Data of Geochemistry

Sixth Edition

Chapter D. Composition of the Earth's Crust

GEOLOGICAL SURVEY PROFESSIONAL PAPER 440-D

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849

Parker—COMPOSITION OF THE EARTH'S CRUST—Geological Survey Professional Paper 440-D

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Sixth Edition

MICHAEL FLEISCHER, *Technical Editor*

Chapter D. Composition of the Earth's Crust

By RAYMOND L. PARKER

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Discussion of methods of determining
the crustal composition and a summary
of abundance figures of the elements

U.S. DEPARTMENT OF THE INTERIOR
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DATA OF GEOCHEMISTRY, SIXTH EDITION

Michael Fleischer, *Technical Editor*

The first edition of the Data of Geochemistry, by F. W. Clarke, was published in 1908 as U.S. Geological Survey Bulletin 330. Later editions, also by Clarke, were published in 1911, 1916, 1920, and 1924 as Bulletins 491, 616, 695, and 770. This, the sixth edition, has been written by several scientists in the Geological Survey and in other institutions in the United States and abroad, each preparing a chapter on his special field. The current edition is being published in individual chapters, titles of which are listed below. Chapters already published are indicated by boldface.

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DATA OF GEOCHEMISTRY

COMPOSITION OF THE EARTH'S CRUST

By Raymond L. Parker

ABSTRACT

The crust of the earth is composed principally of igneous (and metamorphic) rocks of granitic and basaltic composition. Since 1890 many geologists have computed averages for the major-element composition of the crust based on the following general approaches: (1) Averages of available analyses, (2) averages weighted in proportion to occurrence, (3) computations of an indirect nature based on the composition of sediments and various combinations of mafic and felsic rocks, and (4) abundances of elements based on crustal models. Most of these averages fall within a remarkably small range in composition. Less attention has been given by geologists to the computation of abundance of minor elements in the crust and in various types of rocks. The abundance of some minor elements still is poorly known, and the estimation of their abundance is hampered by lack of available analyses, inadequate sampling, inaccurate results of some analytical procedures, and imprecise methods of estimation.

Abundance figures for the chemical elements in the earth's crust and in the common rocks, as summarized from available literature, are presented.

INTRODUCTION

The crust of the earth is discussed in the following pages to serve as background for succeeding chapters of the "Data of Geochemistry." An attempt is made to present the data that relate to the composition of the lithic crust and to present the most recent tabulations of abundances of the elements in the crust and in certain general rock categories. A principal purpose of this chapter is to point out the problems involved in computing abundance figures and in determining accurately the composition of the crust. Our knowledge of crustal composition since about 1890 is presently through a summary of the most important works in this field.

The abundance data given in tables 19 and 20 will no doubt be subject to revision shortly after they are published because of the rapid accumulation of modern analytical data and the detailed compilation of data for each element now in progress. A final tabulation on completion of such compilation will be presented in chapter DD of the "Data of Geochemistry."

CONSTITUTION OF THE EARTH

The earth is considered to have a primary threefold division—crust, mantle, and core. These divisions, which are concentric zones in depth, are established principally by their differing behavior with respect to the transmission of *P* (compressional) and *S* (shear) seismic waves and are separated from each other by distinct discontinuities in transmission velocity. The crust and the mantle are separated by the Mohorovičić discontinuity at an average depth below sea level ranging from 37 km under parts of the continents to about 11 km beneath the deep sea basins (Poldervaart, 1955); the mantle and core are separated by the Wiechert-Gutenberg discontinuity at a depth of approximately 2,900 km. These discontinuities are clearly shown in figure 1, a plot of velocity of *P* and *S* waves versus depth in the earth. Inasmuch as the velocity of *P* and *S* waves varies with density and elasticity of the medium through which the waves pass, the curves indicate that the earth is heterogeneous in respect to these properties in zones

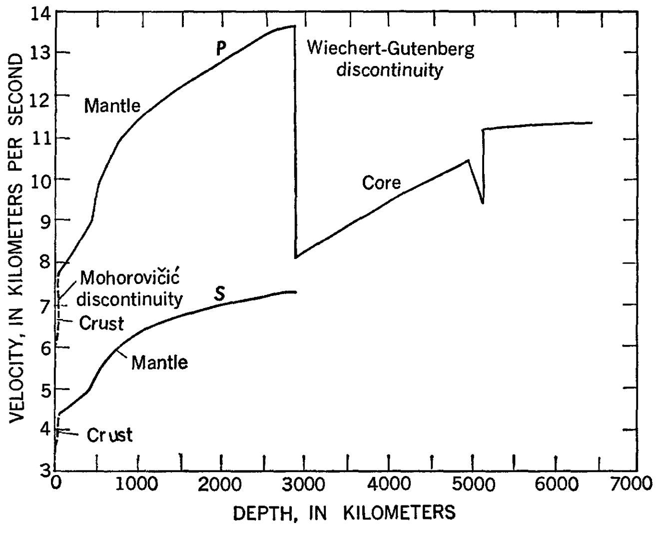

Figure 1.—*P* and *S* velocity distributions in the earth's interior. Modified from Bullen (1963, p. 223).

in depth separated by the above-mentioned discontinuities. That *S* waves have not been observed to pass through the central core suggests that part of the core is not rigid, as are other zones of the earth, and is probably in a fluid state. Reasons for believing that the inner part of the core is solid are discussed by Bullen (1963).

The average density of the earth was determined by Cavendish in 1799 to be about 5.5 g per cm^3 (grams per cubic centimeter); a more precise recent estimate is 5.517 g per cm^3 (Bullen, 1963, p. 226). Inasmuch as the surface rocks have a mean density of about 2.8 g per cm^3, inner parts of the earth must consist of material with density greater than 5.5 to account for the density of the earth as a whole. A detailed mathematical treatment of the density variation in the earth is given by Bullen (1963, p. 229), showing the general increase in density to 11.9 g per cm^3 for a depth within the core. (See figure 2.) Birch (1964) points out that densities proposed for the inner core by Bullen are excessive and are in conflict with modern shock-wave data. Inner-core densities of 12.86 and 13.26 g per cm^3 for two earth models have been postulated by Clark and Ringwood (1964) and are considered plausible and consistent with those data.

The density distribution within the earth may be explained by a change in physical state of the material by contraction into smaller volume under great pressure or by a change in chemical composition involving heavier substances. Concepts currently favored by most physicists and geologists to explain the density variation with depth are based both on changes in physical state and chemical composition (Birch, 1964). The following constitution of the earth is consistent with known facts concerning its mass, moment of inertia, and seismic behavior.

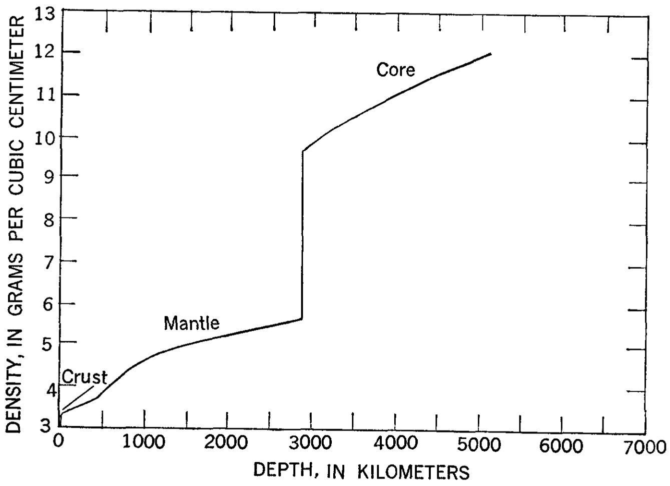

FIGURE 2.—Variation in density of the earth Model A. Modified from Bullen (1963, p. 231).

