contain notable amounts of titanium, phosphorus, and probably chromium and nickel, and the more alkalic ones should probably contain easily determinable quantities of zirconia and other minor constituents. Considered as a whole German analyses of rocks from Germany as well as of those from other countries present a dreary monotony of mediocre work, which is not creditable to German chemists or petrographers. We may see in this, possibly, the influence of Rosenbusch, who was profoundly ignorant of the chemistry of igneous rocks[57] and disregarded it.

As a consequence of this poor work the German average is not so femic as a representative assemblage of good analyses would show it to be. It is comparatively easy to make a passable analysis of a granite, but an analysis of a diabase, basalt, or tephrite demands greater analytical care and skill. The German average is distinctly femic, but this fact is not sufficiently shown by the number of good analyses that can be used. Furthermore, we have practically no knowledge as to the amounts or the distribution of most of the minor constituents, which is to be deplored because of the number of comagmatic regions in the German area and their considerable variety and interest. On the whole, therefore, the average for Germany must be regarded as not properly representative and thus not satisfactory.

Austria-Hungary.—The area now to be considered includes the Empire of Austria-Hungary as it was before the war, with Bohemia but not the Austrian Tyrol, which is grouped with Switzerland. The rocks of Bosnia-Herzegovina are regarded as in the Balkan Peninsula.

The Austrian average is low in silica, lower than that of Germany as calculated from our data, and is exceeded in this respect, among the European averages, only by the average for European Russia. Apart from this it presents no especially noteworthy features. The almost total lack of determinations of the rarer minor constituents may be mentioned, but as this is common to nearly all European analyses it is no novelty.

Average and norm for rocks of Austria-Hungary (148 analyses).

Average.		Norm.	
SiO_2	56.93	Q	6.30
Al_2O_3	15.86	Or	17.79
Fe_2O_3	3.72	Ab	30.39
FeO	3.78	An	18.35
MgO	4.15	Di	9.13
CaO	6.45	Hy	9.44
Na_2O	3.61	Mt	5.34
K_2O	2.96	Il	1.06
H_2O	1.45	Ap	.67
TiO_2	.58		
P_2O_5	.27		
MnO	.14		
Inclusive	.10		
	100.00		

Symbol, II.″5.″3.″4.

The number of analyses available to represent the former Austrian Empire is not very large, not so large proportionately as the number for

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[57] It should be remembered that the ratings of analyses in U. S. Geol. Survey Prof. Papers 14 (1903) and 99 (1917) were made before the World War. The remarks as to the ratings of German analyses in Prof. Paper 99 apply equally to those in Prof. Paper 14.

Germany, for though Austria has about half the area of Germany it is represented by less than one-third the number of analyses. The analyses seem to be fairly well distributed, though some well-known districts (as that of Schemnitz) are not represented among recent analyses. A considerable number (41) are of Bohemian rocks, rather sodic, described by Hibsch. There would seem to be an insufficient number of granitic rocks represented, but, on the whole, the Austrian average is more satisfactory than that of Germany and may be considered as more representative, although it is in need of thorough revision by means of more and better analyses.

Switzerland-Tyrol.—The average for Switzerland is very like that for Europe. It shows about the same amount of silica and of most of the other constituents but a little more potash, so that it is sodipotassic instead of dosodic, as is the European average. The chemical uniformity of the rocks of Switzerland and the Tyrol, and the comparatively narrow limits of variation for most of the rocks are perhaps the most striking features. Most of the rocks are granitic.

Average and norm for rocks of Switzerland-Tyrol (217 analyses).

Average.		Norm.	
SiO_2	60.69	Q	11.10
Al_2O_3	14.67	Or	21.13
Fe_2O_3	2.76	Ab	29.34
FeO	3.28	An	13.90
MgO	4.56	Di	5.75
CaO	4.37	Hy	11.44
Na_2O	3.52	Mt	3.94
K_2O	3.56	Il	1.22
H_2O	1.68	Ap	.34
TiO_2	.65		
P_2O_5	.19	Symbol, II.4(5).2″.3(4).	
MnO	.03		
Inclusive	.04		
	100.00		

This average is made up of rocks from Switzerland and the Tyrol. About 70 per cent of the analyses represent Swiss rocks, and the remaining 30 per cent is about equally divided between the Monzoni-Predazzo massifs and the rest of the Tyrol. Most of the analyses of Swiss rocks were made by the late Fräulein Hezner and have been or are being published by Grubenmann. These analyses are of exceptionally high average quality except for the deplorable paucity of determinations of the minor constituents. The proportion of inferior analyses is lower than that for almost any other country. They are of much better quality than the analyses of Austrian rocks.

The area is remarkably uniform in chemical character. Most of the rocks are granitic, yet there are a few small areas of rocks with a decidedly sodic cast, notably those of Monzoni-Predazzo, but dikes of diabase and such femic rocks do not seem to be abundant. Although the rocks of the Monzoni center have been the object of special interest and much study, their analyses are probably not unduly represented in the average. The average for the Switzerland-Tyrol area may be considered representative—easily the most representative among the European averages. It is, indeed, among the half dozen best averages here considered except—it must be repeated—for the deplorable neglect of the minor constituents, the determination of which would have been of great interest.

Italy.—The analyses of the rocks of Sicily, Sardinia, Pantelleria, and Linosa are included with those of the peninsula of Italy. The average for Italy shows rather high alumina, very high potash, and a high ratio of potash to soda, its potash percentage being equaled only by that of the Arkansas-Texas area. The titanic oxide is about that of the European average, but there are perceptible though small amounts of zirconia and baria. The percentage of manganese is much too low.

Average and norm for rocks of Italy (276 analyses).

Average.		Norm.	
SiO_2	58.98	Q	5.52
Al_2O_3	16.28	Or	27.80
Fe_2O_3	2.53	Ab	31.44
FeO	3.44	An	13.90
MgO	3.03	Di	7.82
CaO	5.16	Hy	6.62
Na_2O	3.72	Mt	3.71
K_2O	4.67	Il	1.67
H_2O	.94	Ap	.67
TiO_2	.85		
P_2O_5	.22	Symbol, II.″5.2.3.	
MnO	.04		
Inclusive	.14		
	100.00		

The most important areal factors that go to make up the Italian average are the Eocene gabbroic rocks of Liguria, Tuscany, and other parts of northwestern Italy; numerous intrusions of granitic rocks in northern Italy, at Elba and other coastal islands, along the Apennines, and in southern Italy; the so-called Roman region, embracing the row of volcanoes from Lake Bolsena (and possibly from Monte Amiata) to Vesuvius, the lavas of which are mostly leucitic, including many trachytes, and some andesites and basalts; the basaltic subareas of Etna and Val di Noto on Sicily and the basaltic-rhyolitic Aeolian Islands; the island of Sardinia, which is composed principally of large areas of granitic rocks that have been little studied and many extinct volcanoes, large and small, the rocks of which are decidedly sodic; the island of Pantelleria, with its highly sodic rocks; and the small basaltic island of Linosa. Corsica should probably be included in the Italian average, rather than in that of France. The rocks of the Euganean and Berici hills and of Monte Vulture and the Ponza Islands are inadequately represented.

Reckoning up roughly the relative importance and number of analyses of the rocks of the chief districts of Italy, we find that they are very unevenly represented. There are a few usable analyses of the early gabbroic rocks, and there is a fairly representative number of the granitic rocks of north Italy, but there are none of these rocks of southern Italy. The main western row of volcanoes is by far the best represented, many analyses of their lavas having been published by the junior author and by Lacroix (Vesuvius). There is a fair number of analyses of the lavas of the Sardinian volcanoes, but none of its abundant granitic rocks. The basalts of Sicily are inadequately represented, but there are many analyses of the lavas of the Aeolian Islands, and the number for Pantelleria and Linosa are ample for the size of the areas. There are many gaps, some areas are overrepresented, and some areas are underrepresented.

It is rather difficult to decide whether the average for Italy is fairly representative or not. That a part of the area is potassic is evident from the abundance of leucitic and trachytic rocks in the Roman region, and this fact is shown in the average as its most characteristic feature. The normatively high silica, which seems to be inconsistent with the abundance of leucite, is in harmony with the number of granitic rocks, and their aggregate amount is so great that the average silica might justly be even slightly higher. On the whole, we are inclined to think that the average for Italy shows fairly well the general character of the whole rather heterogeneous area.

Russia.—The area included in Russia as here considered comprises the Ural Mountains, the Caucasus, the Crimea, and some scattered districts. It does not include Finland and the Kola Peninsula, which are considered elsewhere.

The average is markedly different from the other European averages. The silica is the lowest; the iron oxides, magnesia, and lime are high, and the alkalies are low. Here, again, the minor constituents are almost wholly neglected, and it would have been interesting to have data as to some of them in connection with a general average that is so peculiar. The Russian average resembles most closely that of the Antarctic Continent, and although its content of silica is about the same as that in the averages for Canada and Madagascar, these are much higher in alkalies and lower in iron oxides, magnesia, and lime. The norm shows that the average is near salfemane and is almost docalcic.

Average and norm for rocks of Russia (98 analyses).

Average.		Norm.	
SiO_2	54.22	Q	5.88
Al_2O_3	16.30	Or	11.12
Fe_2O_3	4.28	Ab	25.15
FeO	5.54	An	25.58
MgO	5.02	Di	9.88
CaO	7.60	Hy	13.62
Na_2O	2.99	Mt	6.26
K_2O	1.92	Il	1.22
H_2O	1.17		
TiO_2	.66	Symbol, II.(4)5.3″.4.	
P_2O_5	.07		
MnO	.14		
Inclusive	.09		
	100.00		

The Russian average is dominated by the analyses of rocks from the Ural Mountains, which have been described by Duparc and his collaborators. These analyses number forty-nine, about one-half of the whole. These Ural rocks are mostly gabbros, pyroxenites, dunites, and other highly femic kinds; they include very few granites, syenites, anorthosites, and nephelite syenites. The used analyses of rocks from the Caucasus represent granite, dacite, and andesite, but the good analyses of them number only 11. The Caucasus area should probably be placed with the Balkans, not with Russia. The Caucasus rocks thus have little effect on the average; those of the Crimea, of which the analyses are still fewer, have still less.

There are large areas of granitic rocks in Russia, especially in its northern part, and of these there are an inadequate number of analyses among our data. Many analyses of Russian rocks have been published only in the Russian language, and few of these have been used here.

The average for Russia must be regarded as unsatisfactory and not representative, for several reasons. The area covered is very large and is divisible into at least five chief comagmatic regions; the granitic region of northern Russia; the Ural Mountains (possibly divisible into at least two subregions); the Crimea and Mariupol (which is probably a separate region); the plains of southern Russia (including Volhynia), in which exposures of igneous rocks are rare but sufficient to indicate their existence; and the Caucasus, which may best be referred to some Anatolian connection. None of these is sufficiently represented except the Ural Mountains, studied by Duparc, and even many of the analyses for those mountains are not exceptionally good, and in almost none of the analyses of Russian rocks are the minor constituents determined.

The average, if regarded as one for the Urals, is probably fairly representative, but it can not be accepted as a satisfactory average for the whole of European Russia. It is probably too low in silica, too calcic, and otherwise not representative.

Balkan Peninsula.—The islands of the Greek Archipelago and a few localities in western Asia Minor are here included with the peninsular countries, the Balkan States and Greece. The average for this region presents a striking contrast to that for Russia, as it is the highest in silica among all the European averages and in this respect stands next to that of Utah-Nevada among all the averages. With this high content of silica it is naturally low in the other constituents, which occur in much the same proportions as in the European average. The norm shows that it falls in persalane, as does also that for Utah-Nevada, the two resembling each other in many respects.

Average and norm for rocks of the Balkan Peninsula (33 analyses).

Average.		Norm.	
SiO_2	64.73	Q	21.06
Al_2O_3	15.92	Or	15.57
Fe_2O_3	3.15	Ab	31.44
FeO	2.28	An	18.90
MgO	1.76	Di	2.65
CaO	4.49	Hy	4.19
Na_2O	3.69	Mt	4.64
K_2O	2.56	Il	.61
H_2O	1.03		
TiO_2	.31		
P_2O_5	.03		
MnO	.03		
Inclusive	.02		
	100.00		

Symbol, I(II).4.3.4.

The analyses of rocks from the Balkan area are so few as to be, perhaps, not quite representative, yet the rocks of the area are on the whole so generally alike that this factor is of less moment than it would be with a larger area.

The largest groups of analyses are eleven from Aegina and Methana (not of very satisfactory quality), six from Santorini, and five from Asia Minor. A few of the granites of the Greek mainland are represented, but none of the rather abundant gabbros, all the analyses published by Lepsius being of altered rocks so that they are not included among our data. The lavas of Milos and Nisyros, and other small volcanic islands are not represented. There are two analyses each of Rumanian and Montenegrin rocks, but none of those of Bosnia, Bulgaria, or Serbia. On the whole, however, in spite of its manifest defects, the average for the Balkans probably represents very well the chemical character of the rocks of the area. It should be noted that the analyses, with scarcely an exception, represent volcanic lavas, most of them somewhat glassy, a fact that has a bearing on some other problems.

Average for Europe.—The average for Europe is almost a replica of that for the whole earth—that is, it is a thoroughly average average. It also resembles closely that for North America, which, however, is very slightly more sodic, although the three are in substantial agreement.

Average and norm for rocks of Europe (1,985 analyses).

Average.		Norm.	
SiO_2	59.84	Q	10.50
Al_2O_3	15.12	Or	20.02
Fe_2O_3	3.17	Ab	31.44
FeO	3.67	An	14.46
MgO	3.61	Di	6.67
CaO	4.97	Hy	8.71
Na_2O	3.73	Mt	4.64
K_2O	3.40	Il	1.52
H_2O	1.24	Ap	.67
TiO_2	.83		
P_2O_5	.23		
MnO	.08		
Inclusive	.11		
	100.00		

Symbol, II.(4)5.2(3).(3)4.

The average for Europe can not be said to be greatly dominated by the analyses for any one country. Those of Germany are the most numerous, forming about 24 per cent and with the Austrian about 31 per cent. These averages are not quite femic enough and are slightly too high in silica. The next most numerous group, that of Fennoscandia, forms about 19 per cent, and then come Italy, Switzerland, Great Britain, and France in the order named, with the quotas of Russia, Spain, and the Balkans practically negligible and more or less mutually compensatory.

The averages for Great Britain, France, Fennoscandia, Switzerland, and Italy are fairly representative of their respective areas and as these together make up just 60 per cent of the analyses for Europe, and as the 9 per cent of analyses of the smaller groups is negligible, the averages of the five countries named largely compensate for the defects of the German and Austrian averages, especially as the Austrian average is probably not very far astray. The compensation is, however, probably not quite complete, so that the average for Europe must be regarded as fairly representative but somewhat too salic and too high in silica. It is also deficient in that the minor constituents are not properly represented, titanic oxide and manganese being too low and the others being almost entirely neglected. It is unfortunate that so good an opportunity for a study of the distribution of the rarer elements as was afforded by the numerous and varied European analyses has been passed by—an opportunity that will probably never return.

AFRICA.

The analyses of the rocks of Africa number 223 and are distributed as shown below. They are so few for so large a continent and they represent areas so widely scattered that we have not yet calculated the averages for different areas within the continental area, although we have calculated that for Madagascar and Reunion.

Madagascar.—The analyses of rocks from Reunion are included in this average. The average is different from almost all those that we have been examining, although it shows some resemblance to those of Greenland, East Canada, and East Brazil. The low silica and its distinctly alkalic and dominantly sodic characters are well marked. An interesting minor feature in the complete average is the notable percentage (0.09) of zirconia, which reminds us of that of the Greenland average. Baria unfortunately was not determined, and manganese, of which there were only seven determinations, is much too low. The norm shows that this average is among the few in which there is no excess of silica but a little olivine, although there is no normative nephelite.

Average and norm for rocks of Madagascar (140 analyses).

Average.		Norm.	
SiO_2	54.67	Or	18.35
Al_2O_3	16.21	Ab	36.68
Fe_2O_3	3.02	An	15.57
FeO	4.93	Di	11.15
MgO	4.21	Hy	8.14
CaO	6.51	Ol	.80
Na_2O	4.36	Mt	4.41
K_2O	3.05	Il	2.74
H_2O	1.13	Ap	1.01
TiO_2	1.44		
ZrO_2	.09		
P_2O_5	.35		
MnO	.01		
Inclusive	.02		
	100.00		

Symbol, II.5.2″.″4.

We owe our knowledge of the chemistry of the rocks of Madagascar and of Reunion almost wholly to Lacroix. Since the analyses that we have used were published, Lacroix has had made and has published many more analyses of the rocks of Madagascar, so that this island is probably the one noncontinental area for which we have a great number of data. It is not practicable nor necessary here to divide the island of Madagascar into separate regions. The inclusion of the 28 analyses of the rocks of Reunion has but a very slight effect. They form only 20 per cent of the whole number of analyses, and nearly all of them have their counterparts among those of Madagascar. The rocks of Reunion are somewhat more basaltic than those of Madagascar, so that the average as given here is slightly lower in silica, more femic, and less alkalic than it should be. But the difference can be but slight, and is probably quite negligible, so that the average for Madagascar is among the best and most representative of those here given.

Average for continental Africa.—For reasons given above, the continent of Africa will be considered here as a whole, without division into separate small areas. The averages for Madagascar and the islands to the west will not be considered.

The average for Africa is lower in silica than most of the others and is notably alkalic and sodic. It most resembles that of Norway, and it is also somewhat close to that of East Brazil, but it is altogether unsatisfactory. The complete average includes some zirconia, and the manganese is notably low because of its nondetermination in many analyses.

Average and norm for rocks of continental Africa (223 analyses).

Average.		Norm.	
SiO_2	58.21	Q	3.66
Al_2O_3	15.28	Or	19.46
Fe_2O_3	3.52	Ab	40.87
FeO	3.73	An	10.29
MgO	3.51	Di	11.34
CaO	5.09	Hy	6.02
Na_2O	4.83	Mt	5.10
K_2O	3.28	Il	1.52
H_2O	1.26	Ap	.34
TiO_2	.84		
ZrO_2	.02	Symbol, II.5.2.4.	
P_2O_5	.20		
MnO	.07		
Inclusive	.16		
	100.00		

We have little or no exact information as to the chemistry or even the petrography of the rocks of the interior of the African continent, nearly all the specimens analyzed having been collected near the coast. We may, however, glean some approximate knowledge of the rocks of the interior from incidental remarks in narratives of travel and from some more exact statements as to the rocks, although without analyses, that are found in geologic papers. The petrology of the continent of Africa, therefore, like that of most of the other continents, is very imperfectly known.

The analyses used for the average of Africa are fairly numerous, about twice as many as those for the much larger continent of Asia, and considerably more than those for South America. Most of them represent localities near the coast, yet they are rather well distributed along it, although there are some very notable gaps.

Of areas along the Ethiopian Rift Valley the analyses represent especially rocks from Abyssinia (4 analyses), described by Prior; Eritrea (28), described by Manasse; French Somali (14), described by Arsandaux; British East Africa (5) described by Prior; and the districts of Lake Kivu (19) and Kilimanjaro (9), in Tanganyika Territory, formerly German East Africa, described by Finckh. All these rocks are very alkalic and dominantly sodic. There is a long interval of unknown rocks along the east coast, extending from British Somali to Lourenco Marques, including Zanzibar and Mozambique.

In South Africa the best-known areas are those of highly sodic rocks in the Transvaal, described by Brouwer, who gives us 13 good analyses. There are some 28 usable analyses from other localities in the Transvaal, Cape Colony, and Natal. Altogether there are about 40 from South Africa—not a large number of good analyses from such a large, important, and diversified area.

We find among our data no analyses to represent German Southwest Africa, Angola, Belgian Congo, or the coastal portion of French Congo. There are 10 analyses from two districts in the Cameroon (described by Esch) and about 30 from French Guinea (including the Los Islands) and the Ivory Coast, described by Lacroix. There are four from the district of Lake Chad in the interior. There are five from Cape Verde in French Senegal, but none from Mauretania, farther north, and but two or three from Morocco. Practically all these rocks along the west coast are strongly alkalic, and most of them are sodic.

When we come to the northern coast of Africa we meet another serious gap. Duparc gives us 39 analyses of rocks from one district in Algeria, of which only 14 are usable, although the others are closely similar in character. There are but two from Tripoli, and these do not appear to represent the common rocks of this region. We have none from the Cyrenaica, and only 16 from Egypt and Kordofan. These rocks of north Africa, it may be noted, are distinctly more silicic and less sodic (except those between the Nile and the Red Sea) than those on or near the east and west coasts.

The average for Africa is thus made up almost entirely of analyses of rocks from the coast; it is without adequate representation of the interior; but even for rocks along the coast there are long gaps in the data. The average is therefore not very satisfactory; it is almost undoubtedly too alkalic and too sodic and is probably too low in silica and the femic constituents. Many more data are needed for Africa, even for some of its well-known parts.

ATLANTIC ISLANDS.

The average for the islands in the Atlantic Ocean includes analyses of rocks from the Azores, Madeira, Canary, Cape Verde, Ascension, and St. Helena islands. It differs widely from those already given in its low silica, rather high iron oxides, magnesia, and lime, and it includes a notable amount of the two alkalies. It is almost basaltic, and the femic constituents are so high that, as shown by the norm, it is nearly in salfemane. At the same time, the norm shows a little normative nephelite, the average resembling in this respect those of the Pacific Islands and Greenland, the only others that show the same feature. The average suffers from the defect already mentioned, that of neglect in the determination of the minor constituents. For this reason, manganese is unquestionably too low, and probably titanic oxide also. The average shows that no attention has been paid to baria or to strontia. It also shows, however, some chlorine and sulphur trioxide.

Average and norm for rocks of the Atlantic Islands (56 analyses).

Average.		Norm.	
SiO_2	50.59	Or	13.34
Al_2O_3	15.81	Ab	33.80
Fe_2O_3	4.44	An	18.35
FeO	5.79	Ne	1.28
MgO	5.79	Di	12.20
CaO	7.36	Ol	9.35
Na_2O	4.27	Mt	6.50
K_2O	2.31	Il	3.04
H_2O	1.47	Ap	1.39
TiO_2	1.63		
P_2O_5	.43		
MnO	.04		
Inclusive	.07		
	100.00		

Symbol, II''.5.''3.4.

The average for the Atlantic islands is clearly dominated by the 32 analyses of rocks from Madeira, described by Gagel. The analyses of rocks from the Azores, Canary, Cape Verde, and Ascension islands consist of small groups of four to seven, and there is one each from St. Helena and Gough's Island. There may perhaps be a slightly undue representation of "interesting" sodic rocks, which gives the average its distinctly alkalic and sodic cast. This is true of the rocks of Madeira, of which there is a fairly adequate representation, and this cast may be considered a marked character of the Atlantic islands rocks. To complete the average for the Atlantic islands analyses of rocks from Fernando Noronha and from St. Paul's Rocks should be included. But these islands are small, and their omission is not a serious defect. On the whole, the average may be considered fairly satisfactory, but we are much in need of more analyses from the large islands and island groups.

ASIA.

The data for Asia are like those for Africa in that the analyses which represent the continental mass are so few and inadequate that no averages can be calculated for any separate areas on the continent. Indeed, the total number of analyses (114) for Asia, in spite of its much greater size, is fewer than that of Africa. We have, however, two groups of fairly numerous analyses to represent the adjacent island areas of Japan and Malaysia, which we shall consider separately before taking up the Asiatic continent.

Japan.—The average for Japan belongs to the group of those which are high in silica, such as those for Appalachia, Alaska, Utah-Nevada, and the Andes. The content of normative quartz and that of the feldspars is indeed so high that the average is almost in the persalane class, as are those just mentioned. It differs, however, from most of these in its lower alkalies and relatively higher lime, so that it is distinctly alkalicalcic. It resembles most the averages for Alaska and the Andes, although the Japanese average is somewhat lower in alkalies, and it also bears a marked similarity to the average for the West Indies, although that is distinctly higher in lime and lower in silica.

Average and norm for rocks of Japan (69 analyses).

Average.		Norm.	
SiO_2	61.81	Q	18.24
Al_2O_3	15.73	Or	15.01
Fe_2O_3	2.07	Ab	26.20
FeO	4.41	An	21.41
MgO	2.49	Di	1.83
CaO	5.16	Hy	10.58
Na_2O	3.11	Mt	3.02
K_2O	2.51	Il	1.52
H_2O	1.48	Ap	.67
TiO_2	.76		
P_2O_5	.27		
MnO	.17		
Inclusive	.03		
	100.00		

Symbol, "II.4.3.(3)4.

The analyses on which the Japanese average is based are fairly numerous and seem to be well distributed over nearly all the chief areas. Most of them, however, are analyses of volcanic rocks; the abundant granites are not quite sufficiently well represented. The inclusion of more analyses of granitic rocks, however, would probably not have a very disturbing effect on the average, which may be considered fairly representative, especially in view of the apparent and rather remarkable general uniformity among Japanese igneous rocks.

Malaysia.—Malaysia is made up of the large islands of the Dutch East Indies (Sumatra, Java, Timor, Borneo, and Celebes) and a few smaller, dependent islands (as Bawean), the Moluccas, and the Philippines.

The average for Malaysia differs widely from that for Japan and is almost identical with those for Europe and the earth. The most interesting features are shown among the minor constituents, and for their determination we are indebted to the long series of excellent and very complete analyses of rocks from the Dutch East Indies made by Dr. E. W. Morley for Iddings. These analyses show that in this area zirconia is almost entirely absent, being present in traces (up to 0.02) in only a few of the more salic and sodic rocks. On the other hand, the analyses show large amounts of baria and strontia, up to about 0.25 per cent. The amount of chromium is small, smaller than that in the Pacific Islands. The possibility of establishing such relations as these among the minor constituents emphasizes the need of determining these chemical constituents, which are so frequently neglected.

Average and norm for rocks of Malaysia (129 analyses).

Average.		Norm.	
SiO_2	59.72	Q	9.42
Al_2O_3	16.51	Or	17.79
Fe_2O_3	3.18	Ab	31.96
FeO	2.95	An	19.18
MgO	3.03	Di	6.86
CaO	5.76	Hy	7.18
Na_2O	3.78	Mt	4.64
K_2O	3.05	Il	.91
H_2O	1.11	Ap	.34
TiO_2	.50		
P_2O_5	.18		
MnO	.14		
BaO	.03		
Inclusive	.06		
	100.00		

Symbol, II.(4)5."3."4.

In view of the number of volcanoes in Malaysia and the variety of their lavas, the total number of analyses of lavas is not so great as might be desired. Several large series of analyses of rocks from different islands of Malaysia have recently been made by Morley and published by Iddings, and these will be invaluable for a future estimate or study of the rocks of the region. A few of these analyses have been included in the data. The analyses used are fairly well distributed, although those representing Sumatra are the most numerous (37), but many of them are not of the best quality. After Sumatra come Java, the Moluccas, Celebes, and the Philippines, each with about the same number of analyses. Only six represent rocks from Borneo. Although many more analyses are needed, the average is fairly satisfactory and probably shows well the general character of the rocks of the area.