Division	*Physical state*	*Constituent material*
Crust	Solid (with zones of fluid, gas).	Heterogeneous, principally normal silicate rocks but including zones of water, snow, and ice (hydrosphere); gas (atmosphere); and organic and skeletal matter (biosphere).
Mantle	Solid	Iron-magnesium silicates, possibly dunitic or peridotitic material and iron sulfide(?).
Core	Partly fluid, partly solid.	Iron-nickel alloy, perhaps containing silicon.

The physical dimensions of these divisions of the earth are summarized in table 1.

TABLE 1.—*Physical dimensions of earth shells, excluding biosphere*

[Data from Mason (1958, p. 41)]

	Thickness (km)	Volume ($\times 10^{27}$ cm^3)	Mean density (g per cm^3)	Mass ($\times 10^{27}$ g)	Mass (percent)
Atmosphere				0.000005	0.00009
Hydrosphere	3.80 (mean)	0.00137	1.03	.00141	.024
Crust	17 (mean)	.008	2.8	.024	.4
Mantle	2,883	.899	4.5	4.075	68.1
Core	3,471	.175	10.7	1.876	31.5
Whole earth	6,371	1.083	5.52	5.976	100.0

COMPOSITION OF THE CRUST

GENERAL DISCUSSION

The term "crust" stems from the early concept of a molten earth with a solidified outer crust. Our present concept of the earth's structure differs considerably, but the term has persisted and is now applied to the outer shell of the earth above the Mohorovičić discontinuity. Included in the crust are the geochemical spheres—hydrosphere, atmosphere, and biosphere, which are subjects of detailed description in separate chapters of the "Data of Geochemistry." Only the lithic crust above the Mohorovičić discontinuity will be described here.

The term "lithosphere" has been applied to the lithic crust of the earth by other writers (Clarke and Washington, 1924; Poldervaart, 1955) and is used interchangeably with lithic crust in this report. As pointed out by Rankama and Sahama (1950, p. 82), lithosphere, as contrasted to asthenosphere, should refer to strength or state of the constituting material and, as originally defined, should not connote chemical composition. Subsequently, the term "steriosphere" was proposed by Bucher (1955, p. 344) for this relatively strong outermost shell of the earth above the asthenosphere, but the term has been little used. It seems pointless to attempt to refine lithosphere from what it has come to mean through usage.

The lithic crust is frequently and simply referred to as consisting of two layers—sial and sima. In this designation, the sial represents the upper part of the crust of silicic composition and derives its name from silicon and aluminum, which together with oxygen, are the most abundant elements in the material of this region. The sima refers to the underlying, more mafic part, of the crust and derives its name from silicon-magnesium. A less commonly used term "sialma" refers to an intermediate position between the sial and sima (Rankama and Sahama, 1950, p. 81). These terms, though imprecise, have convenient application in some structural and petrologic studies.

The crust of the earth is composed principally of igneous rocks and contains only a minor amount of sedimentary and metamorphic rocks, if the crust is considered as a whole. The proportions of different classes of rocks in the crust have been cited by Clarke and Washington (1924, p. 32) as consisting of 95 percent igneous rocks (including metamorphic rocks) and 5 percent sedimentary rocks (consisting of 4 percent shale, 0.75 percent sandstone, and 0.25 percent limestone). Succeeding workers have not greatly revised these early estimates. Poldervaart (1955) calculated that the crust, including areas beneath the oceanic basins, contains 6 percent sedimentary rocks. Obviously the composition of the crust is close to the composition of igneous rocks.

COMPUTATIONS OF CRUSTAL COMPOSITION

MAJOR ELEMENTS

Studies aimed at determining the composition of the earth's crust have been made over a period of more than 75 years, and considerable controversy has arisen over the approaches to the problem as well as to the values proposed. Four general approaches in determining crustal composition that have evolved during this period are (1) averages of available analyses, (2) averages weighted in proportion to occurrence, (3) computations of an indirect nature based on the composition of sediments and various combinations of mafic and felsic rocks, and (4) abundance of elements based on crustal models. All approaches except the last are concerned chiefly with the continental crust or parts of the crust and do not take into consideration the more than half of the earth's crust covered by the oceans.

AVERAGES OF AVAILABLE ANALYSES

Early studies by Clarke (1889, 1908), Washington (1903), and Harker (1904) derived figures for the composition of the average igneous rock based on the arithmetic mean of a large number of chemical analyses. A final paper by Clarke and Washington (1924) on the composition of the earth's crust was based on computations from 5,159 superior analyses compiled by Washington (1917). The work included averages grouped by geographical areas as well as figures for the crust of the earth as a whole. Averages of analyses grouped on a geographical basis were found to agree fairly well from one area to another, provided the areas chosen were large enough to eliminate local variations. Grout (1938) revised the average for the Canadian Shield area by using more recent analyses not available to Clarke and Washington.

On the basis of 95 percent igneous rocks, 4 percent shale, 0.75 percent sandstone, and 0.25 percent limestone, Clarke and Washington (1924) computed the average composition of the lithosphere to a 10-mile depth. Their averages for igneous rocks, shale, sandstone, and limestone, and the weighted average for the lithosphere are given in table 2. The average for the lithosphere differs little from the average given for igneous rocks.

TABLE 2.—*Average composition of the lithosphere according to Clarke and Washington (1924, p. 32)*

[Tr, trace]

	1	2	3	4	5
SiO_2	59.12	58.11	78.31	5.19	59.07
TiO_2	1.05	.65	.25	.06	1.03
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
ZrO_2	.04				.04
P_2O_5	.30	.17	.08	.04	.30
Cl	.05		Tr	.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	Tr	Tr	.05	.11
NiO	.03				.03
BaO	.05	.05	.05	.00	.05
SrO	.02	.00	.00	.00	.02
Li_2O	.01	Tr	Tr	Tr	.01
Cu	.01				.01
C	.00	.80			.04
Total	100.00	100.00	100.00	100.00	100.00

1. Average igneous rock.
2. Average shale.
3. Average sandstone.
4. Average limestone.
5. Weighted average lithosphere:
   Igneous rock, 95 percent
   Shale, 4 percent
   Sandstone, 0.75 percent
   Limestone, 0.25 percent

Many objections to the validity of the averaging method of Clarke and Washington for determining the average composition of igneous rocks of the crust have been raised, but the Clarke and Washington figures are close to those derived by more recent and sophisticated methods. Principal objectors were Daly (1914), Sederholm (1925), and Vogt (1931), and the principal objections were that the averaging method did not take into account the irregular geographic distribution of the analyses, that the analyses used in calculations were not proportional to the mass of rocks they represented, and that rare and unusual rocks were given undue weight in the calculations because of the abundance of analyses of these types of rocks in the literature. The objections were countered by Clarke and Washington (1924, p. 7) who pointed out that, even though the analyses were not truly representative in terms of the abundance of rocks as they occur in the earth, they showed that the rocks varied from persilicic to subsilicic, and in the average these variations tended to offset each other and approximate the true mean. Such compensation, because of the wide ranges in composition of the unusual rocks, also tended to produce an average near the true mean. Inasmuch as the averages for individual continents were in fair agreement, unequal analytical coverage of areas was considered not to invalidate the overall average. (See table 3.)