Average for continental Asia.—The immense continent of Asia is represented by remarkably few analyses. The averages for Japan and Malaysia are considered above.

The average is very high in silica, like the averages for Japan, Alaska, Utah-Nevada, and the Andes, but it is otherwise not especially noteworthy except that it is relatively so high in alkalies as to be domalkalic, like the Utah-Nevada average, and not alkalicalcic, like those of Japan, Alaska, and the Andes. It is also one of the few that are almost in the persalane class.

Average and norm for rocks of continental Asia (114 analyses).

Average.		Norm.	
SiO_2	61.92	Q	13.32
Al_2O_3	15.49	Or	18.90
Fe_2O_3	3.17	Ab	34.58
FeO	2.75	An	14.73
MgO	2.63	Di	5.31
CaO	4.50	Hy	5.66
Na_2O	4.10	Mt	4.64
K_2O	3.23	Il	1.22
H_2O	1.23	Ap	.34
TiO_2	.68	Symbol, ″II.4″.2(3).″4.	
P_2O_5	.12		
MnO	.10		
Inclusive	.08		
	100.00		

The average for continental Asia is not dominated especially by the analyses of any one district except Siberia. The rocks of Asia are so little known petrographically and chemically that safe generalizations concerning them are scarcely possible. We find, for instance, that the great plateau of Pamir and Tibet is unrepresented, and that the vast expanse of Siberia is represented, at least in our data, by only 51 analyses, a number quite inadequate. There are no analyses of the extensive flows that constitute the traps of Siberia and only scattering analyses of the other fundamental igneous rocks of this area. Similarly, there are among our data but eight mostly rather indifferent analyses to represent the great peninsula of India, and not a single analysis of the enormous flows of the Dekkan traps, which cover about one-seventh of the area.[57a] Of the rocks of Turkestan we have six analyses, and Lacroix has recently published a few analyses of the rocks near Trebizond. Of the rocks of Afghanistan and the adjacent regions there are no analyses. Of the igneous rocks of the vast expanse of China the analyses are lamentably few (21) and they are unsatisfactory as to quality. Of the rocks of Arabia we have a few—six of those of the volcano of Aden published by Manasse. Asia Minor, with its many distinct and interesting comagmatic regions, is represented by but six analyses, and much the same may be said of Indo-China. In fact the whole continent of Asia is petrologically and chemically unknown.

AUSTRALASIA.

The term Australasia includes Australia, Tasmania, New Zealand, and a few small adjacent island groups. The analyses available number 421. We shall discuss here separately the averages for Australia and for New Zealand, but not the combined average for the two.

Australia.—The average for Australia includes the few analyses of rocks from Tasmania, which is structurally a part of the larger mass. The average is much like those of Europe and of the earth, differing only in the slightly lower amount of alkalies. The analyses show small amounts of zirconia, nickel, and baria.

Average and norm for rocks of Australia (287 analyses).

Average.		Norm.	
SiO_2	60.16	Q	12.48
Al_2O_3	14.74	Or	17.79
Fe_2O_3	2.60	Ab	29.34
FeO	4.41	An	15.57
MgO	3.76	Di	5.88
CaO	5.03	Hy	10.77
Na_2O	3.50	Mt	3.71
K_2O	3.03	Il	1.98
H_2O	1.19	Ap	.67
TiO_2	1.01	Symbol, II.4″.3.(3)4.	
P_2O_5	.26		
MnO	.15		
Inclusive	.16		
	100.00		

The average for Australia resembles the averages for South America, Africa, and Asia in being based almost exclusively on analyses of rocks from areas near the coast. The east coast is best represented, the analyses of rocks from New South Wales being the most numerous, although those of rocks from Victoria and Queensland are almost as numerous. South Australia has only 13, and Western Australia only 27. The Northern Territory and Central Australia seem to be unrepresented. Tasmania is represented by but 11 analyses. The rocks of the eastern coast of Australia are distinctly more alkalic and sodic than those of Western Australia, which are more alkalicalcic and probably rather higher in silica. The rocks of Tasmania resemble those of the eastern coast.

The analyses of Australian rocks are of very good quality—most of them are excellent—and in a large proportion of them the minor constituents are determined with great completeness. Indeed, the analyses of the rocks of Australia in general and most of those of the rocks of the United States, those of the

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[57a] Washington, H. S., Deccan traps and other plateau basalts: Geol. Soc. America Bull., vol. 33, p. 765, 1922.

rocks of British Guiana (by Harrison), and the more recent analyses of the rocks of Canada and Great Britain stand in a class apart in this respect. The greater number of the analyses of European rocks suffer by comparison with them.

The analyses of Australian rocks are numerous in comparison with the areas they represent and, in view of their excellent quality, may be called very fully representative. The trend of the rocks of the interior and the less studied areas in the north and west would seem to indicate that the final average for the whole continent will probably be somewhat higher in silica and lower in alkalies.

New Zealand.—The average for New Zealand includes the results of a few analyses of rocks of the neighboring islands, such as Auckland and Antipodes. The average resembles that of Australia but differs from it in slight though probably significant respects. It is lower in silica by 2 per cent, so that there is much less quartz in the norm, and the average is perfelic, not quardofelic, like that of Australia. Although it shows about the same amount of alkalies as the average for Australia, the average for New Zealand shows a little more soda, so that it is distinctly more sodic, which compensates for the slightly higher lime. The minor constituents have not been determined as frequently in the analyses of the rocks of New Zealand as in those of Australia, but the rocks of New Zealand contain 0.04 per cent of chromium sesquioxide, which is not found in the rocks of Australia. The titanic oxide should probably be a trifle higher, and its increase would decrease by that amount the apparently high alumina.

Average and norm for rocks of New Zealand (134 analyses).

Average.		Norm.	
SiO_2	58.04	Q	8.70
Al_2O_3	15.30	Or	17.24
Fe_2O_3	3.83	Ab	31.96
FeO	3.99	An	16.40
MgO	3.95	Di	7.53
CaO	5.39	Hy	9.34
Na_2O	3.78	Mt	5.57
K_2O	2.93	Il	1.37
H_2O	1.70	Ap	.34
TiO_2	.71	Symbol, II.(4)5.″3.″4.	
P_2O_5	.19		
MnO	.09		
Inclusive	.10		
	100.00		

The North and South islands of New Zealand seem to be almost equally represented by analyses. There is a slight preponderance of those from the South Island, where the province of Otago, and especially the neighborhood of Dunedin, is represented by the most analyses. In the North Island the Hauraki district is represented by the most analyses. The few analyses of rocks from the neighboring islands have no appreciable effect on the average. The analyses for New Zealand are not as complete as those for Australia, but they are of good quality, are fairly numerous, and are pretty well distributed, although most of the rocks analyzed are those of mining regions and not many are from the New Zealand volcanoes. The average probably represents the general character of the area.

POLYNESIA.

The islands in the Pacific Ocean are here grouped under the name Polynesia, although the average given includes a few analyses of rocks from islands in Melanesia and Micronesia. The analyses available number 72.

The average is strikingly different from nearly all the others, except that for the Atlantic islands. The silica in the Polynesian average is lower than that in any other, and the whole character of the average is that of a nearly typical basalt. The norm shows that it is almost in salfemane, even nearer the border than the average for the Atlantic islands. This fact is in harmony with the detailed chemical character, the Polynesian average showing about the same amount of iron oxide, a little more magnesia, lime, and titanic oxide, and a little less of the alkalies. There is a small amount of chromium; that shown in the average (0.01) is almost certainly too low.

Average and norm for rocks of Polynesia (72 analyses).

Average.		Norm.	
SiO_2	50.03	Or	12.23
Al_2O_3	15.51	Ab	30.65
Fe_2O_3	3.88	An	18.07
FeO	6.23	Ne	1.85
MgO	6.62	Di	15.76
CaO	7.99	Ol	10.01
Na_2O	4.00	Mt	5.57
K_2O	2.10	Il	3.80
H_2O	1.16	Ap	.67
TiO_2	1.96	Symbol, II(III).5.″3.4.	
P_2O_5	.25		
MnO	.15		
Inclusive	.12		
	100.00		

The analyses that were included in the data used by us—that is, all those of good quality in Professional Paper 99—are neither numerous nor well distributed. Those for the Hawaiian Islands (43) make up about 60 per cent. There are 19 for the Society Islands (nearly all from Tahiti), 5 from Samoa, and the rest are scattered. A rather large proportion of the analyses for Hawaii and most of those for Tahiti are decidedly alkalic, and are therefore especially "interesting," and these analyses therefore have a very marked effect on the average. This fact was pointed out some years ago by Iddings,[58] who suggested that the average for the whole of the Pacific islands is truly much more basaltic—that is, it should be more calcic and generally femic (though with about the same amount of silica), and distinctly less alkalic.

Iddings's suggestion is sustained by the rather numerous analyses of rocks from the Pacific islands that have recently been published, many of them by Lacroix and Iddings, as well as by a series of analyses of Hawaiian and Samoan rocks that are now being made by the junior author of this paper. The analyses for the Society Islands, for example, are thus brought up from 19 to 47, those for Samoa from 5 to 20, those for Fiji from 1 to 11, and so on. The total number of good published analyses of rocks from the Pacific now amounts to about 150, more than twice as many as we had at our disposal. The usable analyses of rocks from Hawaii now number 56.

These new data, then, make it clear that the true Pacific average should be changed somewhat in accordance with Iddings's suggestion, and we shall probably soon be able to calculate a new average for the Pacific islands. The evidence at hand, however, shows that alkalic and more specially sodic rocks are rather abundant in the Pacific islands, a point on which Lacroix[59] lays special stress, so that their effect on a new average will not be entirely negligible and may be considerably greater than was supposed by Iddings. The present condition of our knowledge of the chemistry of the rocks of the Pacific islands has been recently described.[60]

THE ANTARCTIC CONTINENT AND ISLANDS.

The Antarctic average includes the results of analyses of rocks from some adjacent islands as well as of those from the continental mass itself. The analyses number 103. The average is notable for its low silica and its generally somewhat femic character, so that it approaches the salfemane class, as shown by the norm. At the same time the alkalies are high. In these respects the average is like that for East Canada and is not far from that for Greenland, although the alkalies in the rocks of Greenland are much higher; indeed, we may say that the Antarctic average is about halfway between the average for Greenland and those for the Atlantic and Pacific islands. The norm shows that, although there is no normative nephelite (indicating a deficiency of silica), as there is in these three, yet that the Antarctic average shows but a slight excess of silica, very much less than in most of the averages.

Average and norm for rocks of Antarctic Continent and islands (103 analyses).

Average.		Norm.	
SiO_2	53.66	Q	1.86
Al_2O_3	16.82	Or	13.34
Fe_2O_3	4.01	Ab	30.39
FeO	5.34	An	23.07
MgO	4.67	Di	11.18
CaO	7.59	Hy	11.33
Na_2O	3.58	Mt	5.80
K_2O	2.32	Il	1.67
H_2O	.93	Ap	.34
TiO_2	.87		
P_2O_5	.17	Symbol, II.5.3.4.	
MnO	.03		
Inclusive	.01		
	100.00		

The Antarctic average is under the same disadvantage as that for Greenland; the interior is so thickly covered with ice that nearly all the rock exposures lie near the coast. On this account we know and probably shall always know less of its interior than of the interior of South America, Africa, Asia, or Australia.

The analyses are pretty evenly divided between the Victoria quadrant (30) and the Wed-

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[58] Iddings, J. P., Relative densities of igneous rocks calculated from their norms: Am. Jour. Sci., 4th ser., vol. 49, p. 365, 1920; The problem of volcanism, p. 125, 1914.

[59] Lacroix, A., Les roches alcalines de Tahiti: Soc. géol. France Bull., 4th ser., vol. 10, p. 124, 1910.

[60] Washington, H. S., The chemistry of the Pacific volcanoes; the limitations of our knowledge: First Pan-Pacific Sci. Conference Proc., Bernice P. Bishop Mus. Sp. Pub. 7, pt. 2, pp. 325-345, 1921; Petrology of the Hawaiian islands: Am. Jour. Sci., 5th ser., vol. 5 pp. 465-502 et seq., 1923.

dell quadrant (37). Only about four are from the Gaussberg, in the Enderby quadrant, and a few are from small scattered islands. Some analyses of rocks from parts of the Antarctic have recently been published, but they are not considered here. The average probably represents rather well the characters of the border, but many more data are to be desired.

The rocks in the Victoria quadrant, which lies south of the Pacific and of eastern Australia, are generally strongly alkalic and sodic; those in the Weddell quadrant, south of South America and of the western Atlantic, are much less sodic and much more calcic—that is, they are much more like the most common kinds such as we find along the Andes. We have so few analyses of rocks from the Enderby quadrant (only the few from the Gaussberg) that they may not be significant in showing the relations of this area to the areas in the Indian Ocean, which lies to the north.

AVERAGE FOR THE EARTH.

The final average for the igneous rocks of the earth, as calculated from the 5,159 analyses used, is repeated here. To make it comparable with the areal averages discussed in the preceding pages the percentages of TiO_2, P_2O_5, and MnO are given, but the percentages of all the other minor constituents given in Table 10 are added together and are included in their sum.

This being the average of all known igneous rocks analyzed, and used by us, we can not well say that any constituent is either "high" or "low." The percentage given for each constituent may be regarded as the standard to which those in other averages of rock analyses may be referred.

Average and norm for rocks of the earth (5,159 analyses).

Average.	
SiO_2	59.12
Al_2O_3	15.34
Fe_2O_3	3.08
FeO	3.80
MgO	3.49
CaO	5.08
Na_2O	3.84
K_2O	3.13
H_2O	1.15
TiO_2	1.05
P_2O_5	.30
MnO	.12
Inclusive	.50
	100.00

Norm.	
Q	10.02
Or	18.35
Ab	32.49
An	15.29
Di	6.45
Hy	8.64
Mt	4.41
Il	1.98
Ap	.67

Symbol, II.4(5).2(3).''4.

The average for the earth resembles most closely the averages for Europe and North America and slightly less the average for Australia.

The percentage of silica corresponds closely with the mean of the silica in the so-called "intermediate," "medium," or "medio-silicic" rocks, the silica limits of which range from 66 or 65 to 55 or 52 per cent. It would thus appear that the rough idea of what constitutes an average rock based on general, largely qualitative knowledge is corroborated by more exact quantitative statistical study. The percentages of the two iron oxides are nearly alike, as are those of the two alkalies, and the ferrous oxide and soda are, respectively, the higher in each. Oddly enough, each pair is almost a duplicate of the other. Magnesia falls in between the extremes of each of these pairs, and the percentage of lime is distinctly higher. The percentage of water would seem to be a little high in view of the fact that analyses of only supposedly fresh rocks have been used. The notably large amount of titanium is considered elsewhere.

The average for the earth is clearly dominated by the averages for Europe and for North America, the two continents that have been most carefully studied.

The relative proportions of the analyses representing the main geographic divisions and the corresponding areas are shown in Table 19. The percentage of the analyses for Europe (38.48) and for North America (33.12) together make up 71.60 per cent of all the analyses used. The percentages of the analyses from the other areas are small and do not differ greatly, Australasia having about 8, Africa (including Madagascar) about 7, and Asia (including Japan and Malaysia) about 6, and so on, down to 1 per cent for the Atlantic islands. The resemblance between the average for the earth and the average for Europe and North America is thus readily understandable. This resemblance is strengthened by the facts that a few of the averages (as that for Australia) are much like the average for the earth and that several of the averages compensate each other, as that for Asia compensates the two for the oceanic islands.

TABLE 19.—*Comparison of analyses used and areas represented.*

Area.	Quality of average.	Number of analyses.	Percentage of analyses.	Area in thousands of square miles.[a]	Percentage of land area of earth.
North America	Excellent	1,709	33.12	8,544	15.14
South America	Fair; too few analyses; chiefly border, interior little known.	138	2.67	6,861	12.16
Europe	Good	1,985	38.48	3,736	6.62
Africa: Continent	Poor; too few analyses; chiefly margin	223	4.32	11,093	19.66
Africa: Madagascar	Excellent	140	2.72	221	.39
Atlantic islands	Fair; too few analyses	56	1.08	[b] 6	.01
Asia: Continent	do	114	2.21	16,369	29.02
Asia: Japan	Good	69	1.34	141	.25
Asia: Malaysia	do	129	2.50	1,092	1.95
Australasia: Australia	East excellent, west good, center poor	287	5.56	3,045	5.40
Australasia: New Zealand	Good	134	2.60	110	.19
Polynesia	Fair	72	1.40	[c] 75	.13
The Antarctic Continent	Not representative; margin only	103	2.00	[d] 5,122	9.08
		5,159	100.00	56,415	100.00

[a] The areas (expressed in thousands of square miles) are taken from Sir John Murray (On the height of the land and the depth of the ocean: Scottish Geog. Mag., vol. 4, pp. 3-7, 1888) with the exception of those cited below.

[b] Lippincott's Gazetteer (Heilprin, editor), 1906.

[c] Estimate by R. A. Daly (Problems of the Pacific Islands: Am. Jour. Sci., 4th ser., vol. 41, p. 158, 1916).

[d] Estimate of Sir John Murray and Johan Hjort (The depths of the ocean, London, 1912).

The areas given in Table 19 include areas of sedimentary and metamorphic as well as igneous rocks, but it is not now practicable to calculate them separately. But everywhere the thin veneer of sedimentary rocks is underlain by igneous masses, so that the areas considered represent the deeper-lying parts of the continents.

Adopting for the moment the suggestion of Daly and Knopf that proportionality between areal extent and numbers of analyses is essential to representativeness, we may admit that the figures given in Table 19 may not be representative. The discrepancies between the two kinds of percentage are striking. The only area concerning which they are accordant is Australia; the analytical percentage for all the others is either much higher than the areal, or the reverse. The most striking example is continental Asia, which, although it has by far the largest area, is represented by one of the smallest relative number of analyses. The contrary is true of Europe, which, although it is represented by the highest percentage of analyses, has but a relatively small area. As compared with Asia, Europe has eighteen times as many analyses, but only two-ninths of the area.

The figures given in Table 20 below show the results of weighting the analyses of each major division of the earth according to its area.

TABLE 20.—*Averages for the earth obtained by different methods.*

	1	2	3
SiO_2	59.12	59.68	54.79
Al_2O_3	15.34	15.49	15.38
Fe_2O_3	3.08	3.22	3.67
FeO	3.80	3.57	4.86
MgO	3.49	3.33	4.93
CaO	5.08	5.00	6.56
Na_2O	3.84	4.03	4.04
K_2O	3.13	3.08	2.56
H_2O	1.15	1.15	1.17
TiO_2	1.05	.79	1.32
P_2O_5	.30	.17	.23
MnO	.12	.09	.11
Inclusive	.50	.40	.38
	100.00	100.00	100.00

1. Earth average calculated from analyses, uncorrected for areas.
2. Earth average, weighted for areas, South Atlantic and Pacific islands.
3. Earth average, weighted for areas, South Atlantic and Pacific oceans.

Column 2 represents only the land masses of the earth; in the Atlantic and Pacific areas, therefore, only the islands and their areal extensions are reckoned. The original average (column 1) closely resembles this areally weighted average. This concordance may be attributed in part to compensatory factors, notably that of the large area of Asia, which has a percentage of silica considerably above the mean and which compensates the small area of the oceanic islands, which has very low silica.

The close agreement between the two averages indicates that the average in column 1, which was obtained by simply averaging all the available analyses, corresponds closely with the average composition of the igneous rocks of the earth's crust above sea level.

Column 3 shows the result of a tentative calculation in which are reckoned the areas of the whole Pacific and the South Atlantic oceans instead of the areas of the islands in them. The North Atlantic, Indian, and Arctic oceans were not considered in this, because sufficient separate data for them were lacking. The figures are only provisional and suggestive, for they are not based on sufficient data and recalculations will be made when the results of more analyses can be tabulated. The greater weight assigned to the basaltic oceanic averages on the assumption that they represent the ocean floors of course tends to make the results more femic.

The average shows too much silica, soda, and potash for a true basalt, and rather too little silica and alumina and too much iron oxides, magnesia, and alkalies for a normal diorite or andesite. It possibly comes nearest to No. 31 of Daly's[61] averaged types, "Diorite, excluding quartz diorite."

ASSOCIATION AND DISTRIBUTION OF THE ELEMENTS.

NOTEWORTHY FEATURES SHOWN BY THE ANALYSES.

The tables of analyses already given show that about 99.5 per cent of the solid, outer crust of the earth is made up of the compounds of thirteen elements. These elements, named in the order of their abundance, are oxygen, silicon, aluminum, iron, calcium, sodium, potassium, magnesium, titanium, phosphorus, hydrogen, carbon, and manganese, which are combined in various ways to form silicates and oxides and smaller quantities of carbonates, phosphates, and other salts. The carbonates are found almost entirely in the sedimentary rocks. For the present we may limit ourselves to a consideration of the igneous rocks—those which are formed from molten magmas.

In order to frame an idea of the actual rock that would be formed under normal conditions from a magma of the average composition shown in Table 10 we must calculate its presumable mineral composition—its "mode." A magma may have solidified under either of two general conditions, which determined the products of its solidification. It may have solidified at considerable depth, slowly and under great pressure, as an intrusive rock, or it may have solidified on the surface, rapidly and under low pressure, as a lava, and the difference in the conditions of solidification would produce differences in the mineral composition of the rock formed. The intrusive rock would be a granite, a diorite, a granodiorite, or a gabbro, and the lava would be a rhyolite, an andesite, or a basalt.

The results of our calculation can be only approximately correct, for variations in the mode, of slight extent but of different effect, may be brought about by variations in the conditions of solidification. A granodiorite is a rather coarse grained holocrystalline rock composed of feldspar (orthoclase and andesine), quartz, hornblende, biotite, and very small amounts of magnetite and apatite. An andesite is generally a rather fine grained, porphyritic lava containing phenocrysts of hornblende, pyroxene, and feldspar, and possibly of biotite, in a dense groundmass. The groundmass is composed of feldspar, pyroxene (or hornblende), probably a little quartz, and small grains of magnetite and apatite. It contains some or no glass, its content of glass depending on the rapidity with which it cooled.

Stated quantitatively in terms of the modal or actual minerals the average plutonic rock and the average lava would probably have approximately the following composition:

	Granodiorite.	Andesite.
Quartz	11	10
Andesine (soda-lime feldspar)	47	47
Orthoclase (potash feldspar)	16	18
Hornblende and biotite	20	19
Pyroxene	....	
Magnetite	5	5
Apatite	1	1

Whether it is a granodiorite or an andesite the average rock, as might be expected, is composed entirely of the most common minerals. Olivine, nephelite, and leucite, though

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[61] Daly, R. A., Average chemical composition of igneous rock types: Am. Acad. Arts. and Sci. Proc., vol. 44, p. 223, 1910.

they may be called common, are not formed in rocks that contain much silica, which is abundant in the average rock. As most igneous rocks were formed at some depth beneath the surface the average igneous crust may be considered a granodiorite having the general character and mineral composition stated. Locally, of course, as has already been stated, the crustal rock shows wide variations in both chemical and mineral character. We are considering here only the average composition of the outer, visible part of the crust as a whole.

The table giving the relative abundance of the elements (Table 12, p. 29) shows some striking facts. The first is the presence among the elements most commonly determined of some that are generally considered rare. Titanium, for example, occupies the ninth place on the list, although it is generally supposed to be rare and is to many absolutely unknown. Barium, chromium, lithium, nickel, strontium, vanadium, and zirconium are also widely distributed through the crust of the earth and are determined in many of the analyses made in the laboratory of the United States Geological Survey. Copper is determined in fewer analyses, but it is generally found in small traces. Boron, glucinum, and the rare-earth metals are seldom looked for, but they must be present in many rocks in more than mere traces. The credit of having proved the importance of determining the less common elements in making analyses of igneous rocks is due to Dr. W. F. Hillebrand.[62]

Another noteworthy fact is that, of the metals in daily and common use, only aluminum, iron, manganese, chromium, vanadium, copper, and nickel appear among the elements that occur in the igneous rocks in sufficient amounts to be easily determined by the usual methods of analysis. Common and "everyday" metals like zinc, lead, tin, mercury, silver, gold, platinum, arsenic, antimony, and bismuth—metals that are essential to our civilization and our daily needs—are found in igneous rocks, if at all, in scarcely detectable amounts. Although they are derived ultimately from the igneous rocks they are made available for our use only by natural processes of concentration into ore bodies.

PETROGENIC AND METALLOGENIC ELEMENTS.

As has been often pointed out, the most abundant elements in the earth's crust are, on the whole, those of low atomic weight; the rarer ones are, in general, those higher in the scale. It is also evident that, though the first member of any vertical group in the periodic table of the elements is comparatively rare, the second and third are the most abundant (the oxygen group being the only exception), and that the members become rarer with increase of atomic weight. This fact is well seen, for example in group 1 (lithium, sodium, potassium, rubidium, caesium); in group 2 (glucinum, magnesium, calcium, strontium, barium, radium), although here we have inversions of the rule in the relative abundance of magnesium and calcium, and of strontium and barium. It is also seen in group 3 (boron, aluminum, scandium, yttrium); in group 4 (carbon, silicon, titanium, zirconium, cerium); in group 5 (nitrogen, phosphorus, vanadium, arsenic, antimony, bismuth); in group 6 (oxygen, sulphur, selenium, tellurium, here again there being an inversion of the first and second members); and in group 7 (fluorine, chlorine, bromine, iodine). We are evidently dealing here with a tendency whose meaning is yet to be discovered. That the abundance and the associations of the elements are connected with their positions in the periodic table seems, however, to be clear; the coincidences are many, the exceptions are comparatively few.

We find, therefore, that the elements may be divided into two groups as regards their occurrence in the rocks of the earth's crust, its ocean waters, and its atmosphere, and it may be added, in meteorites, either stony or iron. To the one group belong the elements that are most abundant in the crust, the ocean, and the atmosphere (though this group includes some that are less abundant), and all or most of which are readily determined and are regularly reported in analyses. These elements, which are characteristic of rocks, we may call the "rock" or "petrogenic" elements. The others are present in igneous rocks either in nondeterminable or extremely small amounts, or they are wholly absent, but they occur almost entirely in ore bodies, of which they are the characteristic elements and those for which the bodies are exploited. These elements we may call the "ore" or "metallogenic" elements.

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[62] Hillebrand, W. F., A plea for greater completeness in chemical rock analyses: Am. Chem. Soc. Jour., vol. 16, p. 90, 1894; Analyses of rocks, with a chapter on analytical methods: U. S. Geol. Survey Bull. 148, p. 16, 1897.

TABLE 21.—*Periodic classification of the elements.*

Series.	Group 0.	Group 1.		Group 2.		Group 3.		Group 4.		Group 5.		Group 6.		Group 7.		
1			H 1													
2	He 4	Li 7		Gl 9.1		B 11		C 12		N 14		O 16		F 19		
3	Ne 20		Na 23		Mg 24.4		Al 27		Si 28.1		P 31		S 32		Cl 35.5	
4	A 39.9	K 39.1		Ca 40.1		Sc 45		Ti 48.1		V 51		Cr 52.1		Mn 55		Fe 55.9 Co 59 Ni 58.7
5	—		Cu 63.6		Zn 65.4		Ga 70		Ge 72.5		As 75		Se 79.2		Br 79.9	
6	Kr 82.9	Rb 85.5		Sr 87.6		Y 88.7		Zr 90.6		Cb 93.5		Mo 96		—		Ru 101.7 Rh 103 Pd 106.5
7	—		Ag 107.9		Cd 112.4		In 115		Sn 118.7		Sb 120.2		Te 127.5		I. 126.9	
8	Xe 130.2	Cs 132.9		Ba 137.4		La 138.9		Ce 140.3		—		—		—		
9	—		—		—	Rare-earth elements.	—		—		—		—		—	
10	—	—		—		—		Hf 178 (?)		Ta 181		W 184		—		Os 191 Ir 193.1 Pt 195.2
11	—		Au 197.2		Hg 200.6		Tl 204		Pb 207.2		Bi 209		—		—	
12	Nt 222	—		Ra 226		—		Th 232.5		—		U 238.2				

A general comparative study of these two groups of elements reveals the fact that, apart from differences in abundance or occurrence, the two show marked differences in their chemical and chemico-mineralogical relations. These differences are, in general, so profound and so universal as to indicate the possibility that in so far, at least, as their chemico-mineralogical relations are concerned, there may be some fundamental distinction between the two. These differences we shall now point out, presenting as well in some detail the mineralogical data on which they are based. Before doing this, however, we shall for the sake of clarity, present the relations of the petrogenic and the metallogenic elements as shown in the periodic table.

In the periodic table as here given the classification of the elements is slightly modified in order to bring out the division of the elements into the two groups.[63] The atomic weights are rounded off, and most of the elements of the "rare earths" and those of the isotopic elements are omitted. A heavy line separates the petrogenic from the metallogenic elements.

The symbols for the more abundant elements of the earth's crust—most of which are of low atomic weight (or of low atomic number)—are in the upper part of the table. These symbols and those in the downward extensions from this part of the table represent the petrogenic elements. The symbols for the metallogenic elements are in the lower part of the table, in the short columns that interdigitate with the downward extensions of the symbols for the rarer petrogenic elements, from which they are separated by a heavy line.

To the left is the column comprising group 0, which includes the inert gases. To the right is the column comprising group 8, which includes the triads. Of these triads the members of the first—iron, cobalt, and nickel—are regarded as petrogenic, and the members of the two triads of platinum metals are regarded as metallogenic. The true relations of these triads, however, are somewhat doubtful.

The relations and contrasts between the two groups of elements may also be brought out by using another arrangement of the periodic table, suggested by Prof. T. M. Lowry [64] and given below, in which the elements are arranged in a form of tabulation that was first suggested by Mendeleeff.[65] Most of the rare-earth elements are omitted.

TABLE 22.—*Periodic arrangement of the elements.*

	H																
He	Li	Gl	B	C	N	O	F										
Ne	Na	Mg	Al	Si	P	S	Cl										
A	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br
Kr	Rb	Sr	Y	Zr	Cb	Mo	..	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I
Xe	Cs	Ba	La	Ce	..	..	..										
..	..	..	..	..	Ta	W	..	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi.		
Nt	..	Ra	..	Th	..	U											
	Petrogenic elements.							Eighth group.			Metallogenic elements.						

This arrangement brings all the petrogenic elements on the left side of the table and the metallogenic elements on the right, leaving the triad elements between them, to be considered as members of either one or the other group or as members of intermediate or transitional groups. The inert gases are probably best separated from the petrogenic elements, as they form no compounds, but they would seem to be more closely related to the petrogenic than to the metallogenic elements. In effect, the table above is the arrangement shown in the preceding table, modified only by moving the elements in the short columns to the right and leaving at the left those in the upper left part of the table and in the long columns. The groups of triads thus come between the two.

Another arrangement is that used by Walker [66] in which the metallogenic elements together occupy the lower right-hand part of the table. Walker points out the metallogenic character of the heavy metals (among which he includes those of the iron and platinum triads) but does not include with them the electronegative elements (As to I) immediately below them.

The two divisions of the elements in the earth's crust—the "rock elements," called *petrogenic*, and the "ore elements," called *metallogenic*—are distinguished not only by differences in their relative abundance in the igneous rocks or in the ores of the earth's

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[63] This table differs slightly from that originally presented by the junior author (The chemistry of the earth's crust: Franklin Inst. Jour., vol. 190, p. 780, 1920), having been modified, or rather intensified, as a result of further study.

[64] Letter to Dr. Arthur L. Day, dated April 2, 1921.

[65] Cf. Roscoe, H. E., and Schorlemmer, C., A treatise on chemistry, vol. 2, pp. 54, 55, 1907.

[66] Walker, James, Introduction to physical chemistry, 7th ed., p. 44, 1913.

crust but by very definite and distinctive differences in their general chemical relations, which are shown by their combinations to form minerals. The differences are not only quantitative but qualitative.

Some of the differences here studied have been already stated by others, although their statements had escaped notice at the time the distinction between the petrogenic and the metallogenic elements was first pointed out by the junior author.[67] Thus, in 1884 Carnelley,[68] in considering the chemical differences between the elements of the odd and of the even series of the periodic table as shown by their occurrences in nature, says, among other things: "Elements belonging to *odd* series usually occur in nature as sulphides or double sulphides (also as selenides, tellurides, and arsenides), and only in very few cases as oxides, whereas elements belonging to *even* series, on the other hand, usually occur as oxides or double oxides (forming silicates, carbonates, sulphates, aluminates, etc.), and never with two exceptions) as sulphides." Emerson[69] similarly pointed out the difference in the formation in nature of oxides (the silicates are not mentioned) and of sulphides, and their occurrence or nonoccurrence as native metals, apparently without knowledge of Carnelley's suggestions. Neither of these authors, however, brought out the fact that the one group of elements is most abundant in and characteristic of igneous rocks, and that the other is abundant in and characteristic of ores.

The distribution of the elements in the earth's crust is discussed by De Launay in the introduction to his treatise on metallogeny.[70] He refers the elements to seven groups according to the various parts of the crust where they are most abundant and most characteristically present. These are:

1. Primitive and peripheric atmosphere (H, He).
2. Atmosphere (O, N, A, Kr, Ne, Xe, C).
3. Silicate crust (Si, Al, Na, K, Li, Mg, Ca, Ba, Sr, Gl).
4. Mineralizers (Cl, S, P, B, F).
5. Basic segregations (Fe, Mn, Cr, Ti, V).
6. Veins related to basic segregations (Ni, Co, Cu).
7. Vein deposits (Zn, Pb, Ag, Sn, Mo, Bi, W, Au, Hg, U, Ra).

These divisions fall naturally into three groups—the atmosphere (1, 2), the igneous rock crust (3, 4, 5, 6), and the elements of the ore deposits (7). The last two correspond (with a few exceptions) to our petrogenic and metallogenic elements.

Goldschmidt[70a] has recently suggested the division of the elements into the following groups, which respectively characterize zones of the earth assumed by him to exist.

1. Siderophile elements: Fe, Ni, Co, P, C, Mo, platinum metals.
2. Chalkophile elements: S, Se, Te, Fe, (Ni), (Co), Cu, Zn, Cd, Pb, Ge, As, Sb, Bi, Ag, Au, Hg, Pd, (Pt), Ga, In, Tl.
3. Lithophile elements: O, (S), (P), (H), Si, Ti, Zr, Hf, Th, F, Cl, Br, I, B, Al, Sc, Y, La, Ce, rare-earth elements, Li, Na, K, Rb, Cs, Gl, Mg, Ca, Sr, Ba, (Fe), V, Cr, Mn, Cb, Ta, W, U, Sn, C (as CO_2).
4. Atmophile elements: H, N, (O), He, Ne, A, Kr, Xe.

The symbols in parentheses are those of the elements that are less abundant in the zones postulated.

We shall now consider the relations of the elements in the primary minerals in the crust of the earth—the minerals that make up the unaltered igneous rocks and the minerals that make up the deep-seated ore bodies, those that lie beneath the upper zones of weathering and enrichment. As we are considering here the relations of the elements in the original, unaltered crust of the earth, as manifested chiefly by the compounds they formed and by their correlation in distribution, we shall exclude from consideration, so far as possible, the minerals formed by secondary processes, such as weathering, although some of those that seem to have a bearing on our topic may be cited.

In nature the petrogenic elements occur normally and in greatest abundance as constituents of the primary minerals of igneous rocks and of nearly all the secondary minerals that are derived from them by weathering and simple metamorphism. They occur also

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[67] Washington, H. S., The chemistry of the earth's crust: Franklin Inst. Jour., vol. 190, p. 781, 1920.

[68] Carnelley, Thomas, Application of the periodic law to mineralogy: Mineralog. Mag., vol. 6, p. 83, 1884. We are indebted to Prof. Alfred Harker for this reference.

[69] Emerson, B. K., Helix chemica, a study of the periodic relations of the elements and their graphic representation: Am. Chem. Jour., vol. 45, p. 183, 1911; Concerning a new arrangement of the elements on a helix and the relationships which may be usefully expressed thereon: Science, new ser., vol. 34, p. 646, 1911.

[70] De Launay, L., Gîtes minéraux et métallifères, vol. 1, p. 24, 1913.

[70a] Goldschmidt, V. M., Geochemische Verteilungsgesetze der Elemente: Vid.-selsk. Skrifter Mat. naturv. Klasse, 1923, No. 3.

in ore bodies of magmatic origin, but not as essential components, and usually in subordinate amounts in epigenetic ore bodies, or they may have been introduced through secondary processes.

The typical primary compounds of the petrogenic elements in nature, and those that are most common and most abundant, are oxides, silicates, titanates, fluorides, and chlorides. Very few of the petrogenic electropositive elements, and these exceptionally as a rule, form native sulphides, selenides, tellurides, arsenides, antimonides, bismuthides, sulpho-salts, bromides, or iodides. With some notable exceptions none of them are found uncombined in nature.

The metallogenic elements, on the other hand, occur in nature essentially as the constituents of minerals that make up ore bodies, more especially the epigenetic ore bodies in the sense of epigenetic as it is used by Beck and Weed.[71] Some magmatic ore bodies are composed essentially of petrogenic elements, and some metallogenic elements are found in igneous rocks but almost invariably in extremely small amounts.

The typical compounds of the metallogenic elements in nature are sulphides, selenides, tellurides, arsenides, antimonides, bismuthides, sulpho-salts, bromides, and iodides. Many of the metals occur uncombined, as "native" metals. Only a few of them, and most of those exceptionally and in small quantity, form oxides, silicates, fluorides, or chlorides, nearly all of which are of secondary origin.

The compounds of the elements will here be taken up in the order of the groups of the periodic table, except those of group 0, the inert gases, which will not yet be considered. The groups of related negative (acidic) elements will first be considered, as these seem to be in some respects the more significant, and the relations and contrasts between the two large divisions are best brought out in this way. The "native" elements, the oxides, and the silicates will be treated first, as they are regarded as the most important.

Below is a list showing what we consider the petrogenic and the metallogenic elements. For the present the iron, ruthenium, and osmium triads are regarded as intermediate or transitional. The elements are arranged in the order of the groups of the periodic table. The position of hydrogen is doubtful; it may head either group 1 or group 7, but wherever placed it is a petrogenic element. Most of the rare earth elements are omitted.

TABLE 23.—*The petrogenic and the metallogenic elements.*

Petrogenic elements.	Intermediate elements.	Metallogenic elements.
Hydrogen.	Iron.	Copper.
Lithium.	Cobalt.	Silver.
Sodium.	Nickel.	Gold.
Potassium.	Ruthenium.	Zinc.
Rubidium.	Rhodium.	Cadmium.
Caesium.	Palladium.	Mercury.
Glucinum.	Osmium.	Gallium.
Magnesium.	Iridium.	Indium.
Calcium.	Platinum.	Thallium.
Strontium.		Germanium.
Barium.		Tin.
Radium.		Lead.
Boron.		Arsenic.
Aluminum.		Antimony.
Scandium.		Bismuth.
Yttrium.		Selenium.
Lanthanum.		Tellurium.
Carbon.		Bromine.
Silicon.		Iodine.
Titanium.		
Zirconium.		
Cerium.		
Hafnium.		
Thorium.		
Nitrogen.		
Phosphorus.		
Vanadium.		
Columbium.		
Tantalum.		
Oxygen.		
Sulphur.		
Chromium.		
Molybdenum.		
Tungsten.		
Uranium.		
Fluorine.		
Chlorine.		
Manganese.		

The most striking feature of this table is the predominance of the petrogenic over the metallogenic elements in number, and it has already been shown here that they predominate also in abundance in the known crust. Their greater abundance was to be expected, for they form the immense mass of the igneous rocks. Their greater number is of more interest and significance. To the petrogenic elements belong the elements in each group of the periodic table that have the lowest atomic weight, and the elements of the *even* series in that table are all petrogenic. In the series below the third,

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[71] Beck, Richard, and Weed, W. H., The nature of ore deposits, vol. 1, pp. 4, 112, 1905.

however, as was pointed out years ago by Carnelley, the elements of the *odd* series (the fifth, seventh, ninth, and eleventh) are metallogenic. However, traces of the first one or two elements of the perissad metallogenic groups are found (by chemical methods) in some igneous rocks. Among these elements are copper and zinc, and some analyses show traces of silver and cadmium. The metallogenic elements of higher atomic weight, on the other hand, are never or scarcely ever present in detectable amounts in igneous rocks. Many spectroscopic examinations of minerals have been made to discover in them the rarer elements, but comparatively few such examinations have been made of igneous rocks. Dr. E. G. Zies, of the Geophysical Laboratory, is now making a spectroscopic search for the rarer elements in fumarolic incrustations of Katmai and other volcanoes and will probably extend his work to the lavas.

The intermediate elements, those of the triads, show features of occurrence which are both petrogenic and metallogenic. Thus iron sulphides are common minerals, found in igneous rocks, but iron arsenides are comparatively rare, and iron selenides and tellurides are unknown. On the other hand, nickel sulphides are rare, yet nickel arsenides are rather common, and there is a nickel telluride. Similarly, we find a ruthenium sulphide and a platinum arsenide.

In general, the elements, whether petrogenic or metallogenic, that lie farthest from the intermediate triads (as shown in Table 22 on p. 74) have little affinity for the elements of the other group; but there is evident an increase in such affinity toward the other group as the triad groups are approached. We may draw the general conclusion from the distribution of the elements in minerals that there is no hard and fast line between the petrogenic and the metallogenic elements but that the one group grades into the other, the connecting zone being the group of intermediate triad elements.

Despite the intermediate character of the triad elements, study of the mineral relations shows that the iron-cobalt-nickel triad may be classed with the petrogenic elements and that the ruthenium-rhodium-palladium and the osmium-iridium-platinum triads may best be considered as metallogenic.

RELATIONS OF THE PETROGENIC ELEMENTS.[72]

NATIVE ELEMENTS.

The petrogenic elements of groups 1 to 3 in the periodic table, with the exception of hydrogen, which occurs in volcanic gases and in small traces in the lower atmosphere, are not found uncombined in nature. Wherry[73] gives a list of the native element minerals and proposes a new classification of them. It has been suggested that dispersoid sodium, potassium, and calcium are causes, respectively, of blue halite, sylvite, and some fluorite, and this suggestion has been experimentally confirmed as to sodium and potassium, which, with carbon, sulphur, iron, nickel, tantalum, and (doubtfully) phosphorus, are the only native petrogenic metals in his list. Carbon, in group 4, occurs in igneous rocks as a primary mineral, either as diamond or as graphite, and in both forms in meteorites.

Silicon is not found native, although, as has been suggested, it may be the cause of the color of smoky quartz. Silicon carbide (moissanite) has been found in some meteorites. Neither titanium, zirconium, nor cerium are found native. Nitrogen occurs free in the atmosphere and in volcanic gases. Studies of the gases of Kilauea and Mauna Loa by E. S. Shepherd[74] show that they contain both nitrogen and argon in proportions greater than their proportions relative to oxygen in the atmosphere, and that the ratio of argon to nitrogen in these gases is about three times that in the atmosphere. In these gases "helium and neon have been positively identified, although the amounts were not notably larger than in residues from air." Nitrogen has been detected in some rocks and minerals.[75] Silvestri thought that nitride of iron occurred as an incrustation on basalt at Etna, and ammonium chloride is a fairly common salt among volcanic fumarole deposits, as at Etna.[76] Ammonium sulphate has also been found in a barite from Missouri.[77]

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[72] It is impracticable to give all the references to the less well-known minerals. See Dana's System of mineralogy and its appendixes, also the Mineralogical Magazine and the American Mineralogist.

[73] Wherry, E. T., The nomenclature and classification of the native element minerals: Washington Acad. Sci. Jour., vol. 7, p. 447, 1917.

[74] Shepherd, E. S., Kilauea gases, 1919: Hawaiian Volcano Obs. Bull., vol. 9, pp. 83–88, 1921. Also Two gas collections from Mauna Loa: Idem, vol. 8, p. 65, 1920.

[75] Hillebrand, W. F., The analysis of silicate and carbonate rocks: U. S. Geol. Survey Bull. 700, p. 242, 1919.

[76] See Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, pp. 18, 34, 266, 1920.

[77] Luedeking, C., and Wheeler, H. A., Notes on a Missouri barite: Am. Jour. Sci., 3d ser., vol. 42, p. 495, 1891.

Taking all the evidence into account, we may say that nitrogen and argon, and probably helium and neon, are original constituents of the magma of igneous rocks. Uncombined phosphorus has been reported as a constituent of one stony meteorite,[78] but its occurrence must be regarded as doubtful. Native metallic tantalum is known.

Native sulphur is found about volcanic fumaroles and craters, and it fills the vesicles of lava, as in some of the rhyolites of Milos, but it is invariably of secondary origin. An occluded gas with a peculiar ozone-like odor has been found in some fluorite and in emerald, and Moissan and Lebeau, who studied the respective occurrences, regard this as free fluorine,[79] but the occurrence of this element has not been clearly established. Hydrogen fluoride is found in the gases of many volcanoes. Free chlorine also is found in some volcanic gas, and hydrogen chloride is common. Manganese is not known to occur native.

Native iron occurs in basalt at several localities; in large and small masses in west Greenland and in small particles in basalt of New Jersey, Yellowstone National Park, Germany, Catalonia, and Volhynia. This native iron (at least that found in Greenland) contains small amounts of nickel, cobalt, and copper. Nickel-iron alloys—such as awaruite, josephinite, and souesite—are found as terrestrial minerals. Many meteorites are wholly, or almost wholly, composed of nickel-iron. This meteoritic nickel-iron always contains small amounts of cobalt and copper.

OXIDES.

Hydroxyl is a constituent of a number of the silicate minerals of deep-seated origin (such as the micas). Hydrogen oxide (water) occurs as liquid inclusions in the minerals of deep-seated igneous rocks and is an abundant component of volcanic emanations. It is a constituent of rocks in the deeper parts of the earth's crust, and it is there certainly not of meteoric origin, Brun's opinion to the contrary notwithstanding.[80] So far as is known oxides of the alkali and alkali-earth metals do not exist as such in the crust of the earth. In a molten magma they would contribute to the formation of silicates. Near the surface, or where water is present, they would form hydroxides, which would quickly be changed to carbonates or sulphates. The same rule applies to the sulphides of these metals, which are easily oxidized to sulphates. The conditions under which any compound can form or exist are definitely limited.

No native oxide of glucinum is known. Magnesium oxide, the mineral periclase, is a product of the action of volcanic lavas on limestone, but it is not a mineral component of igneous rocks. The oxides of calcium, strontium, and barium do not occur native.

The oxide of boron, as boric acid (sassolite), is found in the craters of volcanoes and in some hot springs. At several volcanoes and springs it is associated with ammonium salts. No native oxides of scandium, yttrium, or lanthanum are known.

Carbon dioxide is a component of the atmosphere, is abundant in springs, is found in gaseous emanations from the earth (mofetti), and is a common volcanic gas. Liquid carbon dioxide occurs as minute inclusions in the minerals of many plutonic rocks, especially quartz, some of which is so thickly peppered with nearly microscopic cavities filled with liquid carbon dioxide that it breaks almost explosively when struck. Silicon dioxide, as the mineral quartz, is one of the most abundant mineral components of the many igneous rocks of the earth's crust. Two other forms of silicon dioxide, tridymite and cristobalite, are also found in igneous rocks, although they are rare. Titanium dioxide also occurs in three forms as rutile, brookite, and anatase, the first as a primary mineral in igneous rocks and in pegmatite, the last two apparently secondary. Zirconium dioxide (baddeleyite) is found in igneous rocks but is rare. No native oxide of cerium is known. Thorianite is an oxide of thorium containing a little uranium. It occurs in intrusive granitic rocks.

There is no native mineral oxide of nitrogen or of phosphorus. There are doubtful hydrated oxides of vanadium, such as alaite, but they are alteration products. No native oxide of columbium, tantalum, or chromium is known. Secondary oxides of molybdenum (molybdite,

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[78] Farrington, O. C., An occurrence of free phosphorus in the Saline Township meteorite: Am. Jour. Sci., 4th ser., vol. 15, p. 71, 1903.

[79] Moissan, H., Traité de chimie minérale, vol. 1, p. 64, 1904. Mellor, J. W., A comprehensive treatise on inorganic and theoretical chemistry, vol. 2, p. 1, 1922.

[80] Brun, A., Considérations sur le magma granitique: Zeitschr. Vulkanologie, vol. 1, p. 3, 1914. Cf. Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, p. 279, 1920.

ilsemannite) are reported to exist, but Schaller[81] has shown that all the molybdites examined by him were ferric molybdate, and that the ilsemannite was molybdenum sulphate.[82] No oxide of chlorine occurs in nature as a mineral. Manganese forms several native oxides (manganosite, hausmannite, polianite, and pyrolusite) and several hydroxides or hydrated oxides, but they are all of secondary origin.

There are two native oxides of iron, hematite and magnetite, both of which are constituents of igneous rocks. Hematite is less common than magnetite in igneous rocks and in many it is secondary. The iron titanate ilmenite is a common mineral in igneous rocks. One definite oxide of nickel (bunsenite) is known, but this and several indefinite oxides of nickel and cobalt are all secondary.

SPINELS.

The spinels and other compound oxides that have the same formula are here considered separately from the other oxides. The spinels are compounds of oxides of bivalent and trivalent elements. The bivalent elements in the spinels are magnesium, iron, manganese, and the metallogenic zinc. There is no known calcium spinel. The trivalent elements are aluminum, chromium, manganese, and ferric iron. Thus, they are aluminates, chromites, manganites, or ferrites of magnesium, manganese, iron, or zinc, in which the several oxides may isomorphously replace one another. They all crystallize in the isometric system, forming typically regular octahedra. Chrysoberyl, an orthorhombic glucinum aluminate, may be mentioned with the spinels.

As simple minerals we have magnesium aluminate (spinel proper), iron aluminate (hercynite), zinc aluminate (gahnite), ferrous ferrite (magnetite), magnesium ferrite (magnesioferrite), and ferrous chromite (chromite). Among the varieties may be mentioned magnesium-iron aluminate (pleonaste), chromium-iron aluminate (picotite), and the ferrimanganites of iron, manganese, zinc, and magnesium (franklinite and jacobsite). The aluminates, ferrites, and chromites of magnesium and iron occur mostly in igneous rocks but also in metamorphic rocks; the zinc and generally the manganese spinels occur in ore bodies or in metamorphic rocks and not in igneous rocks.

Dr. G. W. Morey, of the Geophysical Laboratory, has recently made artificially monopotassium aluminate and monopotassium ferrite, which form well-developed regular octahedra.[83] So far as experimental evidence now goes it appears that sodium does not form compounds of this type. Lithium has not yet been investigated.

SILICATES.

All the electropositive petrogenic elements form or enter into silicates that occur in nature. Indeed, the silicates of the petrogenic elements form an overwhelming majority of all known silicates, certainly more than 99.9 per cent of them by weight, and the silicates are their most characteristic natural compounds.

The simple silicates of the alkali metals are not known to occur free in nature; they are all "soluble" in water, or more properly are decomposed by water into alkali hydroxide and colloidal silica.

On the other hand, the alkali metals form many abundant aluminosilicates. Lithium is the basic element in several of them, such as petalite, spodumene, eucryptite, and lepidolite; and lithium occurs in small amount in other aluminosilicates—beryl, mica, and tourmaline. The rare taeniolite, a member of the mica group containing lithium, potassium, and magnesium, may also be mentioned, and lithium occurs in the micaceous basic lithium-aluminum borosilicate manandonite.

Sodium forms many common and well-known compound silicate minerals. Most of the sodium silicate minerals are either aluminosilicates (albite, carnegieite, nephelite, jadeite, ussingite, marialite), ferrisilicates (acmite, aegirite, riebeckite, glaucophane, and other sodic pyroxenes and amphiboles), or zirconosilicates (lavenite, hiortdahlite, eudialyte, catapleiite). The distinctively sodic silicates are also almost the only ones that contain chlorine or sulphur in the molecule, as in sodalite, haüynite, marialite, lazurite, and noseanite. Sodium is seldom found in large quantity in nonaluminous and nonferric silicates.

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[81] Schaller, W. T., The chemical composition of molybdic ocher: Am. Jour. Sci., 4th ser., vol. 23, p. 297, 1907. Guild, F. N., The composition of molybdite from Arizona: Am. Jour. Sci., 4th ser., vol. 23, p. 455, 1907.

[82] Schaller, W. T., Ilsemannite, hydrous sulphate of molybdenum: Washington Acad. Sci. Jour., vol. 7, p. 417, 1917.

[83] Morey, G. W., Solubility and fusion relations at high temperatures and pressures: Eng. Club Philadelphia Jour., vol. 35, p. 518, 1918. A more detailed publication is to appear later.

Potassium forms very few silicate minerals, among them the common aluminosilicates orthoclase, microcline, muscovite, and biotite, and the less common leucite. The potassic aluminosilicate kaliophilite is very rare. Potassium occurs with calcium in the very rare bialuminosilicate, milarite. It is highly noteworthy that potassium is not found or is found only in traces in the pyroxenes, amphiboles, tourmalines, scapolites, and other common silicate minerals in which notable amounts of sodium may occur. Potassic zeolites are rare. On the other hand, sodium seldom occurs in quantity in the micas, except as the base in paragonite, a rare mica of only metamorphic origin. Potassium does not seem to enter into either ferrisilicates, zirconosilicates, borosilicates, or titanosilicates but is confined strictly to the aluminosilicates.