TABLE 3.—*Average composition of igneous rocks of the continents and oceanic islands and of the earth*

[Clarke and Washington (1924 p. 15)]

	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
TiO_2	1. 01	. 56	. 83	. 84	1. 63	. 68	1. 01	1. 96	. 87	1. 05
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
P_2O_5	. 26	. 11	. 23	. 20	. 43	. 12	. 26	. 25	. 17	. 30
MnO	. 10	. 12	. 08	. 07	. 04	. 10	. 15	. 15	. 03	. 12
Others	. 20	. 16	. 11	. 18	. 07	. 08	. 16	. 12	. 01	. 50
Total	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.

AVERAGES WEIGHTED IN PROPORTION TO OCCURRENCE

A more quantitative approach to the determination of the composition of segments of the earth's crust was conceived by Daly (1914), coincident with his objections to the methods of Clarke and Washington. His approach was based on the use of geologic maps in estimating the relative abundance of rock types. Using 75 U.S. Geological Survey folios covering parts of the Appalachian and Cordillera regions of the United States, Daly measured the areal extent of the principal classes of plutonic, hypabassal, and extrusive rocks (table 4). He also compiled the average compositions of many types of igneous rocks. Knopf (1916), however, first used these data to compute a composition for the average igneous rock (table 5), which is very similar to the composition computed by Clarke and Washington (1924) by their method of averaging available analyses.

Sederholm (1925) computed an average composition of the earth's crust within the borders of Finland by using the areal distribution of various types of rocks and their chemical compositions in a manner similar to Knopf's as the basis for his computations. From geologic maps he deduced the following percentages of rocks as the principal groups that constitute the Finnish crust:

Granitic rocks	52. 5
Migmatites	21. 8
Granulites (leptynites)	4. 0
Schists	9. 1
Quartzites and sandstones	4. 3
Limestones and dolomites	. 1
Mafic rocks	8. 2
Total	100. 0

His average composition for the crust is considerably more silicic than averages for other regions and is shown in table 6, along with other averages for comparison. Column 2, table 6, is the average igneous rock computed by Clarke and Washington (1924) for Finland including the Kola Peninsula. The inclusion of some unusual (alkalic) Kola rocks in the average probably lowered the silica content, modified other oxide percentages, and thus accounted at least in part for the differences between the Sederholm and Clarke and Washington averages.

TABLE 4.—*Areas of igneous rocks in the Pacific Cordillera and Appalachian regions*

[Compiled by Daly (1914, p. 44)]

	Pacific Cordillera region (sq mi)	Appalachian region (sq mi)	Total (sq mi)
Plutonic rocks			
Precambrian granite	2, 089. 0	1, 151. 0	3, 240. 0
Paleozoic and later granite	402. 0	194. 0	596. 0
Total granite	(2, 491. 0)	(1, 345. 0)	(3, 836. 0)
Granodiorite	2, 040. 0	----------	2, 040. 0
Quartz monzonite	11. 0	----------	11. 0
Quartz diorite	45. 3	----------	45. 3
Diorite	103. 5	10. 0	113. 5
Gabbro diorite	98. 5	----------	98. 5
Gabbro	226. 4	47. 5	273. 9
Anorthosite	52. 0	----------	52. 0
Syenite	24. 4	----------	24. 4
Monzonite	17. 5	----------	17. 5
Nepheline syenite	3. 5	. 3	3. 8
Shonkinite	8. 7	----------	8. 7
Fergusite	<1. 0	----------	<1. 0
Missourite	. 1	----------	. 1
Theralite	6. 3	----------	6. 3
Peridotite	73. 3	----------	73. 3
Pyroxenite	2. 2	----------	2. 2
Total	5, 240. 7	1, 402. 8	6, 607. 5
Hypabyssal rocks			
Granite porphyry	17. 9	2. 0	19. 9
Quartz porphyry and rhyolite	26. 5	1. 0	27. 5
Dacite porphyrite	7. 8	----------	7. 8
Quartz-hornblende porphyrite	2. 0	----------	2. 0
Quartz monzonite porphyry	4. 6	----------	4. 6
Diorite porphyrite	20. 1	1. 6	21. 7
Hornblende porphyrite	1. 0	----------	1. 0
Quartz diabase	3. 0	----------	3. 0
Diabase	150. 0	118. 0	268. 0
Syenite porphyry	38. 4	2. 5	40. 9
Monzonite porphyry	9. 4	----------	9. 4
Nepheline syenite porphyry	<. 1	----------	<. 1
Phonolite	2. 7	----------	2. 7
Pseudo-leucite porphyry	. 5	----------	. 5
Total	284. 0	125. 1	409. 1
Extrusive rocks			
Rhyolite	2, 145. 7	1. 0	2, 146. 7
Dacite	82. 1	----------	82. 1
Mica andesite	3. 0	----------	3. 0
Hornblende andesite	21. 6	----------	21. 6
Pyroxene andesite (chiefly)	3, 966. 0	----------	3, 966. 0
Augite porphyrite	255. 0	----------	255. 0
Basalt	3, 079. 0	130. 0	3, 209. 0
Trachyte	6. 5	----------	6. 5
Latite	4. 6	----------	4. 6
Phonolite	5. 5	----------	5. 5
Trachydolerite	. 3	----------	. 3
Teschenite	. 2	----------	. 2
Nepheline basalt (Texas)	1. 2	----------	1. 2
Nepheline-melilite basalt	2. 8	----------	2. 8
Limburgite	2. 5	----------	2. 5
Quartz basalt	8. 0	----------	8. 0
Total	9, 584. 0	131. 0	9, 715. 0
Total igneous rock area mapped	15, 072. 7	1, 658. 9	16, 731. 6

TABLE 5—*Compositions of average igneous rock*

	Compositions computed by—		
	Knopf from Daly's data (1916)	Clarke (1915)	Clarke and Washington (1924)
SiO_2	61. 64	60. 47	59. 12
TiO_2	. 73	. 80	1. 05
Al_2O_3	15. 71	15. 07	15. 34
Fe_2O_3	2. 91	2. 68	3. 08
FeO	3. 25	3. 50	3. 80
MnO	. 16	. 10	. 12
MgO	2. 97	3. 85	3. 49
CaO	5. 06	4. 88	5. 08
Na_2O	3. 40	3. 41	3. 84
K_2O	2. 65	3. 03	3. 13
H_2O-	1. 26	. 48	1. 15
H_2O+		1. 44	
P_2O_5	. 26	. 29	. 30
Others	----------	----------	. 50
Total	100. 00	100. 00	100. 00

TABLE 6.—*Composition of the earth's crust in Finland and composition of the average igneous rock for comparison*

	1	2	3
SiO_2	67. 70	60. 58	59. 12
TiO_2	. 41	. 56	1. 05
Al_2O_3	14. 69	16. 43	15. 34
Fe_2O_3	1. 27	2. 75	3. 08
FeO	3. 14	2. 88	3. 80
MnO	. 04	. 19	. 12
MgO	1. 69	2. 16	3. 49
CaO	3. 40	3. 35	5. 08
Na_2O	3. 07	6. 11	3. 84
K_2O	3. 56	3. 96	3. 13
H_2O	. 79	. 71	1. 15
P_2O_5	. 11	. 27	. 30
Others	. 13	. 05	. 50
Total	100. 00	100. 00	100. 00

1. Sederholm (1925), average Finnish rocks.
2. Clarke and Washington (1924), average igneous rock, Finland including Kola, 59 analyses.
3. Clarke and Washington (1924), average igneous rock, earth.

Vogt (1931) calculated the average composition of the earth's crust after extensive field work in Norway. His calculations were based on averages of plutonic rock types computed by Daly or by himself and on his experience as a mapping geologist in estimating the relative distribution of the plutonic rocks. Only plutonic rocks were considered; hypabyssal, extrusive, and sedimentary rocks were excluded from consideration. The distribution of igneous rock types, as conceived by Vogt, is given in table 7, and his crustal averages are given in table 8. Both tables present two sets of values based on suppositions that the relative abundance of granite is either 50 or 60 percent.

Vogt's averages are somewhat more rich in silica, but less rich in ferrous and ferric oxides, magnesia, and lime, than the Clarke and Washington average. Vogt's figures for titania and phosphorus pentoxide are also considerably lower, facts which are strongly emphasized in his objections to the Clarke and Washington average.

TABLE 7.—*Distribution of plutonic rocks in Norway*

[Compiled by Vogt (1931)]

	Relative abundance of granite assumed to be—	
	50 percent	60 percent
Granite	50	60
Quartz-monzonite and granodiorite	10	9
Quartz-diorite and diorite	8	6
Gabbro	18	15
Anorthosite	4	3
Pyroxenite and peridotite	. 50	. 25
Nordmarkite and pulaskite	1	1
Alkali-lime syenite	3	2
Monzonite	4	3
Nepheline-syenite	1	. 50
Essexite and others	. 50	. 25
Total	100	100

TABLE 8.—*Average composition of the earth's crust (Vogt, 1931) and composition of the average igneous rock for comparison*

	1	2	3	4
SiO_2	64. 03	65. 73	59. 12	59. 87
TiO_2	. 60	. 55	1. 05	1. 06
Al_2O_3	15. 71	15. 41	15. 34	15. 54
Fe_2O_3	2. 20	2. 10	3. 08	3. 12
FeO	2. 66	2. 30	3. 80	3. 85
MgO	2. 67	2. 23	3. 49	3. 53
CaO	4. 62	4. 01	5. 08	5. 14
Na_2O	3. 51	3. 43	3. 84	3. 89
K_2O	3. 52	3. 79	3. 13	3. 17
H_2O+	--------	--------	1. 15	--------
CO_2	--------	--------	. 10	--------
P_2O_5	. 18	. 17	. 30	. 30
Other	. 30	. 28	. 52	. 53
Total	100. 00	100. 00	100. 00	100. 00

1. Vogt's crustal average with granite assumed to be 50 percent of plutonic rocks, water free.
2. Vogt's crustal average with granite assumed to be 60 percent of plutonic rocks, water free.
3. Igneous rocks, Clarke and Washington (1924).
4. Igneous rocks, Clarke and Washington (1924), water and carbon dioxide free.

COMPUTATIONS OF AN INDIRECT NATURE

Indirect approximations of the composition of the earth's crust have been made by determining the composition of the products of crustal weathering and erosion and by combining the analyses of mafic and felsic rocks in various proportions. Some computations involve equating the erosion products with combined mafic and felsic rocks. Supporters justify these approaches on the basis that the products of decomposition of the crust should reflect the original crustal composition and that the crust can well be represented by mafic and felsic rocks inasmuch as they are the principal types exposed. (See table 4.)

Goldschmidt (1933, 1954) conceived the idea that the glacial clays in southern Norway represent a natural sampling of the continent as a result of glacial erosion by the Fennoscandian ice sheet. The glacial erosion was largely mechanical with a minimum of chemical weathering, so that the composition of the resulting glacial clays should be close to that of the original rock flour. Furthermore, the rock flour should have been well mixed during transportation in the ice and in the melt water before deposition. An average of 77 analyses of the glacial clays (table 9) is in remarkable agreement with the average igneous rock of Clarke and Washington (1924), except for sodium and calcium which are considered to have been leached to some degree in the aqueous environment of transportation and deposition.

Instead of calculating the crustal composition, a number of geologists have combined the analyses of granite (felsic rocks) and basalt (mafic rocks) in various proportions to approximate the average for the crust. Daly (1910, p. 238) was one of the first to point out that the mean of his average granite and average basalt approximated his average diorite and andesite. This average is remarkably close to the average igneous rock of Clarke and Washington (1924) (table 10). Daly's observations were in accord with the views of Loewinson-Lessing (1911), who regarded the crust as derived from two fundamental magmas—granitic and basaltic. He erred, however, in suggesting that the average should be syenite instead of a rock of more intermediate composition (Daly, 1914, p. 169).

TABLE 9.—*Average composition of Norwegian loams (clays) and other averages for comparison*

	Goldschmidt (1954)			Clarke and Washington (1924)			Vogt (1931)	
	Norwegian loams			Average igneous rock		Average composition lithosphere	Average composition earth's crust; granite in plutonic rocks assumed to be—	
	Primary zone	Secondary zone	Mean	Earth	Norway and Iceland		50 percent [1]	60 percent [1]
SiO_2	58. 94	60. 82	59. 19	59. 12	59. 83	59. 07	64. 03	65. 73
TiO_2	. 79	. 78	. 79	1. 05	1. 64	1. 03	. 60	. 55
Al_2O_3	15. 87	15. 48	15. 82	15. 34	16. 08	15. 22	15. 71	15. 41
Fe_2O_3	3. 28	4. 35	3. 41	3. 08	3. 65	3. 10	2. 20	2. 10
FeO	3. 69	2. 82	3. 58	3. 80	3. 21	3. 71	2. 66	2. 30
MnO	. 10	. 12	. 11	. 12	. 10	. 11	--------	--------
MgO	3. 33	3. 02	3. 30	3. 49	2. 26	3. 45	2. 67	2. 23
CaO	3. 19	2. 25	3. 07	5. 08	3. 64	5. 10	4. 62	4. 01
Na_2O	2. 05	2. 00	2. 05	3. 84	5. 10	3. 71	3. 51	3. 43
K_2O	3. 95	3. 83	3. 93	3. 13	3. 52	3. 11	3. 52	3. 79
H_2O	3. 01	3. 10	3. 02	1. 15	. 75	1. 30	--------	--------
P_2O_5	. 21	. 23	. 22	. 30	. 12	. 30	. 18	. 17
SO_3	. 09	. 05	. 08	--------	--------	--------	--------	--------
S	. 08	. 03	. 07	. 05	--------	. 06	--------	--------
CO_2	. 60	. 18	. 54	. 10	--------	. 35	--------	--------
Other	--------	--------	--------	. 35	. 10	. 38	. 30	. 28
Total	99. 18	99. 06	99. 18	100. 00	100. 00	100. 00	100. 00	100. 00

[1] See tables 7 and 8. Vogt's averages are computed on a water-free basis; hence allowance must be made in comparison with other averages in this table.