Rubidium and caesium occur as constituents of primary minerals only in aluminosilicates. Caesium is the base of the rare aluminosilicate pollucite, which contains some potassium. Both rubidium and caesium are found in small amounts in several common aluminosilicates, such as beryl and lepidolite, and rubidium (but not caesium) is found in some orthoclase, leucite, spodumene, and mica.

Glucinum alone is the basic element of the simple silicates phenacite, euclase, and bertrandite and of the aluminosilicate beryl. Glucinum forms a small but essential constituent of a number of other silicates, of eudidymite and epididymite (with sodium), leucophanite and meliphanite (with sodium and calcium), helvite (with manganese and iron), danalite (with iron, zinc, and manganese), trimerite (with calcium and manganese), and gadolinite (with iron and yttrium). Of all these glucinum minerals beryl is the only one that contains essential aluminum.

Magnesium is an essential constituent of some silicates, but the number of definite primary minerals in which it is the only base or one of the essential bases is surprisingly small, although some of the magnesian minerals are very common. Enstatite (clinoenstatite) and forsterite are the two purely magnesian silicates, and the other most prominent and almost the only other essentially magnesian silicates are hypersthene (bronzite), diopside, augite, and other pyroxenes, anthophyllite (gedrite), cummingtonite, tremolite, actinolite, hornblende and other amphiboles, iolite (cordierite), pyrope garnet, the olivines, the minerals of the humite group, biotite and other micas, and the rare grandidierite, kornerupine, sapphirine, and serendibite. In most of these minerals magnesium is associated almost only with bivalent iron and calcium, and it is noteworthy that nearly all of them are nonaluminous. The minerals of the humite group, which contain no aluminum, are metamorphic. Of the aluminous magnesium minerals, the micas are igneous, grandidierite is a constituent of pegmatites, but iolite (cordierite), pyrope, kornerupine, sapphirine, and serendibite are metamorphic minerals. These are the only magnesian minerals that can strictly be said to be aluminosilicates, as the alumina in the aluminous augite and hornblende is probably present in solid solution.[84]

Calcium is an essential basic constituent of many silicates, probably of a greater number than any other one element. The calcium silicates are about evenly divided between the nonaluminous and the aluminous groups. Augite and hornblende are not here considered aluminosilicates, for the alumina they contain is regarded as in solid solution. The only pure calcium silicates are the metasilicate wollastonite, the hydrated orthosilicate hillebrandite, and possibly xonotlite. The most prominent nonaluminous calcic silicates are the pyroxenes (diopside-hedenbergite and augite) and the corresponding amphiboles (tremolite-actinolite and hornblende), and monticellite, in which magnesium and bivalent iron are essential; the sodium-calcium pectolite and the doubtful rivaite;[85] a number of zirconosilicates, such as lavenite and eudialyte, most of which contain sodium. The number of calcium aluminosilicates is large, including such common minerals as anorthite and the soda-lime feldspars; haüyne (with sodium and the sulphate radical); the garnets grossularite, andradite (iron replacing aluminum), and uvarovite (chromium replacing aluminum); meionite and other scapolites; the melilite group; vesuvianite and the epidote group (including the cerium-bearing allanite), the boroaluminosilicate axinite; prehnite, lawsonite, and several others.

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[84] Washington, H. S., and Merwin, H. E., Mineralogy; augite of Haleakala, Maui, Hawaiian Islands: Am. Jour. Sci., 5th ser., vol. 3, p. 120, 1922.

[85] Larsen, E. S., The microscopic determination of the nonopaque minerals: U. S. Geol. Survey Bull. 679, p. 127, 1921. Bowen, N. L., Two corrections to mineral data: Am. Mineralogist, vol. 7, p. 64, 1922.

Barium and strontium, apart from their carbonates and sulphates of secondary origin, enter only into silicate minerals. Barium forms no native simple silicates but is the base in the feldspathic aluminosilicates celsian and hyalophane, barylite ($4BaO.Al_2O_3.7SiO_2$), and the zeolites harmotome and edingtonite. It also occurs in some other zeolites and in some mica. A ferrous iron-barium silicate, gillespite, has been recently described,[86] and two barium titanosilicates are known, benitoite and leucosphenite. A peculiar iron-barium ferrisilicate, taramellite, is known, as well as a rare yttrium-barium borosilicate, cappelenite. There is no known native silicate of strontium, but this element occurs in the zeolites brewsterite and heulandite as well as in the lead silicate hancockite. The artificial silicates of strontium and barium have been studied by Eskola.[87] Strontium forms a metasilicate and an orthosilicate; barium forms a bisilicate, a metasilicate, and an orthosilicate.

Boron is an essential constituent of a number of silicates, forming the complex borosilicates, some of which are rather common minerals. Of the nonaluminous borosilicates there may be mentioned the common danburite and datolite (calcium); and the rare homilite (calcium and iron); caryocerite, melanocerite, tritomite (calcium and cerium), hyalotekite (calcium, barium, lead), and cappelenite (barium and yttrium). The best known boroaluminosilicates are dumortierite (aluminum), axinite (calcium), and tourmaline (lithium, sodium, iron, magnesium). The calcium-magnesium serendibite and the lithium manandonite are rare.

Aluminum forms several simple silicates, some of which contain hydroxyl or fluorine replacing hydroxyl. These are the aluminum orthosilicates sillimanite, cyanite, andalusite (basic), and topaz (with HO or F). Dumortierite (with boron) and staurolite (with iron) may also be mentioned here. The aluminosilicates are numerous, and many of them are very common minerals, which are considered elsewhere under headings for their basic elements.

Scandium forms two rare silicates—thortveitite,[88] in which yttrium is also essential, and the little known bazzite.[89] Small amounts or traces of scandium have been found in several silicate minerals that contain the rare earths and in a few micas. The spectroscope shows that scandium is widely diffused in minerals and igneous rocks, although in extremely small amounts. It should be noted that scandium is perhaps not a member of the rare-earth group of elements.[90]

Yttrium and the other elements of the yttrium group form a few rare silicates, which will be considered separately from the silicates formed by the elements of the cerium group. Thalenite [91] and rowlandite are essentially yttrium silicates containing hydroxyl. Yttrialite is a thorium-yttrium silicate; gadolinite is complex but is essentially a silicate of glucinum, iron, cerium, and yttrium; some varieties contain about as much of the cerium earths as of yttria. Thortveitite is a silicate of scandium and yttrium. More complex are cappelenite, a borosilicate of barium and yttrium; hellandite, an aluminosilicate of yttrium, erbium, and calcium; keilhauite, a titanosilicate of calcium and yttrium, and wiikite, a somewhat indefinite and doubtful "euxenite-like" columbate, titanate, and silicate of iron and the rare earths (mostly yttria) containing a little scandium. Cenosite, an yttrium-calcium carbonosilicate may also be mentioned. The yttrium of these minerals seems to be accompanied by small amounts of cerium, in all the samples that have been completely analyzed. It seems to be a minor characteristic of the yttrium silicates, as contrasted with the cerium silicates, that they do not contain sodium and zirconium.

The lanthanum silicates will be considered with those of cerium.

Carbon enters into a few silicates, apparently as the carbon dioxide radical. The most common is cancrinite, an aluminosilicate of sodium

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[86] Schaller, W. T., Gillespite, a new mineral: Washington Acad. Sci. Jour., vol. 12, p. 7, 1922.

[87] Eskola, P., The silicates of strontium and barium: Am. Jour. Sci., 5th ser., vol. 4, p. 331, 1922. See also Bowen, N. L., Crystals of barium silicate in optical glass: Washington Acad. Sci. Jour., vol. 8, p. 265, 1918.

[88] Brögger, W. C., Vogt, T., and Schetelig, J., Die Mineralien der südnorwegischen Granit-pegmatitgänge, II, Silikate der seltenen Erden, (Y-Reihe und Ce-Reihe), p. 49, Kristiania, 1922.

[89] Artini, Ettore, Due minerali contenenti terre rare: weibylite e bazzite: R. accad. Lincei Rendiconti, vol. 24, p. 313, 1915.

[90] For an account of scandium, see Meyer, R. J., Ueber das Scandium: Zeitschr. anorg. Chemie, vol. 86, p. 257, 1914; Levy, S. I., The rare earths: their occurrence, chemistry, and technology, p. 213, New York, 1915.

[91] For thalenite, hellandite, and other rare-earth silicates, see Brögger, W. C., Vogt, T., and Schetelig, J., Die Mineralien der südnorwegischen Granit-pegmatititgänge: II. Silikate der seltenen Erden (Y-Reihe und Ce-Reihe), Kristiania, 1922.

and calcium containing sodium carbonate, occurring as a primary as well as a secondary mineral in nephelite syenite. Cenosite, a carbonosilicate of calcium, yttrium and erbium, occurs in syenite-pegmatite. Spurrite, an anhydrous carbonate-silicate of calcium, and thaumasite, a hydrated carbonate-sulphate-silicate of calcium, are of secondary origin. Some scapolites contain the carbonate radical.

There is no known simple silicate of titanium, but titanium enters into the composition of a number of silicates, forming the so-called titanosilicates. These will be considered with the titanates. The wide distribution of titanium and its relative abundance in igneous rocks have already been pointed out. Titanium is present in considerable amounts in nearly all the ferromagnesian minerals, such as pyroxene, amphibole, biotite, olivine, and garnets.

Zirconium forms two simple compounds with silica—the mineral zircon, which is very commonly found, although in small amounts, in granite and syenite; and the hydrated orvillite. Zircon may be regarded as either a double oxide or as a silicate of zirconium. Several silicates contain essential zirconium. In some of them the zirconium appears to be basic; in others it forms a zirconosilicic acid. These minerals will be considered together here, without discrimination. The list of zirconosilicates includes elpidite and soda-catapleiite, which have sodium alone as their bases; and the sodium-calcium zirconosilicates rosenbuschite, lavenite, wöhlerite, hiortdahlite,[92] eudialyte (eucolite), catapleiite, mosandrite, and hainite. Rosenbuschite, lavenite, and mosandrite contain titanium, hiortdahlite and mosandrite contain fluorine, and wöhlerite a little columbium. Eudialyte is complex, containing notable amounts of cerium, iron, manganese, chlorine, and a little tantalum. Lorenzenite is a sodium-barium zirconotitanosilicate without calcium. Practically all the zirconosilicates are sodium or sodium-calcium salts, and they are among the few silicates that contain columbium or tantalum. Some unpublished analyses show that zirconium is commonly present in small amount in acmite and aegirite.

Cerium, with which are included lanthanum and the other metals of the cerium group, enters into more silicates than yttrium. The only simple cerium silicate is cerite; toernebohmite is very similar but contains a little aluminum. Beckelite is a calcium-cerium silicate; melanocerite, caryocerite, and tritomite are sodium-calcium-cerium fluoborosilicates, the last containing thorium; allanite (found in some igneous rocks)[93] is a calcium-cerium aluminosilicate; johnstrupite, mosandrite, and rinkite are sodium-calcium-cerium titanosilicates; britholite, erikite, and steenstrupite are sodium-calcium-cerium phosphosilicates. The sodium-calcium columbosilicates chalcolamprite and endeiolite contain some cerium. The cerium silicates, unlike the silicates of yttrium, are nearly all sodium-calcium salts, as are most of the zirconosilicates. According to the best analyses lanthanum occurs in amounts about equal to those of cerium in several of the minerals mentioned above.[94] Small amounts of cerium and yttrium have been found in several specimens of acmite and aegirite.

Thorium forms one definite silicate, thorite or orangite, which is much like zircon. Thorite is of primary origin, occurring in syenite and syenite pegmatite. Thorium also forms the base of the indefinite calciothorite, eucrasite, and freyalite, which are probably decomposition products. With uranium it enters into the little known mackintoshite and its decomposition product thorogummite. Uranium forms but one fairly definite silicate, the hydrous calcium-uranium uranophane, but there is an "amorphous" little known hydrous silicate of thorium, uranium, and lead, and a hydrated silicate of lead and uranium, kasolite, has been described recently.[95] Tungsten does not seem to enter into true silicates.

There are no known nitrosilicates, but there are some very rare phosphosilicates, such as the sodium-calcium-cerium britholite, erikite,

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[92] Zambonini and Prior have shown that guarinite contains no titanium but is a sodium-calcium zirconosilicate, probably identical with hiortdahlite. See Zambonini, F., and Prior, G. T., On the identity of guarinite and hiortdahlite, with a note on the chemical composition of guarinite: Mineralog. Mag., vol. 15, p. 247, 1909; and Zambonini, F., Mineralogia vesuviana, R. accad. sci. fis. mat. [Naples] Atti, 2d ser., vol. 14, p. 162, 1910.

[93] Iddings, J. P., and Cross, Whitman, On the widespread occurrence of allanite as an accessory constituent of many rocks: Am. Jour. Sci., 3d ser., vol. 30, p. 108, 1885.

[94] For lists of the rare-earth minerals, see Schilling, J., Das Vorkommen der "seltenen Erden," Munich, 1904; Levy, S. I., The rare earths, New York, 1915; Browning, P. E., Introduction to the rarer elements, 4th ed., New York, 1917; Schoeller, W. R., and Powell, A. R., The analysis of minerals and ores of the rarer elements, London, 1919. Dana's System of mineralogy, with its appendices, is of course invaluable.

[95] Schoep, A., Sur la kasolite, nouveau minéral radioactif: Compt. Rend., vol. 173, p. 1476, 1921.

and steenstrupite, mentioned under cerium. No simple vanadium silicate is known, but vanadium largely replaces aluminum in the potassium mica roscoelite. Ardennite is a manganese aluminosilicate of somewhat uncertain composition, in which vanadium replaces aluminum and arsenic may replace vanadium. Small quantities of vanadium are found in some of the pyroxenes, and some aegirite contains 3 or 4 per cent of vanadium oxide.[96] Hillebrand first showed that vanadium is of common occurrence in subsilicic igneous rocks.

Very few silicates contain columbium or tantalum. Epistolite is a columbosilicate of sodium that contains also some titanium and a little fluorine. Chalcolamprite and endeiolite are similar, but they both contain basic calcium and sodium, and in them cerium and zirconium may partly replace titanium. Steenstrupite, already mentioned, also contains columbium, as does wöhlerite; and lavenite contains a little tantalum.

The only definite chromium silicate is uvarovite, the chromium-calcium garnet, in most specimens of which, however, aluminum largely replaces chromium. A doubtful chromium silicate, cosmochlore, has been found in one meteorite, and chromium is a constant constituent of the mica fuchsite. Chromiferous diopside and other pyroxenes are not uncommon, and many olivines contain small amounts of chromium. The green color of some jadeite is caused by chromium. Miloschite (avalite) is a secondary somewhat indefinite chrome-kaolinite and tammawite is a chrome-epidote. Molybdenum appears to have been found in only one silicate mineral—a sodalite,[97] that contains over 2 per cent of MoO_3 and that is named molybdosodalite. Hillebrand has shown that molybdenum is widely distributed among the more siliceous rocks, although in very small amount.

Sulphur is a rare constituent of silicates. It may occur either as sulphide or as sulphur trioxide or dioxide. Melanophlogite, which is imperfectly known, appears to be a compound of silica and sulphur trioxide.[98] It may be, as Dana[99] suggests, of pseudomorphous origin. The sulphide silicates include the sodium aluminosilicate lazurite, the glucinum-manganese silicate helvite, and the glucinum-iron-zinc silicate danalite. The only sulphitosilicate known is the calcium-lead salt, roeblingite.[1] The sulphatosilicates are the sodium aluminosilicate nosean, the sodium-calcium aluminosilicate haüynite, the potassium-sodium-calcium chlorosulphatosilicate microsommite (davyne),[2] and thaumasite, a compound of calcium silicate, carbonate, sulphate, hydroxyl, and water of crystallization. It may be suggested here that, as Penfield and Pratt's structural formula for thaumasite[3] centers about an asymmetric silicon atom (in the stereochemical sense), thaumasite should show optical activity like that of organic compounds containing an asymmetric carbon atom. Optical inactivity, on the other hand, would be adverse to Penfield and Pratt's interpretation. There are no selenosilicates or tellurosilicates.

Fluorine is an essential constituent of a considerable number of silicate minerals. It may be acidic, replacing oxygen and forming a fluosilicic acid, or it may be basic, replacing hydroxyl, as shown by Penfield.

The simplest fluosilicates are the calcium salts cuspidine and custerite and the aluminum salt topaz. In cuspidine fluorine replaces oxygen and in custerite and topaz it replaces hydroxyl. The iron-magnesium fluosilicate minerals of the humite group are common. Lepidolite, zinnwaldite, and phlogopite contain fluorine as essential constituents, and fluorine occurs in all or nearly all the micas. Other fluorine-bearing silicates are the sodium-calcium leucophanite and meliphanite; the basic aluminum silicate zunyite, which contains chlorine; the calcium-cerium borosilicates melanocerite, caryocerite, and tritomite, the last named containing thorium also; the sodium-calcium zirconosilicate hiortdahlite; the sodium-calcium-cerium titanosilicates johnstrupite, mosandrite, and rinkite; and the complex columbium-bearing zirconosilicate chalcolamprite. Small amounts of fluorine are uniformly present in many other silicates—the

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[96] Larsen, E. S., and Hunt, W. F., Two vanadiferous aegirites from Libby, Mont.: Am. Jour. Sci., 4th ser., vol. 36, p. 289, 1913.

[97] Zambonini, F., Mineralogia vesuviana: R. accad. sci. fis. mat. [Naples] Atti, 2d ser., vol. 14, pp. 214, 358, 1910. The presence of molybdenum in sodalite was discovered by Freda in 1878.

[98] Manzella, E., Ann. chim. applicata, vol. 9, p. 91, 1917; Chemical composition of melanophlogite: Chem. Abstracts, vol. 12, p. 1956, 1918.

[99] Dana, J. D., System of mineralogy, 6th ed., p. 194, 1911.

[1] In Dana's System of mineralogy, Appendix I, p. 60, 1911, under "Roeblingite," sulphur trioxide and SO_3 are erroneously used for sulphur dioxide and SO_2.

[2] Cf. Zambonini, F., op. cit., p. 191.

[3] Penfield, S. L., and Pratt, J. H., On the occurrence of thaumasite at West Paterson, N. J.: Am. Jour. Sci., 4th ser., vol. 1, p. 233, 1896.

hornblendes, vesuvianite, euclase, tourmaline, apophyllite, lavenite, and wöhlerite, and others that are less common.

It is noteworthy that fluorine is not normally present in the pyroxenes nor in acmite-aegirite, scapolite, garnet, or epidote.

Chlorine is an essential constituent of a comparatively small number of silicates. It is present in sodalite and in hackmannite (which is a sulphide-bearing sodalite), as well as in eudialyte, zunyite, marialite, and other scapolites, the manganese silicates friedelite and pyrosmalite, the calcium-cerium-lead silicate nasonite, and a few others. Microsommite contains both chlorine and sulphur.

Manganese is very common and widespread in silicates; indeed, manganese is found (in large or small amount) in a greater number and variety of silicates than either magnesium or potassium, even including only those in which it is essential. The simple manganese silicates are rhodonite and tephroite, and the hydrated agnolite, bementite, and caryopilite. Pyroxmanganite is a manganese-iron pyroxene, as appears to be the triclinic babingtonite. Jeffersonite contains zinc also, and schefferite contains magnesia. The manganese amphiboles are the iron-manganese dannemorite and the sodium-magnesium-manganese richterite. All the iron-bearing pyroxenes and amphiboles contain small quantities of manganese. Besides tephroite we find the manganese olivines knebelite (with iron), roepperite (with iron and zinc), glaucochroite (with calcium and a little lead), and also schizolite, a sodium-calcium-manganese silicate containing cerium or yttrium. Hodgkinsonite is a hydrous zinc-manganese silicate.

The manganese aluminosilicates are not numerous. They include the manganese-aluminum garnet spessartite, the manganese epidote piedmontite, the manganese aluminosilicates carpholite and partschinite, and the rare harstigite and ardennite. The sulphide-bearing glucinum silicates, helvite and danalite, contain manganese, as does the glucinum silicate trimerite. Långbanite is an iron-manganese stibiosilicate, kentrolite is a manganese-lead silicate, and pyrosmalite is an iron-manganese chlorosilicate. With the exception of the alkali and alkali-lime aluminosilicates, there is scarcely a silicate mineral that does not contain at least a tenth or a few tenths of 1 per cent of manganese, especially if the mineral contains iron. So that, except for the feldspars, nephelite, leucite, the scapolites, the melilites, and the zeolites, manganese is almost constantly present in silicate minerals.

The simple iron silicates are not numerous, although in many silicates ferrous oxide replaces isomorphously magnesia, or ferric oxide replaces alumina. The only simple iron silicate that is definitely known is the rare orthosilicate fayalite, an end member of the olivines, which, oddly enough, generally occurs in igneous rocks that contain much silica. There is no known native purely iron pyroxene, either orthorhombic or monoclinic, and the iron amphibole, grünerite, needs further investigation. Hypersthene is orthorhombic iron-magnesium pyroxene. Hedenbergite is the calcium-iron pyroxene, and most of the pyroxenes contain more or less iron. Acmite is the sodium-iron pyroxene, and weinbergite is a doubtful sodium-iron silicate that occurs in meteorites. Unpublished studies by H. E. Merwin and the junior author show that aegirite is a mixture of acmite and diopside-hedenbergite. Most of the amphiboles contain iron, actinolite being the purely iron-calcium-magnesium compound and riebeckite the sodium-iron amphibole. The sodic pyroxenes and amphiboles are richer in iron than in the isomorphous magnesium.

Other common silicates in which iron is essential are the micas biotite, phlogopite, and lepidomelane; some garnet, including the iron-aluminum almandite and the calcium-iron andradite; the olivines, except the purely magnesian end-member, forsterite; most epidote, including the manganese piedmontite and the cerium allanite; much tourmaline; and the humite group of fluosilicates. Almandite, epidote, tourmaline, staurolite, and iolite are common alumino-silicates in which iron is essential, and these occur only rarely as primary constituents of igneous rocks. Iron-bearing silicates that are less common are the iron-glucinum-zinc silicate danalite, which contains sulphur; the calcium-iron borosilicate homilite; the iron-manganese chlorosilicate pyrosmalite; the calcium-iron ilvaite; the barium-iron taramellite, the lead-iron melanotekite; the glucinum-yttrium-aluminum-iron gadolinite; and the rare iron-manganese stibiosilicate långbanite. Iron is essential in minerals of some of the commonest primary mineral groups—the pyroxenes, amphiboles, micas, and olivines—as well as in some that are most common in metamorphic rocks, as staurolite and the garnet, epidote, and humite groups, but it also occurs in a few very rare minerals. Its widespread occurrence among silicate minerals in very small amounts has been already mentioned.

No anhydrous silicate of nickel or cobalt is known, and the hydrous nickel silicates, such as garnierite and genthite, are secondary. Small amounts of nickel, presumably replacing iron as silicate, are common in olivine and in pyroxene, especially augite and hypersthene. Cobalt generally accompanies nickel in nonsilicate minerals, so that cobalt is probably also present in olivine and pyroxene, but in amount so small as not readily to be detected.

TITANATES AND TITANOSILICATES.

The uncertainty as to the part played by titanium in many silicates has been pointed out by Dana and others. In some minerals it is acidic; in others it is basic; in still others it may be both. Again, it may be present either as TiO_2 or, though less often, as Ti_2O_3. It seems best here to group together the simple titanates and the titanosilicates (terms used without implication as to the acidic or basic function of the titanium) rather than to discuss the titanosilicates with the silicates, as was done with the fluosilicates or zirconosilicates.

The simple titanates are comparatively few, and most of them are rather rare. They include the very common ferrous titanate ilmenite, the rather common calcium titanate perofskite, the calcium-cerium titanate knopite, the magnesium titanate geikielite, the ferric titanate arizonite, the manganese titanate pyrophanite, the aluminum-calcium zirconotitanate uhligite, the hydrous zirconium titanate oliveiraite, the calcium-iron-columbium dysanalyte, the iron-yttrium-uranium delorenzite (which contains tin), and the columbium-tantalum titanates strüverite and ilmenorutile. Senaite appears to be a titanate of iron, manganese, and lead; its composition is doubtful.

Relatively few minerals can be considered titanosilicates—that is, minerals in which titanium either forms a complex acid with silicon or replaces it to a large extent or is one of the essential bases. The sodium-calcium guarinite, which Dana[4] places near titanite, has been shown not to contain titanium, but to be a zirconosilicate, probably identical with hiortdahlite.[5] The titanosilicates include the calcium salt titanite, or sphene, which is the most common; keilhauite, which is very similar to titanite but contains also aluminum, iron, and yttrium, and which calls for further investigation; the barium benitoite; the sodium-calcium molengraafite; the sodium-iron narsarsukite; the potassium-iron neptunite; the imperfectly known calcium-iron joaquinite; the little known hainite, probably a sodium-calcium zirconotitanosilicate; the sodium-calcium zirconosilicate rosenbuschite; the sodium-barium leucosphenite; and the sodium-calcium-cerium fluotitanosilicates johnstrupite, mosandrite, and rinkite. The calcium-iron titanium garnet schorlomite and the highly titaniferous sodic hornblendes, enigmatite, kaersutite, and rhönite, are also to be placed here. The wide distribution of titanium in silicate rocks and its common presence in more than traces in nearly all the ferromagnesian minerals have been already noted.

The only simple silicates of zirconium known are the widespread zircon and the hydrous orvillite. The zirconosilicates have been considered among the silicates. In nature zirconium enters into no compounds except oxides and silicates.

BORIDES AND BORATES.

No native terrestrial boride is known, nor has a boride been found in meteorites. The borosilicates have been enumerated under the silicate minerals. Boric acid (sassolite) occurs in the Tuscan and other soffioni and lagoons, and it is found also in the fumarole products of several volcanoes, as Vesuvius[6] and Vulcano.[7] At Vulcano it was formerly so abundant that it was produced commercially to the extent of several tons a year, but since the great eruption of 1888–89 it seems to be no longer given off by the volcano, as an examination of samples of salts from the crater showed that boric acid was absent or that it was present in some samples in mere traces.[8]

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[4] System of mineralogy, 6th ed., p. 717, 1892.

[5] Zambonini, F., and Prior, G. T., Mineralog. Mag., vol. 15, p. 247, 1909. Zambonini, F., Mineralogia vesuviana: R. accad. sci. fis. mat. [Naples] Atti, 2d ser., vol. 14, p. 162, 1910.

[6] Zambonini, F., op. cit., p. 84, 1910.

[7] Bergeat, A., Die aeolischen Inseln; Bayer. Akad. Wiss. Abh., vol. 20, pt. 1, p. 178, 1899.