TABLE 10.—*Average igneous rock formed by combining granite and basalt in proportion 1:1 and other averages for comparison*

	Daly (1914, p. 169)			Clarke and Washington (1924)	
				Average igneous rock	
	Average granite	Average basalt	Mean	Earth	Earth (water and carbon dioxide free)
SiO_2	70. 47	49. 65	60. 06	59. 12	59. 87
TiO_2	. 39	1. 41	. 90	1. 05	1. 06
Al_2O_3	14. 90	16. 13	15. 52	15. 34	15. 54
Fe_2O_3	1. 63	5. 47	3. 55	3. 08	3. 12
FeO	1. 68	6. 45	4. 06	3. 80	3. 85
MnO	. 13	. 30	. 21	. 12	. 12
MgO	. 98	6. 14	3. 56	3. 49	3. 53
CaO	[1] 2. 17	9. 07	5. 62	5. 08	5. 14
Na_2O	3. 31	3. 24	3. 28	3. 84	3. 89
K_2O	4. 10	1. 66	2. 88	3. 13	3. 17
P_2O_5	. 24	. 48	. 36	. 30	. 30
Others	--------	--------	--------	1. 65	. 41
Total	100. 00	100. 00	100. 00	100. 00	100. 00

[1] Includes 0.06 percent BaO and 0.02 percent SrO

Mead (1914), assuming that the average igneous rock could be approximated in composition by some combination of average granite and average basalt, calculated a 65 : 35 ratio of granite to basalt to best explain the composition of sediments as expressed by average analyses of shales, sandstones, and limestones. Simultaneously, with the solution of the granite : basalt ratio, a ratio of 87 : 8 : 5 was calculated for shale, sandstone, and limestone, respectively. Mead's equation for the calculation, which he solved by graphical means, is as follows:

x granite $+ y$ basalt $= a$ shale $+ b$ sandstone $+ c$ limestone

where average analyses of granite, basalt, shale, sandstone, and limestone are given. Solve for x, y, a, b, and c.

Average granite and basalt analyses (Daly, 1910) combined in proportions of 63 : 35 give a composition which is slightly more silicic than that of Clarke and Washington (1924) and the more modern averages of Poldervaart (1955) and Taylor (1964). It is indeed close to the crustal averages computed by Vinogradov (1962) using a 2 : 1 granite : basalt ratio (see table 11).

In a modern version of Mead's method, Wickman (1954) derived a ratio in which granite : basalt $= 2.13 \pm 0.70$, and from this he determined the average igneous rock to be almost identical in composition with that derived by Knopf (1916). Averages of several authors and computations of igneous rock compositions by Wickman can be compared in tables 11 and 12. His computation of the proportions of the sediments formed by complete weathering of the continents is, in percent, as follows: shale, 82.3; sandstone, 8.3; limestone, 6.1; and dolomite, 3.3.

TABLE 11.—*Average igneous rock compositions computed by Mead (1914) and other averages for comparison*

	1	2	3	4	5
SiO_2	63. 19	60. 3	63. 1	59. 4	59. 87
TiO_2	. 74	1. 0	. 8	1. 2	1. 06
Al_2O_3	15. 34	15. 6	15. 2	15. 6	15. 54
Fe_2O_3	2. 96	--------	--------	2. 3	3. 12
FeO	3. 35	7. 2	6. 0	5. 0	3. 85
MgO	2. 79	3. 9	3. 1	4. 2	3. 53
CaO	4. 59	5. 8	4. 1	6. 6	5. 14
Na_2O	3. 28	3. 2	3. 4	3. 1	3. 89
K_2O	3. 24	2. 5	3. 0	2. 3	3. 17
Others	. 52	. 5	1. 3	. 3	. 83
Total	100. 00	100. 0	100. 0	100. 0	100. 00

1. Average granite and average basalt of Daly (1910) combined in ratio of 65:35 (Mead, 1914), water free (computation corrected by Parker).
2. Taylor's felsic and mafic rock combined in ratio of 1:1 (Taylor, 1964); total Fe expressed as FeO; water free.
3. Vinogradov's granite and basalt combined in ratio of 2:1 (Taylor, 1964); total Fe expressed as FeO; water free.
4. Poldervaart's (1955) average continental shield and folded belts regions; water free.
5. Average igneous rock, Clarke and Washington (1924); water and carbon dioxide free.

TABLE 12.—*Compositions of the average igneous rock (Wickman, 1954) and other averages for comparison*

	1	2	3	4	5
SiO_2	61. 45	62. 90	63. 90	59. 87	62. 44
TiO_2	. 89	. 80	. 74	1. 06	0. 74
Al_2O_3	15. 19	15. 22	15. 24	15. 54	15. 91
Fe_2O_3	2. 02	1. 96	1. 90	3. 12	2. 95
FeO	5. 05	4. 43	4. 02	3. 85	3. 29
Fe (total)[1]	(5. 34)	(4. 81)	(4. 45)	(5. 17)	(4. 62)
MnO	. 14	. 13	. 13	. 12	0. 16
MgO	3. 55	3. 08	2. 76	3. 53	3. 01
CaO	6. 01	5. 40	5. 00	5. 14	5. 12
Na_2O	3. 10	3. 22	3. 30	3. 89	3. 44
K_2O	2. 42	2. 65	2. 80	3. 17	2. 68
P_2O_5	. 24	. 23	. 23	. 30	. 26
Others	--------	--------	--------	. 41	--------
Total	100. 06	100. 02	100. 02	100. 00	100. 00

[1] Not included in analysis total.

1. Igneous rocks, Wickman (1954), with granite : basalt=1.43.
2. Igneous rocks, Wickman (1954), with granite : basalt=2.13.
3. Igneous rocks, Wickman (1954), with granite : basalt=2.83.
4. Igneous rocks, Clarke and Washington (1924), water and carbon dioxide free.
5. Average of Cordillera and Appalachian rocks, Knopf (1916), water free.

Taylor (1964) concluded from a study of the relative abundances of rare-earth elements in sedimentary and igneous rocks that both the major and minor element compositions of the continental crust can be represented by a 1 : 1 mixture of mafic and felsic rocks. He found that such a mixture of specially selected mafic and felsic rocks contained approximately the same rare-earth abundance pattern as sedimentary rocks, as well as nearly the same composition, in terms of major oxides, as the continental rocks computed by Poldervaart (1955) and the lithosphere by Clarke and Washington (1924). (See table 11.)

Taylor pointed out that because sedimentary rocks of diverse origin and differing ages have similar rare-earth abundance patterns, no significant fractionation of rare-earth elements occurred during the course of sedimentation, and a thorough mixing of distinctly different rare-earth igneous patterns was accomplished. The sedimentary rare-earth abundance pattern should represent both a large scale sampling and an average pattern of the continental rocks exposed to weathering. Inasmuch as the chief types of crustal rocks are mafic and felsic, duplication of the sedimentary rare-earth abundance pattern by combining these types should, in principle, give their proportion in the continental crust.