[8] Washington, H. S., and Day, A. L., Present condition of the volcanoes of southern Italy: Geol. Soc. America Bull., vol. 26, p. 386, 1915. J. Koenigsberger and W. J. Müller also report boric acid as absent in the salts of Vulcano (Ueber Fumarolenabsätze: Zeitschr. Vulkanologie, vol. 1, p. 196, 1915).

The glucinum borate hambergite, the aluminum borate jeremejefite, and the calcium-tin borate nordenskiöldine occur as probably primary minerals in igneous rocks and pegmatites. The secondary nonhydrated borates include rhodizite, a borate of aluminum, potassium, rubidium, and caesium; boracite, a magnesium chloroborate; sussexite, a magnesium-manganese borate; warwickite, an iron-magnesium titanoborate; and the group of ferriborates, the ferromagnesium ludwigite and vonsenite, the manganomagnesium manganiborate pinakiolite, and the stannoferrous ferriborates hulsite and paigeite. The bases in borates are mostly petrogenic—sodium, magnesium, calcium, manganese, and iron; but tin occurs in two or three and zinc occurs in sussexite. For boron nitride see "Nitrides and nitrates," below.

CARBIDES AND CARBONATES.

Silicon carbide, moissanite, occurs in some meteorites, but it has not been found terrestrially. An iron carbide, cohenite, is common in meteoric irons, and it has been found in the native iron of terrestrial basalts. The few carbonosilicates, such as cancrinite, have been mentioned above, among the silicates. Most of the carbonates in nature are of secondary origin and will not be considered here, but calcium carbonate, calcite, has been observed as a probably primary constituent of some igneous rocks, and Brögger, in his latest work on the Christiania region,[9] holds that a group of calcite-rich rocks—fenite and other rocks—are of igneous origin and that the calcite was once molten. Gaseous and liquid carbon dioxide form visible inclusions in crystals in plutonic rocks.

Shepard[10] long ago reported that he had found ferrosilicite, a silicide of iron, in meteorites, but his observation does not seem to have been confirmed.

NITRIDES AND NITRATES.

The only known natural nitride is the doubtful iron nitride silvestrite, or siderazotite, found by Silvestri as thin films in vesicles of Etna basalt. It has been suggested that the boric acid and ammonium salts that occur together at some volcanoes are produced by the action of steam on deep-seated boron nitride. This idea is plausible and ingenious, but no evidence either for or against it has been produced.

The mineral nitrates, which are all secondary, are salts of the petrogenic elements sodium, potassium, magnesium, calcium, and barium; and there is a rare basic copper nitrate, gerhardtite. Ammonia is a constituent of kleinite, which is composed of mercury, ammonia, chlorine, and sulphur trioxide; and ammonia is present in small amount in some apophyllite and barite.

PHOSPHIDES AND PHOSPHATES.

No phosphides have been identified as terrestrial minerals, but an iron-nickel phosphide, schreibersite, is common in meteorites. No native potassium phosphate is known. Some phosphates occur as primary components of igneous rocks and pegmatites. The basic elements in these are all petrogenic, including lithium, sodium, glucinum, magnesium, calcium, strontium, yttrium and cerium metals, aluminum, manganese, and iron. The most common is the ubiquitous apatite, generally a fluoapatite, less often chlorapatite; xenotime (yttrium phosphate) and monazite (a phosphate of the cerium metals with thorium) are also occasionally found. The other primary phosphates are present chiefly in pegmatites. The lithium phosphates are amblygonite (with aluminum), and triphyllite and lithiophilite (with iron and manganese). The sodium phosphates are beryllonite (with glucinum), fremontite and morinite (with aluminum), jezekite and lacroixite (with calcium, aluminum, and fluorine), and natrophilite (with manganese). The glucinum phosphates are beryllonite and herderite, the former with sodium and the latter with calcium. Magnesium forms the fluophosphate wagnerite, and calcium forms the common apatite, also herderite with glucinum, and jezekite and lacroixite with sodium, aluminum, and fluorine. Hamlinite is an aluminum-strontium phosphate, and hinsdalite contains strontium along with lead, aluminum, and sulphur trioxide. The primary yttrium and cerium phosphates, xenotime and monazite (the latter containing thorium) have been mentioned, but the origin of some rare-earth phosphates from Brazil is

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[9] Brögger, W. C., Die Eruptivgesteine des Kristianiagebietes, IV, Das Fengebiet in Telemark, pp. 194 et seq., 1921.

[10] Shepard, C. U., Examination of a supposed meteoric iron, found near Rutherfordton, N. C.: Am. Jour. Sci., 2d ser., vol. 28, p. 259, 1859. See Wherry, E. T., The nomenclature and classification of sulphide minerals: Washington Acad. Sci. Jour., vol. 10, p. 491, 1920.

doubtful. Of these, gorceixite contains barium, harttite contains strontium and aluminum, and florencite contains cerium and aluminum. The iron-manganese phosphates are rather uncommon. Of these, triploidite and reddingite contain basic iron and manganese alone, triphyllite and lithiophyllite contain also lithium, dickinsonite and fillowite contain also sodium, graftonite calcium, and childrenite and eosphorite aluminum. The phosphates of the metallogenic elements are all secondary and hydrous. The rare phosphosilicates have already been mentioned.

The vanadates are all secondary, although vanadium occurs in silicates, as we have seen. Most of the vanadates are salts of metallogenic elements, but there are a few calcium vanadates—hewettite, pascoite, pintadoite, and fernandinite. Carnotite is a potassium uranovanadate. For a list of native antimonites and antimonates, all secondary and mostly of petrogenic elements, see a paper by Schaller.[11]

COLUMBATES AND TANTALATES.[12]

A considerable number of columbates occur as minerals in pegmatites. They are all rare, or at least they are only locally common. Most if not all of them contain tantalum along with columbium, so that we shall consider here the tantalates as well as the columbates. Many of these minerals contain titanium and are titanocolumbates or titanotantalates, though titanocolumbates are more numerous than the titanotantalates. The columbate and tantalate minerals are so complex and their analysis is so difficult that the actual constitution of most of them is little understood.

Most of the columbates and tantalates are salts of clearly petrogenic elements, especially calcium, iron, manganese, and the yttrium and cerium metals. Some of them contain titanium or zirconium and a few contain sodium. Uranium, tungsten, and thorium are common, lead (a metallogenic element) occurs in a few, and tin (also metallogenic) in many, but only in very small amounts.

The columbates and tantalates named below are among those whose existence is best established, although the composition and relations of many of them are still doubtful. They will at least serve to show the elements with which columbium and tantalum most often combine. The columbosilicates are few and rare, and they have already been considered (p. 83). Columbite is an iron-manganese columbate, and tantalite is the tantalum end of the series. Fergusonite and sipylite are essentially yttrium columbates containing small amounts of calcium, uranium, and other elements. Erbium seems to be especially prominent in sipylite. Samarskite is an iron-yttrium-uranium columbate; annerödite is a complex yttrium-uranium columbate, eschynite is essentially a columbate of cerium and thorium, and risörite is a columbate of yttrium. Among the titanocolumbates are pyrochlore (with basic sodium, calcium, cerium, and thorium), euxenite and polycrase (with yttrium and uranium), the blomstrandite-priorite series (with yttrium, thorium, and uranium), betafite and ampagabeite (with uranium), and polymignite, which is a calcium-cerium-iron zirconotitano-columbate. Samiresite and plumboniobite are columbates of uranium, lead, and other elements.

Among the tantalates are microlite (sodium-calcium fluotantalate), tantalite (iron-manganese tantalate), and skogbölite, which is the iron end of the columbite-tantalite series; with the little known loranskite, apparently a calcium-iron-cerium-yttrium zirconotantalo-silicate. Prominent columbotantalates include the calcium-uranium hatchettolite, the iron series tapiolite-mossite, the yttrium-iron yttrotantalite, the iron group strüverite-ilmenorutile, and the antimonial stibiotantalite.

CHROMATES AND MOLYBDATES.

The native chromates and molybdates, except chromite, are of secondary origin. Other chromates are dietzeite (a double chromate and iodate of calcium), the lead chromates (crocoite and phoenicocrocoite), an arsenic-bearing lead chromate (bellite)[13] and the lead-copper chromate (vauquelinite). The only native petrogenic molybdate would seem to be powellite (molybdate of calcium), as Zambonini[14] has shown that Scacchi's supposed magnesium molybdate, belonesite, is in reality sellaite, magnesium fluoride. Some molybdic ocher has been shown to be ferric molybdate. The

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[11] Schaller, W. T., Mineralogic notes, series 3: U. S. Geol. Survey Bull. 610, p. 104, 1916.

[12] For the columbates and tantalates of Norway, see Brögger, W. C., Die Mineralien der südnorwegischen Granit-pegmatitgänge; I, Niobate, Tantalate, Titanate, und Titanoniobate, Kristiania, 1906.

[13] Dana, E. S., and Ford, W. E., Second appendix to the sixth edition of Dana's System of mineralogy, p. 14, 1909.

[14] Zambonini, F., op. cit., p. 43. See Dana, J. D., System of mineralogy, 6th ed., p. 992, 1892.

native tungstates are the calcium scheelite, the iron ferberite, the manganese hübnerite, and the hydrated iron ferritungstite.

SULPHIDES.

It is somewhat uncertain whether sulphur should be considered as a petrogenic or a metallogenic element. In a former paper by the junior author[15] sulphur was set down as one of the most typical negative metallogenic elements. Further consideration, however, has led us to doubt this judgment, for it now seems to be more probable that sulphur is to be considered a petrogenic element, but with affinity toward the metallogenic elements because of its position in the periodic table near the intermediate triad groups.

The fact that the sulphides [16] of the alkali and alkali-earth metals can not exist under crustal conditions has already been mentioned, and we find that none of them exist in terrestrial rocks. Calcium sulphide (oldhamite) occurs in some meteorites, but we meet no terrestrial sulphide until we reach vanadium in the periodic table. Two rare sulphides of vanadium are known—patronite, a vanadium sulphide, and sulvanite, a sulphide of vanadium and copper. No native columbium or tantalum sulphide is known. A chromium-iron sulphide, daubréelite, occurs in meteoric irons, but there is no known terrestrial chromium sulphide. There is a rare terrestrial tungsten sulphide—tungstenite. Molybdenum sulphide (molybdenite) is common as a primary mineral, occurring in granite, syenite, and pegmatite, as well as in gneiss and as a contact mineral. There are two manganese sulphides—alabandite and hauerite—neither of which, however, is a primary pyrogenetic mineral.

The sulphides of iron, pyrite, marcasite, and pyrrhotite, are common and abundant minerals. Both pyrite and pyrrhotite occur in igneous rocks, and an end member of the pyrrhotites, troilite, a common meteoric mineral, has recently been found terrestrially.[17] Nickel forms several simple sulphides, the best known being millerite; others are polydymite and beyrichite, of somewhat uncertain composition. There are a few iron-nickel sulphides—pentlandite, which occurs in some gabbros and other igneous rocks; bravoite, which occurs in a vanadium sulphide ore body; and the pentlandite-like gunnarite and heazlewoodite. Pyrrhotite is often nickeliferous. Cobalt forms the sulphide linnaeite, in which the cobalt is partly replaced by nickel and a little iron, and the doubtful jaipurite.

Ore bodies of pyrrhotite (generally nickeliferous), pyrite, chalcopyrite, bornite, and possibly other sulphides occur as magmatic segregations—that is, the sulphides, or their constituent elements, originally formed part of the magma, and locally a very considerable part. The abundance of sulphur gases, sulphur vapor, sulphur dioxide, sulphur trioxide, and hydrogen sulphide at volcanoes, and the presence of a notable percentage (0.05) of sulphur in the average igneous rock, considered in connection with the existence of magmatic sulphide ore bodies, indicate that sulphur may be considered one of the petrogenic elements, although it seems also to be decidedly metallogenic, and may, therefore, as already noted, be considered intermediate between the two groups.

FLUORIDES.

Fluorides of the petrogenic elements are rather numerous but, with the exception of fluorite, they are not very abundant minerals. Hydrogen fluoride has been noted at Vesuvius, Etna, Kilauea, Mauna Loa, and Katmai. The bases of the native fluorides are all petrogenic elements. Villiaumite is sodium fluoride, which occurs in nephelite syenite. Sodium and aluminum are the bases in cryolite and several related minerals, and cryolithionite contains lithium as well. The very doubtful hieratite is said to be a double fluoride of potassium and silicon. Magnesium fluoride occurs as sellaite, and calcium fluoride (fluorite) is an abundant and widespread mineral, occurring in a number of igneous rocks as a primary constituent, as a lode or gangue mineral, or as a pneumatolytic product. Magnesium and calcium occur in the doubtful oxyfluoride nocerine, and calcium and aluminum in gearksutite and prosopite. Aluminum forms a hydrated fluoride, fluellite. Pachnolite and thomsenolite are sodium-calcium-aluminum fluorides. There are several

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[15] Washington, H. S., The chemistry of the earth's crust: Franklin Inst. Jour., vol. 190, p. 784, 1920.

[16] For a list of the sulphide minerals, see Wherry, E. T., The nomenclature and classification of sulphide minerals: Washington Acad. Sci. Jour., vol. 10, p. 489, 1920.

[17] Eakle, A. S., Massive troilite from Del Norte County, Calif.: Am. Mineralogist, vol. 7, p. 77, 1922.

fluorides of the metals of the cerium-yttrium groups, among them fluocerite, yttrocerite, and yttrofluorite, the two last containing calcium. Cerium and yttrium fluorides have been found in small amount in fluorite from several localities. Humphreys[18] has shown the common presence of yttrium and ytterbium in fluorite from many localities. Silicon fluoride has been reported at Vesuvius. We have seen above that fluorine is an essential constituent, though in small amount, of a number of simple and complex silicates and of most apatite.

CHLORIDES.

The chlorides that occur as minerals are not so numerous as the fluorides, although sodium chloride makes up for this difference by its abundance. With the exception of the chloride molecules that occur in silicates and that have been mentioned above, the native chlorides that are found in igneous rocks are all fumarolic salts. The chlorides of the petrogenic elements include the simple chlorides of sodium (halite), potassium (sylvite), ammonium (sal ammoniac), magnesium (chlormagnesite), calcium (hydrophilite), aluminum (chloraluminite), manganese (scacchite), and trivalent iron (molysite). Ferrous chloride (lawrencite), as well as nickelous chloride, occur in meteorites, but do not seem to have been found as distinct minerals at volcanoes. Hydrochloric acid is common in volcanic gases. There are a few mixed fumarolic chlorides—rinneite, a chloride of sodium, potassium, and iron; erythrosiderite, a chloride of potassium and iron; kremersite, a chloride of ammonium and iron; and chlormanganokalite, a chloride of potassium and manganese.

ARSENIDES TO IODIDES.

We may now see what native compounds the petrogenic elements form with the negative metallogenic elements. No known arsenides, antimonides, bismuthides, selenides, or tellurides of the petrogenic elements occur in the periodic table until the iron triad is reached.

Iron forms a few simple arsenides—leucopyrite, arsenoferrite, and löllingite, and the sulpharsenide arsenopyrite, and it occurs also isomorphously in arsenides of nickel, cobalt, and copper. No simple antimonide, bismuthide, selenide, or telluride of iron is known. There are also the iron sulphantimonite berthierite and the copper-iron sulphostannite stannite. The copper-silver sulphantimonide stylotypite contains a little iron.

Nickel forms the simple arsenides maucherite, temiskamite, niccolite, chloanthite, and rammelsbergite, as well as the sulpharsenides gersdorffite and wolfachite. There is a nickel antimonide, breithauptite, and there are the sulphantimonides arite and ullmannite, as well as the sulphobismuthides hauchecornite and kalilite. Cobalt forms the simple arsenides smaltite, safflorite, and skutterudite, and also the double sulpharsenide glaucodotite and sulphantimonide willyamite, but no simple antimonide or bismuthide.

No selenide or telluride of either iron or cobalt is known. Nickel forms a telluride (melonite), but no selenide.

The oxygen salts, arsenates, antimonates, etc., of the petrogenic elements are few and are all of secondary origin. Only the more interesting of the anhydrous minerals will be mentioned. Durangite is a sodium-aluminum fluoarsenate. Calcium forms several arsenates, including svabite, an arsenicoapatite, and (with magnesium) berzeliite, adelite, and tilasite, svabite and tilasite being fluoarsenates. Sarkinite is a manganese arsenate.

The antimonates (all of which are secondary) include romeite and atopite (calcium), lewisite (calcium and titanium), mauzeliite (calcium and lead), langbanite (iron-manganese silicoantimonate), tripuhyite (iron), derbylite (iron titanantimonate), and melanostibian (iron and manganese). The uncertain iron tellurites emmonsite and durdenite are products of weathering.

No bromides or iodides of the petrogenic elements are known except in salines and in the water of the ocean and that of a few springs. A rare calcium iodate, lautarite, and a calcium iodate-chromate, dietzite, are found sparingly in the nitrate beds of Chile, and lautarite is said to come also from Tatal, Africa.[19]

RELATIONS OF THE METALLOGENIC ELEMENTS.

NATIVE ELEMENTS.

Many of the metallogenic elements occur in nature uncombined as "native" metals. Nearly all the native metals found seem to

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[18] Humphreys, W. J., On the presence of yttrium and ytterbium in fluorspar: Astrophys. Jour., vol. 20, p. 267, 1904; A few additional fluorspars containing yttrium and ytterbium: Idem, vol. 22, p. 11, 1905.

[19] Larsen, E. S., The microscopic determination of the nonopaque minerals: U. S. Geol. Survey Bull. 679, p. 99, 1921.

be of secondary origin, although the primary origin of some of them appears to be unquestionable,[20] especially the primary copper, silver, and gold that have been detected in igneous rocks, although rarely and in very small amount. The metals of the platinum group are also primary constituents of subsilicic igneous rocks.

The native metallogenic elements [21] are copper, silver, gold, mercury, lead, arsenic, antimony, bismuth, selenium,[22] tellurium, iodine, and the platinum metals, the last either pure or in various alloys or mixtures. The reported occurrences of native zinc and tin are doubtful.

OXIDES.

Few oxides of the metallogenic elements occur as common minerals. No mineral is formed of oxide of silver, gold, gallium, indium, thallium, germanium, selenium (?), bromine, iodine, or of any platinum metal. Of the native metallogenic oxides, that of tin alone (cassiterite) occurs as a primary mineral constituent of igneous rocks. Attention may here be called to the analogies and differences between the stannic and the silicic acids. When stannic chloride is acted on by an alkali or when a soluble stannate is acted on by an acid two forms of stannic acid are produced, one of which is a "precipitate" and the other a colloidal gelatinous mass. Similarly, on treatment with an acid, some silicates yield "granular" silica, and others yield "gelatinous" silica. There are likewise two forms of titanic acid.

The oxides of the other metallogenic elements are of secondary origin. Apart from the hydrated oxides there are the native oxides of copper (cuprite and tenorite), of zinc (zincite), of cadmium (unnamed),[23] as well as of mercury (montroydite), tin (cassiterite, as a contact mineral), lead (massicot, minium, litharge), arsenic (arsenolite and claudetite), antimony (senarmontite, valentinite, cervantite), bismuth (bismite), and tellurium (tellurite). With the exception of cassiterite and cuprite all these metallogenic oxides are very rare.

SILICATES.

There are no known native silicates of silver, gold, cadmium, mercury, gallium, indium, thallium, germanium, or the platinum metals. There is but one silicate of tin (stokesite); this contains calcium. Small amounts of tin occur in several petrogenic silicates as orthoclase and mica. We find an arsenosilicate of manganese (dixenite); two antimonosilicates (langbanite and catoptrite), both of manganese; and two orthosilicates of bismuth (eulytite and agricolite). Copper forms one basic silicate (dioptase), and several hydrated silicates (bisbeeite, chrysocolla, plancheite, and shattuckite). All of these silicates of metallogenic elements are secondary.

Zinc forms a number of secondary silicates. The anhydrous minerals are zinc orthosilicate (willemite) and the manganiferous variety (troostite), the zinc-calcium orthosilicate (hardistonite), the manganese-calcium-zinc orthosilicate (leucophoenicite); and the iron-zinc-glucinum-manganese sulphosilicate (danalite). Small amounts of zinc also enter isomorphously into several other silicates, forming varieties, as the zinc-manganese pyroxene jeffersonite, and the zinc-manganese-iron olivine roepperite. The hydrous zinc silicates include the zinc silicate calamine, the calcium-zinc clinohedrite, and the magnesium-manganese-zinc gageite.

Lead, like zinc, forms a considerable number of silicates, all of secondary origin. They include the essentially lead silicates barysilite and alamosite; the magnesium-lead molybdophilite; the calcium-lead ganomalite, margarosanite, and roeblingite, the last containing a little strontium; the manganese-lead kentrolite; the iron-lead melanotekite; the calcium-cerium-lead nasonite; the complex epidote hancockite, which contains aluminum, iron, calcium, and strontium, with lead; and the barium-calcium-lead borosilicate hyalotekite.

In respect to these silicates of the metallogenic elements, four suggestively important general facts stand out. (1) Although the number of species is considerable most of them are very uncommon minerals, some of them, as stokesite, being known from only a single specimen or from a single locality, and the only ones that may be called minerals of common occurrence are dioptase, chrysocolla, willemite, and calamine, which are silicates of copper and of zinc; (2) they are all of secondary origin or

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[20] See Beyschlag, F., Vogt, J. H. L., and Krusch, P., The deposits of the useful minerals and rocks, vol. 1, p. 345, 1914.

[21] For a recent revised and critical list of the native elements, see Wherry, E. T., The nomenclature and classification of the native element minerals: Washington Acad. Sci. Jour., vol. 7, pp. 450-456, 1917.

[22] Cf. Zambonini, F., Mineralogia vesuviana, p. 24, Naples, 1910.

[23] Wittich, E., and Neumann, B., Ein neues Cadmium-mineral: Centralbl. Mineralogie, 1901, p. 549.

occur in ore bodies, and they do not form primary constituents of igneous rocks; (3) most of them are orthosilicates or subsilicates, that is, they contain a minimum amount of silica; (4) the silicates of lead are the most numerous and varied, those of zinc coming next, and the numerically few secondary silicates of copper are fairly common—indeed, the number of species of the lead and zinc silicates outnumber those of the silicates of all the other metallogenic elements together.

The only known aluminate of a metallogenic element is gahnite, a zinc spinel, which is of secondary origin. There are no aluminosilicates, borosilicates, fluosilicates, zirconosilicates, or titanosilicates of metallogenic elements; that is to say, there are no metallogenic salts of the most characteristic petrogenic acids.

There is a rare columbotantalate of antimony, stibiotantalite, and plumboniobite is an equally rare columbate of yttrium, uranium, lead, iron, or other metal. Small amounts of tin and tungsten are found in some of the rare columbates and tantalates.

CHROMATES AND MOLYBDATES.

The most numerous and common chromates and molybdates of the metallogenic elements are those of lead. These are lead chromate (crocoite), basic lead chromate (phoenicocroite), lead phosphochromate (vauquelinite), lead carbonochromate (beresovite), lead arsenochromate (bellite), lead molybdate (wulfenite) and a hydrous lead-zinc vanadate (descloizite). There is no native chromate or molybdate of copper, but copper enters into the vanadate cuprodescloizite. Pucherite is bismuth vanadate, and there is a basic bismuth molybdate—koechlinite. With these may be mentioned the two lead tungstates (stolzite and raspite), the copper tungstate (cuprotungstite), and the calcium-copper tungstate (cuproscheelite).

ARSENIDES, ANTIMONIDES, AND BISMUTHIDES.

There are several simple arsenides and antimonides and a few bismuthides of the metallogenic elements. Of copper we have the arsenides domeykite, ledouxite, algodonite, and whitneyite, the nickeliferous varieties keweenawite and mohawkite, and the antimonide horsfordite. There is no copper bismuthide. Silver forms no simple arsenide, but there is the antimonide dyscrasite and the bismuthide chilenite. There is no simple arsenide, antimonide, or bismuthide of lead or of the other metallogenic metals, except that platinum forms the arsenide sperrylite.

SULPHIDES.

There are some simple sulphides of the metallogenic metals, but they are not so numerous as the sulpho-salts, although among them are some common and abundant minerals. Copper forms the common sulphides chalcocite and covellite; with iron the mixed sulphides bornite, chalcopyrite, chalmersite, and cubanite; and with cobalt carrollite and sychnodymite. There seems to be no copper-nickel sulphide. Silver forms the simple sulphides argentite and acanthite, the silver-copper sulphide stromeyerite, and the silver-iron sternbergite. No native gold sulphide is known. Zinc forms the two sulphides sphalerite and wurtzite, and cadmium forms greenockite and the hydrous xanthochroite. The sulphides of mercury are cinnabar and metacinnabarite and the mercury-zinc guadalcazarite. Gallium and indium occur in sphalerite, presumably as sulphide, but no independent sulphide of them is known. Thallium does not form a native sulphide, but it occurs in sphalerite and pyrite, presumably also as sulphide. There is no native simple sulphide of germanium, though germanium enters into several sulpho-salts. Tin enters into two sulphides—with copper and iron, forming stannite, and with lead, forming teallite. Lead forms but one simple sulphide, the abundant galena. The cupriferous cuproplumbite and alisonite are probably mixtures of galena and covellite.

Arsenic forms the simple sulphides realgar, orpiment and dimorphite; antimony and bismuth form one each, stibnite and bismuthinite, respectively. Bismuth forms with nickel also the double sulphide kallinite. A rare sulphide of ruthenium, laurite, occurs, this being the only known native sulphide of the platinum metals, just as the platinum arsenide, sperrylite, is the only native arsenide. This latter occurs with sulphide copper ores.

SELENIDES AND TELLURIDES.

The metallogenic selenides and tellurides include only those of copper, silver, gold, mercury, thallium, lead, and bismuth. The only known selenide or telluride of a petrogenic element is melonite, a nickel telluride.

Copper forms the simple selenides berzelianite and umangite, the hydrated copper selenite chalcomenite, the silver-copper selenide eucairite, the thallium-copper selenide crookesite, and the simple copper telluride rickardite. Selenium is present in small amount in many pyritic copper deposits, from which it is recovered electrolytically.

No simple selenide of silver is known, but silver forms the sulphoselenide aguilarite, the copper-silver selenide eucairite, and the lead-silver selenide naumannite, and a little silver is present in the thallium-copper selenide crookesite. Silver tellurides are more numerous. The simple silver tellurides are stutzite (known from only one specimen), hessite, and empressite, as well as the bismuth-silver telluride vondiestite. There are also the gold-silver tellurides petzite, sylvanite, krennerite, muthmannite, and the doubtful speculite.

No definite gold selenide is known, but there are [24] some gold deposits in which the gold appears to be present in combination with selenium, the selenide or selenides being as yet unidentified. Apart from these possible selenides the tellurides of gold are the only compounds of this metal that occur in nature. The simple gold telluride is calaverite; the silver-gold tellurides have just been mentioned. The lead-gold sulphotelluride nagyagite contains a little antimony.