Mafic and felsic rock analyses selected to represent the crustal rocks have been averaged from several available standard rocks. The mafic rocks are a composite of the Atlantic Ridge, Experimental Mohole, Columbia River, and Kilauea Iki basalts and diabase W-1 from Centerville, Va. The felsic rocks are represented by an average of the Kirovograd granite and the granite G-1 from Westerly, R.I. Rare-earth values are normalized on the basis of lanthanum equals 1.00 and are shown in table 13. The table shows also that the average sedimentary pattern is very similar to the 1:1, mafic:felsic composite pattern which is a weighted average computed on the basis of the average abundance of lanthanum of 50 ppm (parts per million) and 10 ppm in granite and basalt, respectively (Taylor, 1965).

TABLE 13.—*Rare-earth abundance patterns (weight ratio) normalized to lanthanum=1.00*

[Data from Taylor (1964, 1965)]

Atomic No.	Element	1	2	3	4
57	Lanthanum	1.00	1.00	1.00	1.00
58	Cerium	2.0	4.25	1.58	2.02
59	Praseodymium	.27	.53	.20	.26
60	Neodymium	.90	2.60	.62	.95
61	Promethium	------	------	------	------
62	Samarium	.20	.80	.10	.22
63	Europium	.040	.32	.0094	.062
64	Gadolinium	.18	1.21	.057	.25
65	Terbium	.030	.21	.0030	.038
66	Dysprosium	.12	------	.018	------
67	Holmium	.040	.28	.0034	.050
68	Erbium	.09	.88	.0090	.16
69	Thulium	.016	.12	.0016	.022
70	Ytterbium	.10	.63	.0035	.11
71	Lutetium	.017	.14	.0008	.023

1. Average rare-earth sedimentary rock pattern (Haskin and Gehl, 1962).
2. Average mafic rock pattern. Average of Atlantic Ridge and Experimental Mohole basalts (Frey and Haskin, 1964), Columbia River and Kilauea Iki basalts (Schmitt and others, 1963), and diabase W-1 (Haskin and Gehl, 1963).
3. Average felsic rock pattern. Average of granite G-1 (Haskin and Gehl, 1963) and Kirovograd granite (Gavrilova and Turanskaya, 1958).
4. Rare-earth pattern resulting from averaging mafic pattern (col. 2) and felsic pattern (col. 3) weighted in the ratio of 1:5, mafic:felsic patterns, respectively.

ABUNDANCE OF ELEMENTS BASED ON CRUSTAL MODELS

The most realistic estimates of the composition of the earth's crust were made by Poldervaart (1955) and Pakiser and Robinson (1967). In reviewing chemical and geological data pertaining to the crust, Poldervaart calculated the masses of the major rock-forming elements in terms of their oxides and computed the average composition of the lithosphere down to the Mohorovičić discontinuity. Pakiser and Robinson computed the composition of the crust underlying the conterminous United States by using seismic data to determine the distribution and proportion of mafic and silicic rocks and by using average compositions of mafic and silicic rocks to deduce abundance of the major oxides.

For convenience Poldervaart divided the lithosphere into four structural divisions: the deep oceanic region, the suboceanic region, the continental shield region, and the region of young folded belts. The deep oceanic and suboceanic regions embrace the pelagic, hemipelagic, and continental shelf areas, and the continental shield and young folded-belts regions (including volcanic islands) essentially compose the continental masses. The following discussion is condensed from Poldervaart's paper.

Pelagic, hemipelagic, and shelf sediments cover an area of about 361×10^6 km^2 (square kilometers) in the oceanic regions. Pelagic sediments consisting of calcareous sands and oozes, red clay, and siliceous oozes in a volume ratio of 72:19:9, respectively, cover an area of 268×10^6 km^2 and have an average thickness of 0.3 km. Hemipelagic sediments underlie an area of about 63×10^6 km^2 and consist of terrigenous mud, coral mud, and volcanic mud in a volume ratio of about 74:22:4, respectively. Shelf sediments cover about 30×10^6 km^2 and have an average thickness of 4 km. Their composition is considered to be similar to the sediments in the young folded-belts region, which is made up of the following constituents, in percent: Shale, 52; sandstone, 13; limestone, 22; graywacke, 5; andesite, 6; and rhyolite, 2. The composition and masses of oxides of the oceanic sediments and the average composition and total masses of the sediments for this part of the crust are listed in table 14.

Igneous rocks lying beneath the oceanic sediments and above the Mohorovičić discontinuity are poorly known and, thus, somewhat arbitrarily assigned. In the deep oceanic region, underlying material is considered to be olivine basalt about 5¾ km thick. In the suboceanic region, including the shelf area, 4 km of rocks of dioritic composition grading downward into 2 km of tholeiite followed by 5 km of olivine basalt are taken to represent the underlying material.

The continental masses contain a solid sedimentary rock cover averaging about half a kilometer in thickness for the continental shield region and about 5 km in thickness for the young folded-belts region. The areal extent of the continental shields is about 105×10^6 km^2 and that of the young folded belts is 42×10^6 km^2. The

TABLE 14.—*Average composition of all sediments*

[Calculated by Poldervaart (1955)]

Region	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	CO_2	Total
Mass ($\times 10^{15}$ tons)													
Deep oceanic	61.8	0.9	17.6	10.9	------	1.3	3.9	66.2	1.7	2.6	0.4	49.7	217
Continental shield	84.8	.6	12.4	3.4	1.7	.1	4.1	14.8	1.1	2.9	.1	14.0	140
Young folded belts	176.5	1.7	38.8	8.8	6.8	.1	12.9	42.8	4.4	8.2	.3	38.7	340
Suboceanic	434.2	7.0	116.6	46.2	6.0	3.0	24.1	212.1	11.1	18.1	1.0	125.6	1005
All sediments	757.3	10.2	185.4	69.3	14.5	4.5	45.0	335.9	18.3	31.8	1.8	228.0	1702
Weight percent													
Deep oceanic	28.5	0.4	8.1	5.0	------	0.6	1.8	30.5	0.8	1.2	0.2	22.9	100
Continental shield	60.6	.4	8.9	2.4	1.2	------	2.9	10.6	.8	2.1	.1	10.0	100
Young folded belts	51.9	.5	11.4	2.6	2.0	------	3.8	12.6	1.3	2.4	.1	11.4	100
Suboceanic	43.2	.7	11.6	4.6	.6	.3	2.4	21.1	1.1	1.8	.1	12.5	100
All sediments	44.5	.6	10.9	4.0	.9	.3	2.6	19.7	1.1	1.9	.1	13.4	100

average composition of the shield sediment is computed by using a ratio of 41:43:16 of shale, sandstone and limestone, respectively, and by using the average analyses of these sediments (Clarke and Washington, 1924). Similarly, the average composition of sediment in the young folded-belts region is computed by using the ratios of 52, shale: 13, sandstone: 22, limestone: 5, graywacke: 6, andesite: 2, rhyolite. Because of the abundance of crystalline rocks at the surface in the folded-belts region, the volume of sediments is considered to be only 60 percent of the upper 5-km-thick shell in this region.