Mercury forms a simple selenide, tiemannite, and a sulphoselenide, onofrite, as well as the lead-mercury selenide lehrbachite. There is a simple mercury telluride, coloradoite.

Thallium does not form a native simple selenide but occurs as the copper-thallium selenide, crookesite. There is no known native telluride of thallium. Lead forms a simple selenide, clausthalite, a silver-lead selenide naumannite, and the mercury-lead selenide lehrbachite. The simple lead telluride is altaite, and the only other lead telluride is the gold-lead sulphotelluride nagyagite.

Bismuth forms the simple selenide selenobismuthite and the sulphoselenide guanajuatite. There appear to be no double bismuth selenides. There are three simple bismuth tellurides, tetradymite, joseite, and wehrlite, all of which usually contain a little sulphur, and joseite contains also a little selenium. Grünlingite is a sulphotelluride of bismuth, and vondiestite is a silver-bismuth telluride. Oruetite, a supposed bismuth sulphotelluride, would appear to be a variety of either grünlingite or wehrlite.

SULPHO-SALTS.

The complex sulpho-salts (or thio-salts, as they are now generally called) are compounds that are especially characteristic of the metallogenic elements. These salts include the sulpharsenites, sulphantimonites, sulphobismuthites, sulphogermanates, sulphostannates, and sulphovanadates. Selenium or tellurium may replace sulphur. We follow the list of Wherry and Foshag,[25] as this is the most recent and the most critical.

Copper forms two simple sulpharsenites, enargite and luzonite, as well as the lead-copper seligmannite, the iron-copper epigenite, and the iron-zinc-copper tennantite (including binnite). Copper forms four simple sulphantimonites—chalcostibite, stylotypite (including falkenhaynite), famatinite, and a "high-sulphur famatinite," as well as the silver-copper freibergite, the lead-copper bournonite, the mercury-copper schwatzite, the iron-zinc-copper tetrahedrite, and the doubtful iron-lead-copper richmondite. The complex sulphotellurantimonite goldfieldite is included in famatinite by Wherry and Foshag. Copper forms three simple sulphobismuthites, emplectite (cuprobismutite), klaprotholite, and wittichenite, as well as the lead-copper aikenite and the iron-copper sulphantimonobismuthites eichbergite and histrixite. Copper forms also the sulphovanadite sulvanite and the sulphostannate cylindrite, which contains antimony.

Silver forms five simple sulpharsenites—trechmannite, smithite, proustite, xanthoconite (including the selenium-bearing rittingerite), and pearceite, as well as the lead-silver lengenbachite. The simple sulphantimonites of silver are miargyrite, pyrargyrite, pyrostilpnite, stephanite, polybasite, and polyargyrite, and the double sulphantimonites are the

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[24] Lindgren, Waldemar, Mineral deposits, pp. 493-495, 1913. Beyschlag, F., Vogt, J. H. L., and Krusch, P., The deposits of the useful minerals and rocks, vol. 1, p. 167, 1914.

[25] Wherry, E. T., and Foshag, W. F., A new classification of the sulfo-salt minerals: Washington Acad. Sci. Jour., vol. 11, pp. 1-8, 1921. A few additions of more recently published minerals have been taken chiefly from volumes 5, 6, and 7 of the American Mineralogist.

manganese-silver samsonite, the copper-silver freibergite, and the lead-silver andorite, owyheeite, brongniardite, diaphorite, and freieslebenite. Silver forms two sulphobismuthites, plenargyrite and matildite, and the lead-silver schirmerite, schapbachite, and alaskaite (doubtful). We have also the silver-lead sulphantimonobismuthite ultrabasite (which contains germanium), the sulphogermanate argyrodite, and the germanium-bearing sulphostannate canfieldite.

Lead forms seven simple sulpharsenites—scleroclasite (sartorite), liveingite, baumhauerite, rathite, dufrenoysite, guitermannite, and jordanite. We have also the copper-lead seligmannite, the silver-copper lengenbachite, and the thallium-lead hutchinsonite. There are nine simple sulphantimonites of lead—zinkenite, plagionite, heteromorphite, plumosite, semseyite, boulangerite, embrithite, meneghinite, and geocronite (kilbrickenite); as well as the iron-lead jamesonite (including warrenite), the copper-lead bournonite, and the silver-lead andorite, owyheeite, brongniardite, diaphorite, and freieslebenite. Of simple lead sulphobismuthites there are eight—chiviatite, bismutoplagionite, rezbanyite, platynite, galenobismutite, cosalite (including kobellite), lillianite, and beegerite, and there is also the doubtfully distinct selenium-bearing weibullite. In addition there are the copper-lead aikenite and the silver-lead schirmerite, schapbachite, and alaskaite (?), as well as the complex silver-lead ultrabasite. Lead forms also the sulphantimonostannates franckeite and cylindrite, which contain a little germanium.

The sulphosalts of the other metallogenic elements are few. Mercury forms the simple sulphantimonite livingstonite and the copper-mercury sulphantimonite schwatzite. Thallium forms the simple sulpharsenite lorandite, the sulpharsenantimonite vrbaite, and the lead-thallium sulpharsenite hutchinsonite. No others are known.

The sulpho-salts are nearly all salts of copper, silver, and lead, but there is one salt each of mercury and thallium. Of the salts formed by these metals with arsenic, antimony, and bismuth, those of arsenic number 18, those of bismuth 19, and those of antimony 33. The copper salts number 20, the silver salts 25, and the lead salts 38. Lead not only forms the greatest number of simple sulpho-salts but enters into the greatest number of double salts. Thus, antimony among the negative elements and lead among the positive show the greatest tendency to form sulpho-salts, and arsenic and copper the least tendency. Of the metallogenic elements named, arsenic and copper are the nearest to the petrogenic elements in the periodic table (Table 22) and bismuth and lead are the farthest away.

HALIDES.

No native fluorides of the metallogenic elements are known. There are chlorides and oxychlorides of copper, silver, mercury, and lead. The simple copper chloride is nantockite; there are two oxychlorides, atacamite and paratacamite; and (apparently) four oxychlorides of copper and lead, percylite, boleite, pseudoboleite, and cumengeite.

Silver forms the simple chloride cerargyrite and the mixed or double salts embolite (with chlorine and bromine) and iodyrite (with chlorine, bromine, and iodine). Mercury chloride occurs native as calomel, and there are also the peculiar mercury-ammonium chlorides kleinite and mosesite and the mercury oxychlorides terlinguaite and eglestonite. Lead forms the simple chloride cotunnite and the potassium-lead chloride pseudocotunnite. There are several oxychlorides of lead, some of them (as matlockite, mendipite, and lorettoite) found in ore bodies; and others (as laurionite, fiedlerite, and penfieldite) found on lead slag. Schwartzembergite is an oxychloriodide of lead. No native bromide of copper is known. Silver forms the simple bromide bromyrite and the chlorobromide embolite, as well as the iodine-bearing iodobromite. Neither mercury nor lead form native bromides.

Copper forms the simple iodide marshite and the silver-copper iodide cuproiodargyrite. Silver forms two iodides, iodyrite and miersite, as well as the somewhat doubtful mercury-silver tocornalite, and the somewhat indefinite iodobromite. There is a doubtful native iodide of mercury (coccinite), none of lead, but there is an oxychloriodide of lead, schwartzembergite.

Leaving aside the oxychlorides, the chlorides and the other halides of silver are the most numerous. There are no fluorides of the metallogenic elements, but, on the other hand, there are no bromides or iodides of the petrogenic elements, chlorine alone being common to the two. It is significant that the native chlorides of the metallogenic elements are all salts that are insoluble or difficultly soluble in water.

SUMMARY.

GENERAL RELATIONS.

The facts already presented, which are derived from a survey of the primary minerals found in igneous rocks (including those in the pegmatites) and in ore bodies, seem to justify a division of the elements that occur in those minerals into two "natural" groups—the petrogenic or rock-forming elements, and the metallogenic or ore-forming elements. About 99.5 per cent of the known rocks of the earth's crust is formed of petrogenic elements.

In order to bring the somewhat complex data more concisely before the eye we give below two tables showing the groups of minerals formed by the petrogenic and the metallogenic elements. In these tables much of the detail already given is necessarily lost, but the salient facts are clearly exhibited. A multiplication mark (×) indicates that the occurrence of the electropositive element in the mineral group is well known either because the minerals formed are abundant or numerous or because (if the element considered is rare) the group so marked is a common one for the element involved, as, for example, the gold tellurides. A small Roman x indicates that the minerals of the group so marked are rather common to somewhat rare, but that they can be considered characteristic. A small italic *x* indicates a group of very rare minerals but one that seems to be significant in spite of its rarity. A capital O indicates that the element is not found in the crust of the earth in the mineral group so marked.

TABLE 24.—*Groups of minerals formed by the petrogenic elements.*

	Native metals.	Oxides.	Spinels.	Simple silicates.	Borosilicates.	Aluminosilicates.	Zirconosilicates.	Titanates.	Titanosilicates.	Columbates.	Sulphides.	Selenides, tellurides.	Arsenides.	Fluorides.	Chlorides.
Lithium	O	O	O	O	*x*	×	O	O	O	O	O	O	O	*x*	O
Sodium	O	O	O	O	x	×	x	O	x	*x*	O	O	O	*x*	×
Potassium	O	O	O	O	O	×	O	O	O	O	O	O	O	O	x
Rubidium-Caesium	O	O	O	O	O	*x*	O	O	O	O	O	O	O	O	O
Glucinum	O	O	O	x	O	x	O	O	O	O	O	O	O	O	O
Magnesium	O	*x*	×	×	O	×	O	*x*	O	O	O	O	O	*x*	x
Calcium	O	O	O	×	×	×	x	x	×	x	*x*	O	O	×	x
Strontium	O	O	O	O	O	*x*	O	O	O	O	O	O	O	O	O
Barium	O	O	O	O	*x*	x	O	O	*x*	O	O	O	O	O	O
Aluminum	O	×	×	×	x	×	x	O	×	O	O	O	O	x	x
Yttrium	O	O	O	*x*	*x*	x	*x*	O	*x*	x	O	O	O	x	O
Lanthanum	O	O	O	x	*x*	*x*	*x*	O	O	O	O	O	O	x	O
Titanium	O	×	O	O	O	x	x	×	×	x	O	O	O	O	O
Zirconium	O	x	O	×	x	x	x	O	x	*x*	O	O	O	O	O
Thorium	O	O	O	*x*	O	O	O	O	O	*x*	O	O	O	O	O
Cerium	O	O	O	x	*x*	x	x	*x*	x	x	O	O	O	x	O
Vanadium	O	O	O	*x*	O	*x*	O	O	O	O	*x*	O	O	O	O
Columbium-Tantalum	*x*	O	O	O	*x*	O	O	x	x	x	O	O	O	O	O
Chromium	O	O	x	x	O	x	O	O	O	O	*x*	O	O	O	O
Molybdenum	O	O	O	O	O	?	O	O	O	O	×	O	O	O	O
Tungsten	O	O	O	O	O	O	O	O	O	*x*	*x*	O	O	O	O
Uranium	O	x	O	*x*	O	O	O	O	O	*x*	O	O	O	O	O
Manganese	O	×	×	×	x	x	O	x	x	x	O	O	O	O	*x*
Iron	×	×	×	×	x	×	x	x	x	×	×	O	x	O	x
Cobalt	O	*x*	O	*x*	O	O	O	O	O	O	x	O	x	O	O
Nickel	×	x	O	x	O	O	O	O	O	O	×	*x*	×	O	O

TABLE 25.—*Groups of minerals formed by the metallogenic elements.*

	Native metals.	Oxides.	Silicates.	Titanates.	Columbates.	Sulphides.	Selenides, tellurides.	Arsenides.	Antimonides.	Bismuthides.	Sulpharsenates.	Sulphantimonites.	Sulphobismuthites, etc.	Bromides.	Iodides.	Chlorides.
Copper	×	×	×	O	O	×	x	×	x	O	×	x	x	O	x	x
Silver	×	O	O	O	O	×	x	O	x	x	×	×	x	x	x	x
Gold	×	O	O	O	O	O	×	O	O	O	O	O	O	O	O	O
Zinc	?	x	×	O	O	×	O	O	O	O	O	O	O	O	O	O
Cadmium	O	*x*	O	O	O	x	O	O	O	O	O	O	O	O	O	O
Mercury	x	*x*	O	O	O	×	x	O	O	O	O	*x*	O	O	*x*	x
Gallium	O	O	O	O	O	*x*	O	O	O	O	O	O	O	O	O	O
Indium	O	O	O	O	O	*x*	O	O	O	O	O	O	O	O	O	O
Thallium	O	O	O	O	O	*x*	*x*	O	O	O	*x*	*x*	O	O	O	O
Germanium	O	O	O	O	O	*x*	O	O	O	O	O	O	*x*	O	O	O
Tin	?	×	*x*	O	*x*	x	O	O	O	O	O	O	*x*	O	O	O
Lead	x	x	x	O	O	×	x	O	O	O	×	×	x	O	O	x
Arsenic	x	x	*x*	O	O	×	O	O	O	O	×	O	O	O	O	O
Antimony	x	x	*x*	O	*x*	×	O	O	O	O	O	×	O	O	O	O
Bismuth	x	*x*	*x*	O	O	x	x	O	O	O	O	O	×	O	O	O
Ruthenium	x	O	O	O	O	*x*	O	O	O	O	O	O	O	O	O	O
Rhodium	x	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Palladium	x	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Osmium	x	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Iridium	x	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Platinum	×	O	O	O	O	O	O	*x*	O	O	O	O	O	O	O	O

The petrogenic elements, with a few exceptions, notably the gases, iron, and nickel, do not occur native, because of their ready oxidizability. Many of them occur as oxides, but only a few as spinels. All of them, except possibly tungsten, occur in silicates, and most of them form complex silicates, nearly all occurring in aluminosilicates, a considerable number in borosilicates, and some in fluosilicates or zirconosilicates. The titanates and titanosilicates of the petrogenic elements are fairly numerous; the columbates and tantalates are fewer, and the basic elements in them are rather characteristic. The petrogenic elements that form fluorides or enter into fluosilicates seem to be more numerous than those that form chlorides. The sulphides are not common, and they are confined chiefly to the members of the iron triad and the elements in its immediate vicinity in the periodic table. There are a few sulphosilicates. Primary phosphates are all salts of petrogenic elements, lithium, sodium, glucinum, magnesium, calcium, strontium, yttrium, cerium, thorium, aluminum, manganese, and iron. The arsenides are confined wholly to the elements of the iron group. There are no antimonides, bismuthides, selenides, or tellurides of petrogenic elements except a single nickel telluride. No bromides or iodides are found except those of the alkali metals, which occur in oceanic and other waters, and there is a rare secondary calcium iodate. There are no sulpho-salts of the petrogenic elements except that a few contain iron and nickel. There are two or three very rare silicates containing arsenic and antimony but none with selenium, tellurium, bromine, or iodine.

Of the petrogenic elements calcium enters into the largest number of combinations; its silicates, aluminosilicates, and other complex silicates are especially numerous and abundant. It is noteworthy that calcium forms no spinel. Sodium comes next but one to calcium in the number of compounds in which it is an essential constituent, and it affects especially the aluminosilicates and other complex silicates. Potassium forms few natural silicates, and these are all aluminosilicates; it does not enter into the other complex silicates. Lithium enters essentially into more minerals than potassium, although the lithium minerals are not so common. Aluminum is next after calcium in the number of its native compounds and is followed by iron and manganese after sodium. Magnesium forms a surprisingly small number of truly magnesium minerals, although it replaces iron isomorphously in some of the essentially iron minerals. The cerium and yttrium elements form a rather large number of minerals, entering into many more kinds than is commonly realized.

Nearly all the electropositive metallogenic elements occur as native metals, which, however, are almost invariably of secondary origin; only the platinum metals normally and uniformly, and copper, silver, and gold rarely, are primary constituents of rocks. Only a few of the metallogenic elements occur as oxides, and these few, with the exception of tin oxide, are all of secondary origin and most of them are rare minerals. Zinc is the only metallogenic element that combines with alumina to form a spinel, and this belongs with the ore minerals. Silicates of the metallogenic elements are very rare, except those of copper and zinc, and all are apparently secondary. There seem to be no titanates or titanosilicates of the metallogenic elements and no aluminosilicates or other complex silicates. Only tin and lead enter into columbates and tantalates. In brief, we may say that the metallogenic elements do not form or do not readily form primary salts of oxygen acids.

Sulphides of the metallogenic elements are numerous, the only exceptions being gold and the metals of the platinum group except ruthenium. Only a few elements form selenides and tellurides, and copper and platinum are the only elements that appear to form simple arsenides. Simple antimonides and bismuthides are also very few and are confined to those of copper and silver. The rarity of these binary compounds may be ascribed to their ready oxidizability. The sulpho-salts, sulpharsenites, sulphantimonites, sulphobismuthites, and some rarer salts of the same type are much more numerous and well distributed, almost all the metallogenic elements forming some of these, either actually or presumably. Gold, zinc, cadmium, mercury, and the platinum metals seem to be the only exceptions. The sulpho-salts are the typical native compounds of the metallogenic elements corresponding to the aluminosilicates among the petrogenic elements.

There seem to be no native metallogenic borides, nitrides, phosphides, or carbides, and the phosphates, sulphates, and carbonates are all secondary, produced by meteoric oxidizing processes. There are no native metallogenic fluorides, few chlorides, but several bromides and iodides, the halides being confined to copper, silver, mercury, and lead.

ELEMENTS HAVING DOUBTFUL RELATIONS.

The relations of several elements seem to be somewhat dubious. The inert gases of group 0 in the periodic table have no valence and form no compounds, so it is difficult to determine their position among the elements. They may be placed provisionally with the petrogenic elements, although not without objection, because of the terminological incongruity. On the other hand, it may appear eventually that they correspond to or form a zone opposed to the group of intermediate triad elements. It is probably best, for the present, to consider them as belonging to neither group.

The relations of sulphur are somewhat dubious. In the first publication of the suggested relations of the elements,[26] sulphur was confidently assigned to the metallogenic group. Further consideration and study, however, cause us to doubt this assignment, and we now consider sulphur a petrogenic element, or at least one having affinities with elements of the petrogenic rather than the metallogenic group. The abundance of sulphur and sulphur oxides at volcanoes; the fairly common occurrence of magmatic sulphide bodies in igneous masses; the great abundance of sulphides of the iron group and the comparative rarity of simple sulphides of the metallogenic elements, except those of copper and zinc, whose positions are near the petrogenic half of the periodic table; and the occurrence of sulphosilicates strongly favor the belief that sulphur is a petrogenic element.

The close relationship between tantalum and columbium; the presence of tantalum in many if not most columbates; the existence of titanotantalates; the presence of tantalum in some silicates (as lavenite); and the general occurrence of tantalum (and columbium) minerals in pegmatites, are conclusive evidence that tantalum, like columbium, should be considered a petrogenic element. There is also reason of the same kind for considering tungsten as petrogenic; it is present in some columbates and, although it does not form silicates, it does not function in general like a metallogenic element.

There may seem to be some doubt also as to the true relations of the radioactive elements,

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[26] Washington, H. S., The chemistry of the earth's crust: Franklin Inst. Jour., vol. 190, pp. 784, 786, 1920.

radium, thorium, and uranium. Thorium and uranium, however, both form silicates and columbates; they are common (for such rare elements) as oxide and phosphate; and they are usually accompanied by calcium, yttrium, and other petrogenic elements. Radium is a member of the calcium group, and it naturally accompanies uranium, of which it is a degradation product. Neither of these elements forms native sulphides, arsenides, antimonides, bismuthides, sulpho-salts, selenides, or tellurides. On the whole, therefore, the evidence seems to be conclusive that radium, thorium, and uranium should be regarded as petrogenic.

Holmes [27] some years ago came to the conclusion, from studies of the radioactivity of rocks, that the radium content of the crust is confined almost wholly to the outer portion; this conclusion is quite in accord with radium being a petrogenic element.

The common occurrence of tin as oxide and as a primary constituent of igneous rocks is the most striking exception to the general relations of the two groups of elements. Its occasional occurrence in silicates and in columbates is also anomalous. Although, for these reasons, there may be some doubt as to its true affinities, yet it seems reasonable, because of the other features of its occurrences and associations, to assign tin to the group of metallogenic elements.

Some general correspondences as to the electronegative elements in the two groups thus seem to be more or less dimly indicated. The trivalent elements arsenic, antimony, and bismuth may possibly function in the metallogenic group much as boron and aluminum function in the petrogenic group. The quadrivalent petrogenic elements silicon, titanium, and zirconium seem to have no strict analogues in the metallogenic group, except that perhaps tin and germanium may be considered their representatives, especially at great depth beneath the crust. This supposition might incidentally furnish some explanation of the otherwise anomalous behavior of tin. The part played by oxygen in the petrogenic group may be played by sulphur (or more probably by selenium and tellurium) in the metallogenic group. Here we seem to see a vague suggestion of an explanation of the fact that tellurides are the only native compounds of the extremely metallogenic gold. The oxides of the petrogenic elements would therefore correspond to the metallogenic sulphides, selenides, and tellurides; the borosilicates, zirconosilicates, aluminosilicates, and other such complex petrogenic compounds would be analogous to the metallogenic sulpharsenites, sulphantimonites, and other less common sulpho-salts. These suggestions may seem to be highly speculative, yet our survey of the mineral associations of the elements gives us some ground for considering them.

DIFFERENCES BETWEEN THE TWO GROUPS.

The principal differences between the chemico-mineralogic features of the elements of the petrogenic and the metallogenic groups in the earth's crust are contrasted in Table 26, and with them are given the analogous principal features of the elements in meteorites. The mineral groups are arranged according to the valence of the negative element, and only the more common are included.

There are evidently essential differences between the mineral combinations of the petrogenic and the metallogenic elements, so that the distinction between them is justified. At the same time, several minor yet significant features indicate that the two groups are not sharply sundered but that they are connected by groups of intermediate elements. These intermediate groups are those of the triads—the iron, ruthenium, and osmium groups; to the elements in these groups, on either hand, the more definitely petrogenic or metallogenic elements seem to have affinities. Furthermore, as we approach these intermediate groups from either the petrogenic or the metallogenic side we note their tendency to combine with the elements of the other group, especially those that lie nearest the triads.

The tendency toward either affinity is well shown in the triad column of the periodic table. (See p. 74.) Thus, in the iron group, iron forms many and abundant sulphides, but nickel, which is nearest the metallogenic side, forms comparatively few and less abundant ones. On the other hand arsenides of nickel are more abundant, while arsenides of iron are rare. Nickel also is the only element of this triad that forms a telluride. Cobalt is known

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[27] Holmes, Arthur, Radium and the evolution of the earth's crust: Nature, vol. 91, p. 398, 1912; The terrestrial distribution of the radio elements: Idem, p. 582, 1912.

in only a few sulphides, but it forms more arsenides. The platinum metals form only two native compounds; ruthenium, which stands next to the petrogenic side, forms a sulphide; and platinum, the closest to the metallogenic side, forms an arsenide.

Vanadium, chromium, manganese, molybdenum, and tungsten, petrogenic elements that lie nearest the triads, are the only ones that form native sulphides. On the other side, copper and zinc form the most common metallogenic silicates, and the sulphides of copper, zinc, and silver are very common, but cadmium occurs in nature only as a sulphide. Copper is especially prone to form double sulphides with iron.

TABLE 26.—*General occurrence of mineral groups in the earth.*

Valency of negative element.	Petrogenic (crust).	Meteoritic (intermediate).	Metallogenic (core).
Native	Rare.	Nickel-iron (abundant).	Abundant.
Univalent	Fluorides, chlorides (common); bromides, iodides (none).	Chlorides (rare); bromides, iodides (none).	Fluorides (none); chlorides (rare); bromides, iodides (rare).
Bivalent	Oxides [a] (abundant); sulphides (common); selenides [b] (none).	Sulphides (common); oxides (none); selenides [b] (none).	Sulphides (common), selenides [b] (rare); oxides (rare).
Trivalent	None.	Phosphides (common).	Arsenides, antimonides (common).
Bi-trivalent	Spinels [c] (common); sulpho-salts (none).	Chromite (common); sulpho-salts (none).	Sulpho-salts (abundant); spinels [d] (none).
Bi-quadrivalent	Silicates (abundant); titanates (common).	Silicates (abundant); titanates (none).	Silicates (secondary); titanates (none).
Bi-tri-quadrivalent	Aluminosilicates [e] (abundant).	Aluminosilicates [e] (rare).	Aluminosilicates [e] (none).

[a] Aluminates, ferrates, etc., not included.
[b] Tellurides included.
[c] Magnetite, chromite, and spinels.
[d] Except zinc spinel.
[e] Includes zirconosilicates, borosilicates, fluosilicates, etc.

SPECTROSCOPIC DIFFERENCES.

There seem to be differences in the character of the spectra of at least some of the petrogenic and metallogenic elements that may be connected with the chemical differences between the two groups which we have just studied. The spectra of the most characteristically petrogenic elements are produced at low temperatures (flame spectra), as well as at higher temperatures (arc and spark spectra). Their spectra show sharp lines, most of them in the ocularly visible part of the spectrum, and they are free from bands or hazy lines. Their flame spectra are also very simple, consisting of comparatively few lines, notably those of sodium, lithium, potassium, and indium. Thallium is unique among the metallogenic elements in its extremely simple spectrum. The flame spectra of the alkali-earth metals—calcium, strontium, and barium—are slightly more complex but are still in general simple as compared with the spectra of many other elements. The spectra of titanium, vanadium, chromium, molybdenum, manganese, iron, cobalt, and nickel appear only with the arc or spark, and they show a great multitude of lines. These petrogenic elements occupy positions in the periodic table nearest to the metallogenic elements. Some of the most typical metallogenic elements—as silver, gold, lead, and bismuth—show prominent and characteristic hazy lines and many sharp lines, and their spectra are best seen in the ultra-violet. It is noteworthy that the spectra of copper, zinc, and cadmium, metallogenic elements which are near the triad group, are comparatively simple and without bands or hazy lines. These well-known peculiarities may be kept in mind in any consideration of the groups of the petrogenic and metallogenic elements, as they may possibly be related phenomena.

ELEMENTS FOUND IN METEORITES.

In some respects the chemico-mineral features of meteorites are intermediate between or partake of some of the chief features of the two terrestrial groups of elements and their minerals. Merrill[28] has shown by a long series of excellent analyses (made by Whitfield), in which

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[28] Merrill, G. P., On the minor constituents of meteorites: Am. Jour. Sci., 4th ser., vol. 35, p. 509, 1913; Report on researches on the chemical and mineralogical composition of meteorites, with especial reference to their minor constituents: Nat. Acad. Sci. Mem., vol. 14, Mem. 1, 1916; Second report on researches on the chemical and mineralogical composition of meteorites: Idem, Mem. 4, 1919.

the rarer elements were especially looked for, the following general chemical features of meteorites, which may be compared with those of terrestrial rocks and ores.