Most of the continental crust consists of crystalline rocks which are generally agreed to be more silicic at the surface than at depth. An average composition for shield crystalline rocks is derived by averaging (1) the averages for the Finnish Precambrian (probably too silicic; Sederholm, 1925) and the Canadian Precambrian (probably too mafic; Grout, 1938), (2) a mixture of quartzo-feldspathic gneiss and amphibolite in the proportions 5:1, (3) the average plutonic rock of Vogt (1931), and (4) Nockolds' (1954) average granodiorite. From the assumption that the crust is in isostatic adjustment, materials of increasing density and mafic composition are assumed in depth to the Mohorovičić discontinuity. According to Poldervaart's schematic cross section, the average composition and approximate thicknesses are—granodiorite, 22 km; diorite, 3 km; and basalt, 10.5 km. Presumably the basalt includes both tholeiitic and olivine-bearing types, but their relative proportions are not given.

The young folded-belts region contains material with average composition and thickness as estimated from Poldervaart's schematic section: granodiorite, 22.5 km; diorite, 2.7 km; and basalt, 7.3 km (both tholeiite and olivine basalt, but not specified as to relative proportions). Also 40 percent of the 5-km-thick surface layer is considered granodioritic, according to the abundance of surface outcrops of such batholithic rocks. Included with the continental crust are volcanic islands of the oceanic regions totaling about 2×10^6 km^2 in area and considered to consist of 4 km andesite, 4½ km tholeiitic basalt, and 6 km olivine basalt.

The composition of the whole lithosphere in terms of the major elements is summarized in table 15.

Pakiser and Robinson (1967) divided the conterminous United States into 10 regions on the basis of seismic structure and further grouped 7 western and 3 eastern regions into a western and an eastern superprovince. Two distinct layers of the crust were distinguished from seismic velocity data (upper layer, 5.8–6.4 km per sec; lower layer, generally 6.7–7.5 km per sec) and formed the basis for computation of the volume of the crust under the regions and superprovinces. Seismic velocities in the crust, correlated with rock composition from recent laboratory experiments, were found to be appropriate for rocks of mafic composition in the lower layer and for rocks of silicic composition in the upper layer, and rocks of these general compositions were assumed to constitute the crust. Using the average compositions of mafic and silicic rocks of Nockolds (1954), these authors computed the average composition of the crustal layers and the crust beneath the seismic regions, the superprovinces and the entire conterminous United States. These computations are summarized in tables 16 and 17.

The average composition of the crust computed by Pakiser and Robinson is similar to that computed by Poldervaart; although the former authors found the Western superprovince slightly more siliceous than the analogous crust of Poldervaart (young folded-belts region) and found the Eastern superprovince to be more mafic than his continental shields region. These differences arise from new seismic results showing that the crust is thinner and more silicic in tectonically active regions than in stable regions, rather than the reverse relation as assumed by Poldervaart.

TABLE 15.—*Composition of the lithosphere*

[Modified from Poldervaart (1955, table 20)]

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Percent
Mass composition ($\times 10^{15}$ tons)													
Sediments	757.3	10.2	185.4	69.3	14.5	4.5	45.0	335.9	18.3	31.8	1.8	1,474	6.2
Granodiorite [1]	4,141.5	37.4	966.7	112.3	174.6	6.2	124.7	237.0	218.3	205.8	12.5	6,237	26.3
Granodiorite [2]	1,765.9	19.8	450.0	84.9	93.4	5.7	84.9	144.3	96.2	76.4	8.5	2,830	12.0
Andesite	12.5	.3	4.0	.8	1.3	------	1.0	1.8	.9	.3	.1	23	------
Diorite	1,182.7	33.9	372.4	60.9	158.0	4.5	137.7	191.8	76.7	29.4	9.0	2,257	9.6
Tholeiite	1,342.7	36.8	410.7	28.9	258.1	5.3	184.4	276.5	57.9	26.3	5.4	2,633	11.1
Olivine basalt	3,851.4	246.4	1,240.0	303.9	681.6	16.4	656.9	895.1	213.5	82.1	24.7	8,212	34.8
Lithosphere	13,054.0	384.8	3,629.2	661.0	1,381.5	42.6	1,234.6	2,082.4	681.8	452.1	62.0	23,666	100.0
Weight percent													
Oceanic region	46.6	2.9	15.0	3.8	8.0	0.2	7.8	11.9	2.5	1.0	0.3		
Suboceanic region	49.4	1.9	15.1	3.4	6.4	.2	6.2	13.2	2.5	1.3	.3		
Young folded-belts region	58.4	1.1	15.6	2.8	4.8	.2	4.3	7.2	3.1	2.2	.3		
Continental shield region	59.8	1.2	15.5	2.1	5.1	.1	4.1	6.4	3.1	2.4	.2		
Lithosphere	55.2	1.6	15.3	2.8	5.8	.2	5.2	8.8	2.9	1.9	.3		
Continental crust—average-young folded-belts and continental shield regions	59.4	1.2	15.6	2.3	5.0	.1	4.2	6.6	3.1	2.3	.2		

[1] Continental shield region.
[2] Young folded-belts region.

MINOR ELEMENTS

The minor elements form a relatively insignificant proportion of the earth's crust when compared to the major elements. This fact is well illustrated in table 18 in which the 25 most abundant elements are listed in terms of their weight percentages in the crust. Accordingly, the 10 most abundant elements comprise 99.17 percent of the crust, whereas the 15 next most abundant elements make up only 0.556 percent. Thus an even smaller percentage remains for the 67 other elements. Relative abundances of the elements, in which the magnitude of abundance is plotted against atomic number, are shown graphically in figure 3.

The abundance of some minor elements is well known from much work on specific rocks and groups of rocks during the last 20 years; however, the abundance of others is still poorly known. Abundance tables based on these data are, therefore, variable as to accuracy and completeness among these elements listed, and such tables are being revised constantly as modern data are accumulated. Many recent studies of the abundances of specific elements are reviewed and cited in the summaries of Turekian and Wedepohl (1961), Vinogradov (1962), and Taylor (1964) and need not be discussed further here. The abundance of elements, both minor and major, in various igneous and sedimentary rocks listed in the tables of Turekian and Wedepohl (1961) and Vinogradov (1962) are assembled in table 19.

TABLE 16.—*Proportions of major crustal units*

[Computed by Pakiser and Robinson (1967)]

Region	Area (km^2 x 10^{-4})	Silicic crust		Mafic crust		Total crust	Mafic rocks	
		Thickness (km)	Volume (km^3 x 10^{-4})	Thickness (km)	Volume (km^3 x 10^{-4})	Volume (km^3 x 10^{-4})	Volume percent	Weight percent [1]
Western superprovince								
California coastal region	43	15	645	5	215	860	25.0	26.3
Sierra Nevada	7	25	175	25	175	350	50.0	51.7
Pacific Northwest coastal region	29	10	290	25	725	1,015	71.4	72.8
Columbia Plateaus	30	10	300	35	1,050	1,350	77.7	78.8
Basin and Range province	121	20	2,420	10	1,210	3,630	33.3	34.8
Colorado Plateaus	34	25	850	15	510	1,360	37.5	39.1
Rocky Mountains	61	25	1,525	15	915	2,440	37.5	39.1
Subtotal	325		6,205		4,800	11,005		
Average		[2]19		[2]15			43.6	45.3
Eastern superprovince								
Interior Plains and Highlands	358	20	7,160	30	10,740	17,900	60.0	61.6
Coastal Plain	154	20	3,080	15	2,310	5,390	42.8	44.4
Appalachian Highlands and Superior Upland	162	15	2,430	25	4,050	6,480	62.5	64.2
Subtotal	674		12,670		17,100	29,770		
Average		[2]19		[2]25			57.4	59.2
Continental crust, conterminous United States:								
Total	999		18,875		21,900	40,775		
Average		[2]19		[2]22			53.7	55.4

[1] Average weight percent of mafic rocks based on average densities of 2.8 g per cm^3 and 3.0 g per cm^3 for silicic crust and mafic crust, respectively.