1. Meteorites (stone and iron) contain as essential and abundant constituents sodium, potassium, magnesium, calcium, aluminum, carbon, silicon, phosphorus, sulphur, chromium, manganese, chlorine, iron, cobalt, and nickel.

2. Titanium and copper are found in many meteorites, but in very small quantities. Vanadium is also occasionally found in traces.

3. Some of the platinum metals—platinum, palladium, ruthenium, and iridium—are unquestionably present in small amount in some iron meteorites.

4. Strontium, barium, and zirconium seem to be altogether absent, even from the most feldspathic meteorites. According to Holmes radium is not present in meteorites.

5. Arsenic, antimony, gold, lead, molybdenum, silver, tin, tungsten, uranium, and zinc were not found in any meteorite analyzed, so that the previous reported occurrences of them are more than doubtful.

It is significant that meteorites are composed essentially only of petrogenic elements, which, however, do not occur in the order of abundance in which they are found in the igneous rocks of the earth. The rarity of titanium in meteorites presents a striking contrast to its relative abundance in terrestrial rocks. The apparently complete absence of barium, strontium, and zirconium is also very notable. The occurrence of some of the platinum metals in meteoric irons is of great interest in view of their terrestrial occurrence as magmatic segregations in igneous rocks like those which compose the stony meteorites. The entire absence of the metallogenic elements, except slight and sporadic traces of copper, is also highly significant. Copper is the only metallogenic element that accompanies iron and nickel in the terrestrial native irons, and it is also especially prone to be associated with iron and nickel in the double sulphides and in other combinations.

Some meteorites contain petrogenic elements that approach in position the triad column in the periodic table. The whole chemico-mineralogic aspect of meteorites is, therefore, petrogenic, but there is a marked tendency toward what we have some reason to believe are the chemical features of the lower zones of the earth's crust. There seems to be little, if any, justification for the assumption by Suess[29] of an interior shell of "crofesima"—that is, basic rocks characterized by much chromium. The figures for this element given in this paper and the studies by Merrill and others on the composition of meteorites indicate that chromium is of very subordinate importance in the constitution of the earth.

CORRELATION OF THE ELEMENTS.

We may now summarize the data already given as to the occurrences of the elements in minerals and consider their mutual associations, or what has been termed their correlation with reference to their apparent preferences for each other and their presence in greater or less amount in igneous rocks of different dominant chemical character.

Vogt [30] seems to have been the first, at least in recent times, to attempt to show the relation of the elements in igneous rocks to the chemical character of the rocks. He and several later writers [31] considered the selective tendencies of the elements with reference to silica only. The junior author [32] has pointed out that the silicity of the rocks is not the only factor to be considered in this connection, but that "the relations are more complex and dependent not so much on the amount of silica as on the relative amounts of other constituents, notably soda, potash, iron, magnesia, or lime." Study of the mass of data here assembled, taken in connection with the occurrence of different minerals in different kinds of igneous rocks, as well as study of several thousands of rock analyses, strengthen this view.

In dealing with the most abundant elements we shall speak of them as oxides, following the general mode of statement in rock analyses, and we shall speak of the less abundant constituents as elements.

As a first generalization, one that has long been recognized in petrology, the alkalies

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[29] Suess, Eduard, The face of the earth, vol. 4, p. 545, Oxford, 1909.

[30] Vogt, J. H. L., Ueber die relative Verbreitung der Elemente besonders der Schwermetalle: Zeitschr. prakt. Geologie, 1898, p. 323.

[31] Kemp, J. F., The ore deposits of the United States and Canada, 3d ed., p. 34, 1900. De Launay, L., La science géologique, pp. 636 ff., 1905, and Traité de métallogénie: Gîtes minéraux et métallifères, vol. 1, pp. 26–51, 1913. Beyschlag, F., Vogt, J. H. L., and Krusch, P., The deposits of the useful minerals and rocks, vol. 1, p. 157, 1914. Vernadsky has published a series of papers on the distribution of the elements in the Bulletin of the Imperial Academy of Sciences at Petrograd for 1916, but as they are in Russian they are practically unavailable.

[32] Washington, H. S., Manual of the chemical analysis of rocks, 1904, pp. 18–21; The distribution of the elements in igneous rocks: Am. Inst. Min. Eng. Trans., vol. 39, p. 751, 1909.

(soda and potash) and alumina tend to be high or low together, and silica tends, on the whole, to be associated with all three conjointly. Lime also tends to go with alumina but less markedly than soda and potash, and the same general statement is true of its relations to silica. Lime is much more often present than the alkalies in nonaluminous silicates, as well as in subsilicic rocks. Magnesia and iron, on the other hand, show little or no partiality for alumina, magnesia slightly more so than iron; and they are seldom if ever found in relatively large amount in the highly silicic rocks. The few highly aluminous subsilicic rocks therefore owe their high alumina to the presence of abundant nephelite (soda), leucite (potash), or anorthite (lime). Iron, again, is the only one of the more abundant basic elements that can occur in igneous rocks as oxide uncombined with silica, and it so occurs in many rocks containing a notable excess of silica and having quartz as one of their component minerals.

The table below shows for the different chief minerals the proportions of silica and alumina that are satisfied by the basic oxides that are most abundant in the earth's crust—potash, soda, lime, magnesia, and ferrous oxide. The most abundant minerals are indicated in the table by SMALL CAPITALS, those that are common but not "abundant" by small letters, and those that are very rare by *italics*. The orthorhombic pyroxenes are taken as a type of all the various pyroxenes and amphiboles in order to condense the matter into a table. A similar table is given by Iddings.[33]

TABLE 27.—*Relations of some oxides to silica and alumina.*

$RO : Al_2O_3 : SiO_2$

	1 : 1 : 6	1 : 1 : 4	1 : 1 : 2
K_2O	ORTHOCLASE.	Leucite.	*Kaliophilite.*
Na_2O	ALBITE.	*Analcite.* (Acmite).	Nephelite.
CaO			ANORTHITE.
MgO			
FeO			

	1 : 0 : 1	2 : 0 : 1	No SiO_2.
K_2O			
Na_2O	Na_2SiO_3.[a]		
CaO	Wollastonite. DIOPSIDE.	*Melilite.*	
MgO	Enstatite. HYPERSTHENE.	Forsterite. OLIVINE.	
FeO	(Ferrosilite).	*Fayalite.*	MAGNETITE.

[a] Excess of soda over alumina is evident in the sodic amphiboles; it is expressed in the norm as sodium metasilicate.

This general correlative distribution was pointed out some twenty years ago,[34] and the calculation of the "norm" in the "quantitative system of classification" was based on this so-called "order of affinity" of the chief oxides for silica. Although objections have been made against the use of the term "affinity" and questions of relative solubility, etc., have been raised, that term seems to convey satisfactorily the idea to be expressed. The order of affinity for silica is as follows:

$$K_2O > Na_2O > CaO > MgO > FeO.$$

So far as these elements go the order of their affinity for alumina is identical with that for silica.

This order of affinity or selective preference is based on the broadest and most generally observed relations of the elements in rock-forming minerals and, as much experience with it since its introduction into petrological literature has proved, it expresses remarkably well the general relations of the elements in minerals. Exceptions occur, in plenty perhaps, but some departures from the general law are to be expected in dealing with masses so complex as igneous magmas, during the consolidation of which into rocks there enter factors so variable as pressure, temperature (initial, final, and the gradient), presence of gases, and influence of the containing walls, as well as others. Perhaps the most striking corroboration of the validity of this order of affinity is the fact that it holds good not only for the minerals in rocks consolidated from igneous magmas, but in those of pegmatites, in those formed by pneumatolytic and fumarolic processes, and in those of ore deposits; in fact, throughout the mineral kingdom and under the most diverse conditions.

The general relations of the minerals in igneous rocks that led to the formulation of this "order of affinity"[35] for silica and alumina, may be restated (with minor changes and additions) as follows:

1. Quartz does not occur with nephelite and leucite; that is, the feldspathic (alkalic)

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[33] Iddings, J. P., The study of igneous rocks: Science, new ser., vol. 29, p. 208, 1909.

[34] Cross, Whitman, Iddings, J. P., Pirsson, L. V., and Washington, H. S., A quantitative chemico-mineralogical classification and nomenclature of igneous rocks: Jour. Geology, vol. 10, p. 648, 1902; Quantitative classification of igneous rocks based on chemical and mineral characters, with a systematic nomenclature, p. 192, 1903.

[35] Cross, Whitman, Iddings, J. P., Pirsson, L. V., and Washington, H. S., A quantitative chemico-mineralogical classification and nomenclature of igneous rocks: Jour. Geology, vol. 10, p. 647, 1902; Quantitative classification of igneous rocks based on chemical and mineral characters, with a systematic nomenclature, p. 191, 1903.

molecules will be polysilicates (orthoclase and albite) if sufficient silica is available.

2. Of the feldspathoids, the metasilicates (leucite and analcite) are rarer than the orthosilicates (nephelite and the sodalite group). Analcite is so rare as a primary mineral that it may be omitted from consideration and may be regarded as representing albite and nephelite plus two molecules of water. Nephelite is more commonly associated with orthoclase than leucite is associated with albite, from which it appears that potash will form a polysilicate if possible, leaving the soda to form orthosilicate.

3. Hypersthene and other simple metasilicates of magnesium and iron are seldom found with nephelite or leucite, and olivine commonly occurs with these minerals. It thus appears that the development of a metasilicate or orthosilicate of magnesium-iron oxide—(Mg, Fe)O—is generally determined by the amount of silica available in excess of that needed to form feldspar molecules, if their formation is possible.

4. The disinclination, if we may so express it, of magnesia to combine with silica is exemplified by the observation of Bowen and Anderson [36] that, on cooling a melt in the binary system $MgO-SiO_2$, the magnesium orthosilicate forsterite (Mg_2SiO_4) crystallizes out from a residual liquid that contains an excess of silica, and only on further cooling does the magnesium orthosilicate take up silica to form the metasilicate enstatite ($MgSiO_3$). The behavior of ferrous oxide in this respect has not yet been fully studied experimentally because of its ready tendency to oxidation, and the somewhat complex and experimentally difficult conditions that control the relations of iron to oxygen,[37] but its behavior as regards silica is much like that of magnesia.

5. The subsilicate calcic mineral melilite, which as a constituent of magmas may be regarded as calcium orthosilicate, occurs only in lavas in which the alkalies never form feldspars (except that soda may combine with lime to form highly calcic plagioclase) but only leucite or nephelite. It evidently forms only because of the presence of an amount of silica insufficient to produce the normal alkali aluminosilicates of igneous rocks—the alkali feldspars. Orthoclase does not occur with melilite.

6. Magnetite, the uncombined oxide of iron, is found in many rocks (both intrusive and effusive) in which there is an excess of silica above that needed to combine with all the basic oxides present to form silicates. Fayalite, the iron orthosilicate, is found almost exclusively in highly silicic rocks, such as the granite of Rockport, Mass., the obsidian of Lipari and the Yellowstone Park, and the pantellerite of Pantelleria. Forsterite, the magnesium orthosilicate, on the other hand, is found only in mediosilicic and subsilicic rocks.

We find, therefore, that potash will combine with six parts of silica to form orthoclase, the most abundant potash mineral, less often with four parts to form leucite, and very rarely with two parts to form kaliophilite. Although the micas may seem to be minerals in which potash binds a small amount of silica, as the general formula for mica is $(H,K)_2O.Al_2O_3.2SiO_2$, yet if the amount of hydroxyl is twice that of potash, as it usually is, the amount of silica is six times that of the potash, as in orthoclase, and if the amount of hydroxyl equals that of potash the silica is four times the amount of potash, as in leucite. Soda binds six times its amount of silica in the abundant albite, four times its amount in analcite, and twice its amount in the fairly common nephelite. Lithia, in petalite, binds eight times its amount of silica. Lime, in contrast to the alkalies, can bind but twice its amount of silica in anorthite and an amount equal to its own in the simple pyroxenes and amphiboles and in wollastonite; and calcium orthosilicate is very rare, being present in melilite and monticellite, which has recently been found as a primary constituent of igneous rocks.[38] Magnesia and ferrous oxide can bind but an equal amount of silica in metasilicate pyroxene and amphibole, as the simple hypersthene and anthophyllite, and but one-half the amount in the olivines, as in fayalite; and iron oxide also occurs uncombined with silica, as magnetite and hematite.

The alkalies bind an equal amount of alumina, as in orthoclase, albite, leucite, and nephelite; potash binds more than its amount

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[36] Bowen, N. L., and Andersen, O., The binary system $MgO-SiO_2$: Am. Jour. Sci., 4th ser., vol. 37, p. 487, 1914.

[37] Cf. Sosman, R. B., Some problems of the oxides of iron: Washington Acad. Sci. Jour., vol. 7, p. 55, 1917.

[38] Bowen, N. L., Genetic features of alnoitic rocks from Isle Cadieux, Quebec: Am. Jour. Sci., vol. 3, p. 1, 1922; The genesis of melilite: Washington Acad. Sci. Jour., vol. 13, p. 1, 1923.

in mica, and sodium metasilicate (never potassium metasilicate) exists in excess of alumina in some of the sodic amphiboles. Lime binds an equal amount of alumina in anorthite and other minerals, less than its amount in melilite, and forms nonaluminous silicates, such as pyroxene and amphibole. Magnesia and iron have little affinity for alumina, magnesia more than iron, as it forms the magnesium aluminate spinel, while no iron-alumina spinel is known.

Confirmation of this order of affinity—potassium, sodium, and calcium—for silica is furnished by the study of the artificial silicates, especially in the Geophysical Laboratory of the Carnegie Institution. There have been prepared in well crystallized form the following compounds: Potassium hydrogen disilicate ($K_2O.H_2O.4SiO_2$), potassium disilicate ($K_2O.2SiO_2$), and potassium metasilicate ($K_2O.SiO_2$); sodium disilicate ($Na_2O.2SiO_2$) and sodium metasilicate ($Na_2O.SiO_2$); no orthosilicates of either potassium or sodium have yet been formed.[39] Lithium is said to form orthosilicate, metasilicate, and disilicate.[40] Calcium forms the simple salts, metasilicate ($CaO.SiO_2$), and the artificial orthosilicate $2CaO.SiO_2$ and intermediate $3CaO.2SiO_2$.[41]

So much for the silicates and the aluminosilicates of the most abundant elements.

There are several subsidiary affinities among the more abundant elements that call for brief mention. Soda shows a strong tendency to go with lime, as in plagioclase and many zeolites, but potash shows no affinity for lime, although a little potash is generally found in plagioclase. Soda and lime are found together in many zirconosilicates and other such complex salts.

Other subsidiary relations, scarcely less significant, are those of iron and soda on the one hand and potash and magnesia on the other.[42] Minerals that are essentially sodic contain iron rather than magnesium, as is exemplified in acmite, aegirite, and the sodic pyroxenes and amphiboles generally, as well as in other minerals named above. On the other hand, magnesium, rather than iron, accompanies potash in the few potassic silicates. as well as in potassic nonsilicate minerals, This association is seen in the group of micas, in which potash is the prominent alkali, for the sodic paragonite is rare and is only a product of metamorphism. In the micas magnesium is the more prominent bivalent element, iron replacing it to only a limited extent and being almost invariably subsidiary in amount except in the rare lepidomelane, which is usually found in distinctly sodic rocks. The occurrence of these two contrasted pairs of oxides in igneous rocks is considered and shown graphically in a paper cited above. It would also seem that the same correlation exists in the organic world, sodium and iron in hemoglobin being both essential to higher animal metabolism, and potassium and magnesium replacing them in chlorophyll of plants.[43]

The selective distribution and associations of the rarer elements must be treated very briefly here. These associations are shown not so much in their relations to silica and alumina as in those to the other most abundant elements and to one another. They are shown in minerals, as illustrated by many examples given in the mineralogical data here assembled, and also in igneous rocks, as illustrated by the many chemical analyses available. We shall now consider the correlations of the elements in the order, generally, of their successive groups in the periodic table, but more or less intercrossing will be inevitable. The petrogenic elements will be considered first.

The lithium minerals are almost exclusively silicates and phosphates; the silicates of lithium are aluminosilicates, except a few extremely rare species. Among the silicates, as well as in igneous rocks in general, lithium shows a decided preference for sodium, the lithium min-

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[39] Morey, G. W., New crystalline silicates of potassium and sodium; their preparation and general properties: Am. Chem. Soc. Jour., vol. 26, p. 215, 1914. Morey, G. W. and Fenner, C. N., The ternary system $H_2O-K_2SiO_3-SiO_2$: Idem, vol. 39, p. 1174, 1917.

[40] Jaeger, F. M., and Van Klooster, H. S., K. Akad. Wetensch. te Amsterdam Proc., vol. 16, p. 9, 1914. For artificial lithium aluminosilicates, see Ballo, R., and Dittler, E., Die binaren Systeme $Li_2SiO_3 : Al_2(SiO_3)_3$, $Li_4SiO_4 : Al_4(SiO_4)_3$, $LiAlO_2 : SiO_2$ und die Lithium-Aluminiumsilikatmineralien: Zeitschr. anorg. Chemie, vol. 76, p. 39, 1912.

[41] Ferguson, J. B., and Merwin, H. E., Wollastonite ($CaO.SiO_2$) and related solid solutions in the ternary system lime-magnesia-silica: Am. Jour. Sci., 4th ser., vol. 48, p. 165, 1919. References to previous papers are given here.

[42] Washington, H. S., The distribution of the elements in igneous rocks: Am. Inst. Min. Eng. Trans., vol. 39, p. 750, 1909; The correlation of potassium and magnesium, sodium and iron, in igneous rocks: Nat. Acad. Sci. Proc., vol. 1, p. 574, 1915.

[43] Washington, H. S., An apparent correspondence between the chemistry of igneous magmas and of organic metabolism: Nat. Acad. Sci. Proc., vol. 2, p. 623, 1916.

erals being found almost only in nephelite syenite and the pegmatites of sodic granite. As a phosphate it seems to show a rather odd preference for glucinum and manganese, the lithium-manganese phosphates being especially common. Minerals containing rubidium and caesium are so rare that it is somewhat dangerous to generalize concerning these elements, but rubidium appears to show a marked preference for potassium and caesium seems inclined to associate with sodium and lithium. Neither lithium, rubidium, nor caesium shows a tendency to associate with calcium and still less with magnesium, although lithium is found with iron.

Glucinum, like lithium, is essentially a silicate-forming element, although (again like lithium), it enters into a few phosphates, and one borate (hambergite). It favors sodium and lithium, rather than potassium, as is evident by the composition of various beryls. It may possibly be significant that glucinum is an essential constituent of the sulphur-bearing silicates helvite and danalite, and of the rare-earth metals it seems to prefer yttrium to cerium, as shown by the composition of gadolinite. The analytical determination of glucinum, and especially its separation from aluminum, offer difficulties so great that it has very possibly often escaped detection.

Strontium is not decisive in its few apparent affinities. It would appear to be most abundant in connection with calcium, as in the zeolites brewsterite and some heulandite. It occurs with lead in hancockite.

Barium is much more widespread than strontium and is far more definite in its associations. It is essentially a silicate-forming element, as in the feldspars and micas and in edingtonite, yet, unlike strontium but like calcium, it forms a titanosilicate, benitoite. Barium has a marked preference for potassium rather than for sodium, as is shown by its presence in potassic feldspars and micas, and in the potassic zeolites wellsite, phillipsite, and harmotome. The prevalence of barium in lavas that are distinctly potassic has been pointed out elsewhere.[44] The decided richness in barium of the igneous rocks along the east slope of the Rocky Mountains was mentioned by Hillebrand years ago[45] and is well brought out in the averages of the rocks of the States from Montana to Arizona, which have already been noted. The rocks of this zone are distinctly potassic. The same correlation of barium and potassium is seen in Morley's series of excellent analyses of rocks collected by Iddings from Java, Celebes, and the Philippines.[46]

In spite of its extreme rarity, there appear to be some definite indications of the correlations of radium. To quote Holmes:[47] "Radium shows a marked preference for alkaline and acid rocks, and to a less extent for volcanic as compared with plutonic rocks." Radium appears to show, like the closely related barium, a marked affinity toward potassium, as Joly and others[48] found maximum amounts of radium in the lavas of Vesuvius, which are highly potassic. This apparent correlation of radium and potassium is of special interest because potassium, alone among the alkali elements, shows some radioactivity, and a rather abundant source of radium is the potassium uranovanadate carnotite. The matter deserves further investigation.

Boron forms salts of calcium rather than of any other element except, perhaps, magnesium. It seems to show no other very decided preference, but may be most at home in sodic rocks. Scandium appears to be widely diffused in rocks, but the published data show no very definite selective occurrence. Yttrium differs markedly from cerium in its mineral associations; it appears to be associated with calcium rather than with sodium and zirconium, and with columbium rather than with tantalum. Satisfactory rock analyses in which the metals of the yttrium and cerium groups are separately determined are not numerous, and we may leave in abeyance for the present the affinities of yttrium as well as of lanthanum.

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[44] Washington, H. S., The Roman comagmatic region: Carnegie Inst. Washington Pub. 57, p. 188, 1906.

[45] Hillebrand, W. F., Am. Chem. Soc. Jour., vol. 16, p. 81, 1894; The analysis of silicate and carbonate rocks: U. S. Geol. Survey Bull. 700, p. 22, 1919.

[46] Iddings, J. P., and Morley, E. W., Contributions to the petrography of Java and Celebes: Jour. Geology, vol. 23, p. 240, 1915; A contribution to the petrography of the Philippine Islands: Nat. Acad. Sci. Proc., vol. 2, p. 533, 1916; A contribution to the petrography of the island of Bawéan, Netherlands Indies: Idem, vol. 3, p. 108, 1917; A contribution to the petrography of southern Celebes: Idem, p. 596; A contribution to the petrography of the South Sea Islands: Idem, vol. 4, p. 114, 1918.

[47] Holmes, Arthur, The terrestrial distribution of radium: Sci. Progress, vol. 9, p. 19, 1915.

[48] Joly, J., On the radioactivity of certain lavas: Philos. Mag., vol. 18, p. 577, 1909; The radioactivity of terrestrial surface materials: Idem, vol. 24, p. 697, 1912.

Titanium, the ninth most abundant element in the earth's crust, is of much interest, and its associations should be well marked. When we examine its mineralogic relations, however, we find little that is decisive. The rather abundant ferrous titanate, ilmenite, and the frequent presence of titanium in much "magnetite," together with the prevalence of titanium in subsilicic rocks and magnetic iron ores, indicate that iron is a common associate of titanium, at least in the earth's crust. The excellent analyses published by Merrill and other reliable information as to the chemistry and mineralogy of meteorites show that the amount of titanium in these bodies is very small. Calcium seems to be a rather common associate of titanium, as is indicated by the fairly frequent occurrence of titanite in the more silicic and alkalic rocks and of perofskite in the more subsilicic. The titanium minerals include a considerable number of salts of calcium and several salts of sodium. The preference of sodium for titanium, indeed, seems to be very decided, as decided, perhaps, as its preference for iron. This correlation of sodium with titanium is best shown in the sodic hornblendes, most of which contain much titanium and some of them very much. It also accords with this interpretation that both titanite and perofskite are most at home in sodic rocks, which vary in their content of silica from highly silicic granite to nephelite syenite and nephelite tephrite. Titanium is found in many zirconosilicates, in which sodium is one of the most common bases. On the other hand, rocks that contain much potash contain little titanium, and this element is but sparingly present in such highly calcic rocks as the anorthosites and many gabbros. Titanium, furthermore, shows no strong liking for highly magnesian rocks.

Among the rarer elements, zirconium is one of the most instructive and most characteristic as to its distribution and affinities. Zirconium, in the silicate zircon, is commonly supposed to be most abundant in highly silicic rocks, especially granites, of whatever subsidiary chemical character, and the occurrence of small crystals of zircon in syenitic rocks caused early petrographers to place such rocks in a distinct group, the "zircon syenites," although the percentage of zircon in them was almost negligibly small. Granite and syenite, however, that contain notable amounts of zircon are invariably sodic, many of the syenites contain nephelite, and the complexes of rocks to which they belong are eminently those of dominantly sodic magmatic regions. Apart from the presence of zircon, the sodium-zirconium association of these rocks is abundantly shown by the occurrence in them of the zirconosilicates, most of which are sodium salts and occur in sodic rocks, and by the figures furnished by a host of complete analyses of igneous rocks. Indeed, this close association of zirconium with sodium and its rarity in potassic, calcic, and magnesic rocks, is one of the most marked and best established correlations to be found. So general is it that an analyst who has had large experience in petrology will now scarcely waste time in determining the amount or proving the absence of zirconia in rocks other than sodic ones. It should be noted, furthermore, that the aversion of zirconium to calcium is so decided that notable amounts of zirconia are seldom found in rocks like nephelite tephrite, which, although highly sodic, are at the same time notably calcic. Except for these relations with the more abundant elements, little that is definite can now be said of zirconium. It seems, however, to tend to be associated with cerium rather than with yttrium, which is perhaps not surprising in view of the fact that cerium and zirconium belong to the same periodic group. Some unpublished analyses of acmite and aegirite show that zirconium and cerium occur in many samples of these sodic pyroxenes.

The general relations of cerium have already been indicated. Of the more abundant elements it is most decidedly associated with sodium and to a less extent with calcium, its association with calcium being common in minerals but not in igneous rocks. Cerium is one of the few elements that form native fluorides, but it forms no native chlorides. Its close association with zirconium has just been mentioned. The thorium minerals also are found almost always in sodic rocks.

Among the elements of the fifth group in the periodic table we find phosphorus universally associated with calcium; and phosphorus, in the form of primary phosphates, is also commonly associated in some rather rare minerals with iron, manganese, lithium, and glucinum. On the other hand, phosphorus shows no affinity for either potassium or magnesium, although it does show some tendency toward correlation with sodium.

Vanadium is most likely to occur in determinable amount in the less silicic rocks, as was first pointed out long ago by Hillebrand.[49] It is worthy of note, however, that vanadium is found in the metasilicate pyroxene rather than in the orthosilicate olivine. It is difficult to determine its exact relations. The native vanadates, which are all secondary, seem to cast no light on the problem; but we may say, at least, that it tends to go with iron. There is some highly vanadiferous aegirite,[50] and a study of rock analyses in which vanadium has been determined indicates this relation fairly well. It seems to be somewhat prone to association with calcium, not at all with magnesium, and with sodium rather than with potassium.

The affinities of columbium and tantalum are not clear. They have but slight affinity for silica and none at all for alumina. Iron is the most common element in the columbium-tantalum minerals. Manganese also occurs in them, but somewhat less frequently. Calcium is found in some columbium-tantalum minerals, but sodium rarely occurs in them, and potassium never. Uranium is a common constituent in the columbium-tantalum minerals, as well as tungsten and tin. Of the rare-earth elements, yttrium is more often present in such minerals than cerium. In short, columbium, tantalum, and uranium show, so far as is known, rather peculiar associations. Those elements apparently tend to occur in highly sodic rocks.

The silicate minerals that contain notable amounts of chromium are so few that we are here again confronted with difficulties of interpretation. The general association of chromium with iron is shown by the abundance of chromite, and chromium is decidedly most often present in rocks that contain much magnesium, especially those that are rich in olivine and are consequently subsilicic. Chromium apparently shows no tendency to associate with calcium, and still less with the alkali metals. Molybdenum is rather common in rocks that contain much rather than little silica, as was first shown by Hillebrand,[51] yet it shows no tendency to associate with silica among minerals. The sulphide (molybdenite) probably occurs as a primary mineral in granites and pegmatites. The affinities of tungsten, like those of molybdenum, are little known. It is most commonly associated with iron and manganese in the ferberite-wolframite-hübnerite series,[52] and there is some indication [53] that phosphorus occurs with it rather commonly. Tungsten occurs also with tin. No attention seems to have been paid to the general chemical character of the igneous rocks or of the comagmatic regions in which tungsten occurs.

Fluorine is the typical petrogenic element of the halogen group, as is evident from the nonexistence of native fluorides of the metallogenic elements, the comparative abundance of fluosilicates, and the fact that all of the native fluorides are salts of elements whose names appear in the periodic table in the petrogenic side. Thus, we find native fluorides of aluminum, sodium, and calcium, the calcium salts (fluorspar and fluorapatite) being especially prominent and widespread. Lithium also occurs in fluorides, and there are several sodium-calcium-aluminum fluorides. Most of the fluosilicates are also salts of sodium, calcium, and aluminum; and cerium and, probably to a less extent, yttrium form a number of fluorides or fluosilicates. The usual presence of fluorine in micas and hornblendes, although it is not found in the members of the pyroxene group, is undoubtedly of great significance when considered in connection with the general mode of formation of the minerals of these groups. The very common presence of fluoride minerals, even the calcium salt fluorite, in nephelite syenite, phonolite, and other highly sodic rocks deserves special mention, as it seems to be seldom recognized.

The affinities of chlorine are also decidedly petrogenic, and the chlorine-bearing primary minerals in igneous rocks are essentially salts of sodium and calcium, with alumina, and these salts are most frequently present in sodic rocks. It is perhaps significant that fluorapa-

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[49] Hillebrand, W. F., Distribution and quantitative occurrence of vanadium and molybdenum in rocks of the United States: Am. Jour. Sci., 4th ser., vol. 6, p. 209, 1898; Distribution and quantitative occurrence of vanadium and molybdenum in rocks of the United States: Chem. News, vol. 78, p. 216, 1898; U. S. Geol. Survey Bull. 167, p. 49, 1900.

[50] Larsen, E. S., and Hunt, W. F., Two vanadiferous aegirites from Libby, Mont.: Am. Jour. Sci., 4th ser., vol. 36, p. 289, 1913.

[51] Hillebrand, W. F., Distribution and quantitative occurrence of vanadium and molybdenum in rocks of the United States: Am. Jour. Sci., 4th ser., vol. 6, p. 209, 1898.

[52] Hess, F. L., and Schaller, W. T., Colorado ferberite and the wolframite series: U. S. Geol. Survey Bull. 583, p. 37, 1914.

[53] Idem, p. 15.

tite is much more abundant than chlorapatite in igneous rocks. The relative abundance of hydrochloric acid and sulphur oxides among the gases of volcanoes furnishing lavas of quite different chemical character deserves more study than it has yet received.

Manganese seems to be one of the elements that are ubiquitous in small amounts in silicate rocks and minerals, and it is generally associated with iron, not often with magnesium or calcium and still less with sodium or potassium. Its subsidiary association in minerals that contain glucinum is worthy of notice, as well as its association with lithium and glucinum in phosphates. On the other hand, manganese is present in considerable amount in but few aluminosilicates, fluosilicates, borosilicates, or zirconosilicates.

The associations of iron have already been considered, its association with sodium being especially noteworthy. Cobalt and nickel furnish few indications. The rather frequent occurrence of cobalt-bearing wad (hydrous manganese oxide), often with considerable amounts of barium, deserves notice. Although wad is always of secondary origin, yet the frequency of the association of these three elements indicates some sort of common origin or "affinity" in the original rocks from which the wad was derived. The association of nickel with iron and magnesium is rather more definite than that of cobalt. Nickel occurs principally in nickeliferous pyrrhotite, as at Sudbury in Canada, and in magnesian rocks, such as peridotite, in which the nickel sometimes appears in the form of silicates, its primary source having been nickeliferous olivine. Sulphides and arsenides of nickel are also found in ore bodies. Nickel is also a large constituent of meteoric iron.

We begin the associations of the metallogenic elements with copper, which is the one that is most common and most abundant in igneous rocks. Although copper is a primary constituent of many kinds of igneous rocks, yet it is most at home in decidedly femic and somewhat subsilicic rocks, especially those that contain much pyroxene or amphibole rather than olivine. It appears to prefer iron to other petrogenic elements, a preference shown by the kinds of rocks in which it generally occurs as well as by the occurrence of copper with iron in several rather common mixed sulphides.

Silver and gold seem to occur most often as primary constituents in igneous rocks that contain much silica (such as rhyolite, granite, syenite, pegmatite, and andesite), but they have been observed also in basalt and diabase.[54] The list of the minerals most likely to contain gold, as given by Lincoln, is rather long, but, as he points out, except quartz (the most abundant), pyrite, and galenite, the gold-bearing minerals are those of the typically metallogenic elements, silver, mercury, bismuth, and tellurium, the last named being the only element with which gold is found combined in nature. Alloys of gold with palladium and rhodium are also known.

As to zinc and cadmium the exact data available are very few. Leaving out of consideration the zinc and cadmium found in limestones by precipitation and replacement we find small amounts of zinc reported in some granites, of uncertain affinities but probably connected with rather calcic magmas, as in Greece, as well as in quartz porphyries from Colorado and Missouri.[55] Mercury is not generally distributed in igneous rocks, although it is associated with volcanic eruptives in certain districts, whose igneous rocks, however, are of various kinds, so we have no definite clue as to the associations of mercury.[56]

Gallium and indium occur mostly in zinc blende, but here again we have little or no knowledge of their true relations. Thallium also occurs mostly in zinc blende, as well as in iron and copper pyrites, and it has been detected in some mica, but its affinities are unknown. Germanium also occurs in zinc blende, as well as with tin in the silver minerals argyrodite and canfieldite, but nothing definite can be said of its general relations.

Tin (as the oxide cassiterite) is almost invariably found in granite, greisen, and granitic pegmatite.[57] Little is known of the exact chemical characters of the rocks in which it occurs. Because of some of the elements and minerals with which tin is commonly associated it has been thought[58] that it occurs mostly in sodic granites, but Ferguson and Bateman

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[54] Lincoln, F. C., Certain natural associations of gold: Econ. Geology, vol. 6, pp. 252-301, 1911.

[55] Cf. Lindgren, Waldemar, Mineral deposits, p. 9, 1913.

[56] Cf. Lindgren, Waldemar, op. cit., p. 459.

[57] Hess, F. L., and Graton, L. C., The occurrence and distribution of tin: U. S. Geol. Survey Bull. 260, p. 161, 1905. Ferguson, H. G., and Bateman, A. M., Geologic features of tin deposits: Econ. Geology, vol. 7, p. 209, 1912. Lindgren, Waldemar, op. cit., p. 623.

[58] Washington, H. S., The distribution of the elements in igneous rocks: Am. Inst. Min. Eng. Trans., vol. 39, p. 759, 1909.

show that it is possibly connected rather with potassic granites. The question must, for the present, be left in abeyance. Tungsten, columbium, tantalum, uranium, and germanium are often associated with tin.

As to the affinities or relations of arsenic, antimony, bismuth, selenium, and tellurium little can be said here except that all of them are especially associated with typically metallogenic elements. Nothing is known definitely as to the character of the rocks in which their ores occur.

Lead has been detected and even determined quantitatively as apparently a primary constituent of a number of igneous rocks, but the evidence is undecisive as to its general chemical relations with other elements in rocks.

The metals of the platinum group occur as magmatic segregations in subsilicic igneous rocks, most commonly in rocks that contain much olivine and that are distinctly magnesic, rather than in rocks high in iron. But iron is present in all native platinum. Calcium, indeed, seems to be more common than iron in platinum-bearing rocks, which contain no alkali metals. Platinum arsenide (sperrylite) occurs with copper sulphides and with magmatic nickel ores. Chromite is commonly associated with platinum.

From the very rapid and inadequate survey given above several conclusions seem to stand out clearly. One is that the various electropositive elements tend to be associated with magmas of certain rather definite dominant chemical character. This fact is best shown as to the petrogenic elements, as would be expected. It is not so well indicated as to the metallogenic elements, as the very small amounts usually found and their occurrence for the most part and most typically in veins and other ore bodies tend to mask their true relations.

It is also clear that of the various different magmas of some dominant chemical character, those that are distinctly or highly sodic are most likely to contain the rarer elements and to have the largest number of these elements typically associated with them. Thus we find lithium, caesium, yttrium, titanium, zirconium, cerium, tin (?), fluorine, and chlorine, and less strikingly columbium, tantalum, tungsten (?), and uranium closely and generally, if not exclusively, bound up with sodic magmas. The association of iron with sodium is also of great interest.

This characteristic of sodic magmas is of special importance in theoretical petrology as bearing on Daly's widely spread and often accepted theory as to the origin of alkalic rocks by the influence of limestones on basaltic magmas. As Lindgren points out,[59] it is scarcely possible that the alkalic rocks have received their content of the rarer elements from limestones, in most of which they are not found. Furthermore, as we have seen, these elements are present either in very small amount or are quite absent in gabbros, basalts, and even in such sodic but at the same time highly calcic rocks as nephelite tephrite. This association of so many and such characteristic rare elements with sodic rocks appears to be definitely decisive against Daly's theory.

Of all the most abundant elements potassium appears to be the most independent, barium and possibly radium, among the rarer elements, being the only ones that show any preference for it. It is associated only with silicon, aluminum, and magnesium among the abundant elements.

The association of certain elements with high or low silica, which so strongly attracted the attention of the first students of this phase of chemical petrology, is apparent rather than real. We have seen that certain of the rare elements are associated with sodium, others with calcium, others again with magnesium or iron. Now, it is clear from the order of ability of the most abundant oxides to bind silica, as shown in Table 27, that the sodic and potassic rocks will in general be the most silicic, that those which are dominantly calcic will be less silicic and that those which are distinguished by high magnesia and iron will be the least silicic of all. The apparent associations of the elements, then, with rocks of varying silicity are brought about not directly by the amount of silica but indirectly by the ability of the basic oxides to combine with it.

The various correlations stated appear, on the whole, to be concordant with the distinction here made between the petrogenic and the metallogenic elements. Silica and alumina

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[59] Lingdren, Waldemar, Igneous geology of the Cordilleras, in Problems of American geology, p. 276, New Haven, 1915.

are distinctly the most abundant and characteristic petrogenic constituents, and with them are most frequently associated those elements toward the extreme petrogenic end of the periodic table, especially potassium, sodium, and calcium in the order named; and these elements are associated with each other. As we approach the triad column and the metallogenic half of the table, the affinities of the less abundant elements for these typically petrogenic elements become less well marked; they show greater liking for the elements of the triad groups and tend even to overleap these and form associations with the truly metallogenic elements.

EVOLUTION OF THE ELEMENTS.[60]

For many years philosophic chemists held the opinion that the so-called chemical elements are not absolutely elementary but that they really represent different aggregations of some much simpler form of matter. This opinion, however, was nothing more than a venturesome speculation until the invention of the spectroscope made it possible to determine the composition of the heavenly bodies. These bodies were then found to show a progressive chemical complexity from the gaseous to the solid form. The nebulae are the simplest; the hotter stars are more complex; next come the cooler stars, including our sun; and finally the cold earth, the most complicated of all. In short, it appeared that the evolution of planets from nebulae involves an evolution of the chemical elements.[61]

Thus was taken the first definite step toward confirming the ancient speculations. It had long been recognized, however, that the elements exhibited peculiar relations; that they formed groups in which the several members had similar properties and yielded similar compounds. These facts were generalized by Mendeleef, who found that when the elements were arranged in the order of their atomic weights, beginning with the lowest, hydrogen, they exhibited a regular periodicity, although there were certain breaks or gaps in the series which he attributed to the existence of unknown members. For three of these he predicted their atomic weights and their chief characteristics, and in due time his predictions were verified. Scandium, gallium, and germanium have since been discovered, and they filled three gaps in the table. Their atomic weights, melting points, and specific gravities were foretold almost precisely, as well as the class of compounds that each of the new elements would form. The properties of the elements, as generalized by Mendeleef, are periodic functions of their atomic weights—a statement that is briefly expressed as "the periodic law." The periodic table, which has been variously modified by later workers, appears on page 109 in a simple form. For simplicity the atomic weights are rounded off from the more exact values. The atomic weights are placed below the symbols of the elements, the atomic or ordinal numbers above them. The elements of the rare-earth group, which are anomalous, are inclosed within a heavy black line. Spaces in which an atomic number alone appears are yet to be filled by some unknown element. The element of number 72 has recently been discovered, but its exact atomic weight has not yet been determined.

The inert gases, of zero valency, form a natural group, which finds a place in the table, although they were unknown to Mendeleef. The elements in each vertical column of the table are closely allied, forming the natural groups to which reference has already been made. The alkali metals; the series calcium, strontium, and barium; the carbon and sulphur groups; and the halogens are examples of this regularity. In other words, similar elements appear at regular intervals and occupy similar places. If we follow any horizontal line of the table from left to right, we find a progressive change in valency, and in both directions we find a systematic variation in properties. Furthermore, the members of the same elementary group are commonly associated in nature—that is, similar elements have similar properties, form similar compounds, and give similar reactions, and are therefore usually found together. We see now, however, that the elements are not independent forms of matter but must have some community of origin. It is strange that this belief was not favored by Mendeleef.

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[60] Cf. Clarke, F. W., The evolution of matter: Washington Acad. Sci. Jour., vol. 11, p. 289, 1921.

[61] Clarke, F. W., Evolution and the spectroscope: Pop. Sci. Monthly, vol. 2, p. 320, Jan., 1873.

TABLE 28.—*Periodic table of the elements.*

[The upper numerals in the headings indicate natural groups; the lower numerals (arabic) indicate valencies. The rare-earth elements are inclosed within a thick line.]

0 0	I +1	II +2	III +3	IV +4	V −3-5	VI −2-6	VII −1-7	VIII (a)
	1 H 1.008							
2 He 4.00	**3** Li 6.9	**4** Gl 9.1	**5** B 10.8	**6** C 12.00	**7** N 14.01	**8** O 16.00	**9** F 19.00	
10 Ne 20.2	**11** Na 23.00	**12** Mg 24.32	**13** Al 26.96	**14** Si 28.07	**15** P 31.04	**16** S 32.06	**17** Cl 35.46	
18 A 39.9	**19** K 39.1	**20** Ca 40.07	**21** Sc 45.1	**22** Ti 48.1	**23** V 51.0	**24** Cr 52.0	**25** Mn 54.93	**26** Fe 55.85 **27** Co 58.97 **28** Ni 58.68
	29 Cu 63.57	**30** Zn 65.37	**31** Ga 70.1	**32** Ge 72.5	**33** As 74.96	**34** Se 79.2	**35** Br 79.92	
36 Kr 82.92	**37** Rb 85.45	**38** Sr 87.83	**39** Y 89.33	**40** Zr 90.6	**41** Cb 93.5	**42** Mo 96.0	**43** —	**44** Ru 101.7 **45** Rh 102.9 **46** Pd 106.7
	47 Ag 107.88	**48** Cd 112.40	**49** In 114.8	**50** Sn 118.7	**51** Sb 121.7	**52** Te 127.5	**53** I 126.92	
54 Xe 130.2	**55** Cs 132.81	**56** Ba 137.37	**57** La 139.0	**58** Ce 140.25				
	59 Pr 140.6 **60** Nd 144.3 **61** — **62** Sm 150.4 **63** Eu 152.0 **64** Gd 157.3 **65** Tb 159.2							
	66 Ds 162.5 **67** Ho 163.5 **68** Er 167.7 **69** Tu 168.5 **70** Yb 173.5 **71** Lu 175 **72** —				**73** Ta 181.5	**74** W 184.0	**75** —	**76** Os 190.9 **77** Ir 193.1 **78** Pt 195.2
	79 Au 197.2	**80** Hg 200.6	**81** Tl 204.0	**82** Pb 207.2	**83** Bi 209.0	**84** [b]	**85** —	
86 Rn 222.0	**87** —	**88** Ra 226.0	**89** [c]	**90** Th 232.15	**91** [d]	**92** U 238.2		

[a] Valencies diverse. [b] Polonium? [c] Actinium? [d] Protoactinium?

A third great advance toward the solution of our problem, and perhaps the most conclusive one of all, was the discovery of radioactivity by Becquerel and of radium by Madame Curie. It was then found that the elements that stand highest in the scale of atomic weights and that are presumably the most complex are actually unstable—they are undergoing a spontaneous but slow decomposition. From uranium radium is derived, and from radium helium, these changes ending in the production of a new form of lead, which, although identical with lead in its chemical reactions, is different in atomic weight and specific gravity. Thorium undergoes similar changes, and a swarm of other substances, some of them extremely short lived, have also been more or less perfectly identified as products of this atomic degeneration. Whether they can be regarded as true elements is questionable, for they appear to represent matter in a state of transition from one form to another. One feature of these changes, however, deserves special attention. Radium, as it decomposes, does so with evolution of heat, and this process has something to do with maintaining the temperature of the earth's crust. The potential energy of the original uranium is becoming partly kinetic.

It is now evident that the evolution of the chemical elements is a reversible process, but whether the reversibility is general is not yet absolutely determined. Are all the elements unstable, or only a few? The results of investigations now in progress seem to indicate an affirmative answer to the first of these questions, for Rutherford has generated hydrogen from nitrogen, and we can hope for further transformations equally startling. There is also the evidence furnished by the novæ, those faint stars which suddenly flash forth into the first magnitude, rivaling Sirius in brilliancy, only to relapse after a brief period of splendor into insignificance. If the appearance of these "new" stars is due to a collision between two heavenly bodies, enormously high temperatures must be thus generated, which might produce some dissociation of the elements. In fact, the spectra of at least some of the novæ indicate a partial return to the nebular condition; but this phase of our problem needs more systematic study than it has yet received.

That helium is derivable from uranium is an established fact of fundamental significance. Helium and hydrogen are the two simplest elements of which we have certain knowledge, and they appear throughout the cosmic evolution from nebula to planet. They are the oldest elements, and from them Harkins and other chemists suppose that all the other elements have been built up. But this supposition is beset with much uncertainty. Lines in the spectra of the gaseous nebulæ are ascribed to an element named nebulium, which has not yet been found in the earth. Coronium, another gas, which is supposed to be even lighter than hydrogen, is only known from lines in the spectrum of the solar corona. These elements, if we can call them so, are quite certainly low in the scale of atomic weights, nebulium falling between hydrogen and helium, and they may represent part of the primordial matter from which our known elements were evolved.

All this evidence relative to the evolution of the elements bears directly upon the composition of the earth's crust. The simplest elements, taken all in all, were naturally developed first, and in the largest quantities. This statement applies also to the solar system as a whole, but it needs some qualification as regards the composition of any single planet. First, we do not know the conditions that exist in the interior of the earth, although we may make more or less plausible guesses concerning it. Second, we can not assume that the elements are distributed in exactly the same relative proportions in all parts of the solar system. The interior and denser planets may differ from the outer and less dense. On this subject all we can do is to recognize possibilities. In the crust of the earth, however, the order of abundance is about what we should expect and is in harmony with the evidence. The abundant elements all lie between hydrogen and iron, including both, but the order of their abundance does not follow the order of their atomic weights.

The question at once arises as to whether the process of evolution was regular and smooth or irregular, interrupted by breaks and branchings. The process was probably irregular, for regularity in the evolution of the elements would depend in great part upon regularity in the rate of cooling. If from time to time there were great fluctuations of temperature the development of new elements would depend upon their possible stability at a given stage of the evolutionary process, and a sharp increase of temperature might even decompose some of the substances that had been already formed. Here again we enter the realm of speculation, but the suggestions we offer are legitimate. Differences of stability among the elements may determine the exact order of their evolution.[62]

Now, ignoring the possibility that some form of matter simpler than hydrogen once existed in the solar system, only to be consumed in building the known elements, we may follow Harkins and assume that hydrogen and helium, which are both present in the nebulæ, were the foundations of our present elementary scheme. In doing this we must also assume that the original mass of these two elements, available in the solar system, was finite. As

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[62] On the stability of atoms see Harkins, W. D., The stability of atoms as related to the positive and negative electrons in their nuclei, and the hydrogen, helium, H_3, H_2 theory of atomic structure: Am. Chem. Soc. Jour., vol. 42, p. 1956, 1920. On the abundance of the elements see Harkins, W. D., The abundance of the elements in relation to the hydrogen-helium structure of the atoms: Nat. Acad. Sci. Proc., vol. 2, p. 216, 1916. Harkins has published many other papers on the same general theme.

the evolution of the elements progressed, the quantity of the two primal forms of course diminished, and their relative abundance in the crust of the earth is therefore comparatively small. They have been largely absorbed as constituents of the higher elements; but in the decomposition of radium some helium reappears. Some primordial helium is still locked up in the lithosphere, and notable quantities of it are emitted by certain mineral springs and are found in natural gas.

Another plausible hypothesis, more speculative than the last, is that the process of evolution, starting with hydrogen and helium, began slowly and generated the lower elements in relatively small amounts. Then, gathering impetus, it advanced with greater but perhaps fluctuating velocity until the points marked by iron and nickel were reached. Beyond nickel, with less and less of the original material for atom building, the process became slower and slower, until the limit of permanent stability at or a little above uranium was attained, and the upward curve of evolution ended. This hypothesis, of course, can not be proved; its value lies wholly in its suggestiveness. It is in harmony with the other hypothesis regarding possible fluctuations of temperature during the process of evolution. High temperature would favor the formation of the more stable elements, and these would appear in larger quantities than the less stable. Through hypotheses of this kind the irregularities in the order of evolution become somewhat intelligible.

The detailed application of these hypotheses to the problem of the evolution of the elements is not easy. Our figures for the relative abundance of the elements apply only to the surface of the earth, but the composition of its denser, unknown interior can not be quite the same. There is direct evidence that below the lithosphere, but penetrating it, there are large masses of native iron—how large we do not know. The native iron of Ovifak, Greenland, and the iron particles disseminated in some basalts are familiar examples of the evidence. Such minerals as awaruite and josephinite, in which native nickel predominates over iron, are also significant. They are derived from magnesian igneous rocks, such as peridotite. It is practically certain that in the interior of the earth iron is relatively more abundant than at the surface, and that oxygen is much less abundant.

Although the evolution of the chemical elements seems to have ended with the generation of uranium, the evolutionary process nevertheless continued, but along a new line. Compounds, to use the term in its ordinary sense, began to be formed, and even at the temperature of the sun some of them, such as cyanogen, titanium oxide, magnesium hydride, and calcium hydride, have been reported. Only the most stable compounds could be formed at first, and it is conceivable that among them carbides, silicides, phosphides, borides, and nitrides would be generated. Such compounds, which have iron, nickel, or manganese as bases, are substances of high density and would be likely to sink deep into the cooling mass. At the surface of the earth, and probably throughout the lithosphere, they would cease to exist, for water, especially as superheated steam, transforms them into other compounds, such as hydrocarbons, oxides, silicates, borates, and salts of ammonium. This speculation, which is not entitled to rank as a theory, receives some support from the study of volcanic emanations, of which carbon dioxide, boric oxide, and ammonium chloride are common constituents. Hydrocarbons are also found in small amount among volcanic gases. The existence of boron nitride within the earth is suggested by the association of boric acid and ammonium salts, as at the Tuscan fumaroles and at Vulcano. As for the silicates and oxides they are the chief constituents of the lithosphere.

If the iron of the earth's interior is strictly analogous to meteoric iron it probably contains inclusions of graphite, as well as of carborundum (CSi), which has been found in the iron of Canyon Diablo. Lawrencite, ferrous chloride, should also be present in the interior and would furnish the chlorine of volcanic emanations. Phosphides of iron and nickel, the minerals schreibersite and rhabdite, are also common in meteoric iron. The meteoric analogy, however, must not be pushed too far. The results of attempts to determine the average composition of meteoric matter are not significant, for meteorites, or at least some of them, are now known to be fragments of much larger bodies, which in some unknown way have broken to pieces. To reconstruct in imagination an asteroid from the fragments which happen to be found is impossible. Much of the stony parts of meteorites has doubtless been scattered as dust, and some meteorites consist only of fragments of the nucleus of iron that reached the earth.

In passing from the evolution of elements to the evolution of compounds, we pass from a field of relative simplicity and stability to one of complexity and instability. Stability, however, is governed by three prime conditions—temperature, pressure, and environment. A given mineral deposited from a molten magma is for the time being stable; in the presence of water it becomes unstable and may be partly decomposed. In the development of the crust of the earth such changes are continually occurring, one set of equilibria being destroyed in order to establish a new one. At what stage of the evolutionary process water was first formed we do not know, but its appearance made a vast number of chemical changes possible. It is the most active of all reagents in the chemistry of the earth's crust, but the intervention of a high temperature may undo its work. The igneous rocks were formed at high temperatures; the sedimentary rocks are the product of aqueous action in a relatively cool environment.

The association and distribution of the elements, whether free or in their compounds, has already been considered. In this section we are endeavoring to show that the process of the evolution of the elements has been continuous, from its beginning in the nebula to all the chemical reactions that are now occurring on the face of the earth. In its first phase it went on slowly; now it moves more rapidly; but throughout there seems to have been a striving after equilibrium and permanent stability, which perhaps can never be reached. It may be approached asymptotically, but its actual attainment, with the cessation of all chemical reactions, would mean the death of the universe—its transformation into a changeless, inert mass. At present the maximum of terrestrial stability is probably to be found in the deep-seated igneous rocks at points undisturbed by volcanic activity. Its minimum, with the most frequent and rapid changes, appears on the surface of the earth in the film of organic matter that forms the physical and chemical basis of life. The advance, however, is always upward, in spite of all relapses. The combinations tend to permanency; decomposition may be regarded as a temporary incident in the evolution of matter and is rarely complete. In the chemistry of our planet few compounds are ever resolved into their component elements. On the contrary, new compounds are produced, which in their turn are stable.

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