[2] Average thicknesses of total crust:
Western superprovince, 34 km;
Eastern superprovince, 44 km.
All regions, 41 km.

TABLE 17.—*Estimates of abundance of major oxides in continental crust, by Pakiser and Robinson, and other estimates for comparison*

Oxides	Pakiser and Robinson (1967)					Other estimates			
	Silicic rocks [1]	Mafic rocks [1]	Western superprovince [2]	Eastern superprovince [2]	Continental crust [2]	Continental crust [3]	Continental crust [4]	Young folded belts [5]	Continental shield [5]
SiO_2	69.3	48.8	60.0	57.1	57.9	60.3	63.1	58.4	59.8
TiO_2	0.5	1.8	1.1	1.3	1.2	1.0	0.8	1.1	1.2
Al_2O_3	14.6	15.6	15.1	15.2	15.2	15.6	15.2	15.6	15.5
Fe_2O_3	1.7	2.8	2.3	2.3	2.3	([6])	([6])	2.8	2.1
FeO	2.2	8.2	4.9	5.7	5.5	[6]7.2	[6]6.0	4.8	5.1
MnO	0.1	0.2	0.1	0.2	0.2	[7]0.1	[7]0.1	0.2	0.1
MgO	1.1	8.7	4.5	5.6	5.3	3.9	3.1	4.3	4.1
CaO	2.6	10.8	6.3	7.5	7.1	5.8	4.1	7.2	6.4
Na_2O	3.9	2.3	3.2	3.0	3.0	3.2	3.4	3.1	3.1
K_2O	3.8	0.7	2.4	2.0	2.1	2.5	3.0	2.2	2.4
P_2O_5	0.2	0.3	0.2	0.3	0.3	[7]0.2	[7]0.2	0.3	0.2
Total	100.0	100.2	100.1	100.2	100.1	99.8	99.0	100.0	100.0

[1] Nockolds' (1954) averages of 794 silicic igneous rocks and 637 mafic igneous rocks.

[2] Based on weight percent of mafic crust from Pakiser and Robinson (1967) and Nockolds' (1954) averages.

[3] Taylor's (1964) averages based on 1 part mafic and 1 part silicic rocks.

[4] Vinogradov's (1962) averages based on 1 part mafic and 2 parts silicic rocks.

[5] Poldervaart's (1955) averages based on assumed crustal models.

[6] Total Fe expressed as FeO.

[7] Estimated to complete table.

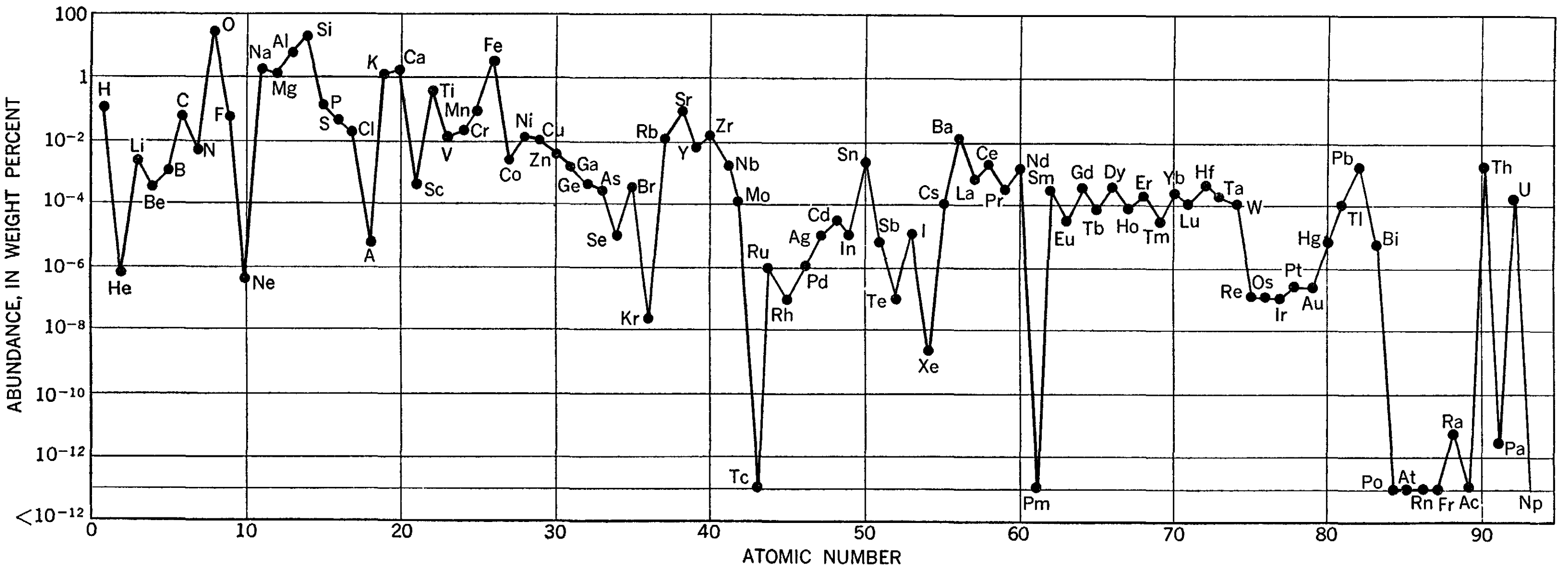

FIGURE 3.—Crustal abundance of elements of atomic numbers 1–93. Modified from Fleischer (1953, figs. 1 and 2).

TABLE 18.—*Weight percentages of 25 of the most abundant elements of the earth's crust*

[Data from Mason (1958, p. 44)]

Rank	Element	Weight percent	Rank	Element	Weight percent
1.	Oxygen	46.60	14.	Sulfur	.052
2.	Silicon	27.72	15.	Strontium	.045
3.	Aluminum	8.13	16.	Barium	.040
4.	Iron	5.00	17.	Carbon	.032
5.	Calcium	3.63	18.	Chlorine	.020
6.	Sodium	2.83	19.	Chromium	.020
7.	Potassium	2.59	20.	Zirconium	.016
8.	Magnesium	2.09	21.	Rubidium	.012
9.	Titanium	.44	22.	Vanadium	.011
10.	Hydrogen	.14	23.	Nickel	.008
			24.	Zinc	.007
	Total of first 10	99.17	25.	Nitrogen	.005
11.	Phosphorus	.118			
12.	Manganese	.100		Total of all 25	99.726
13.	Fluorine	.070			

Estimates of the abundance of minor elements in the earth's crust have been compiled by different authors for many years. Some of the principal works that serve to show the accumulation of data and improvements in their accuracy and completeness are Clarke and Washington (1924), Goldschmidt (1937), Fleischer (1953), Rankama (1954), Mason (1952, 1958), Vinogradov (1962), and Taylor (1964). Tabulations by these authors for the abundance of elements in the crust, or parts thereof, are assembled in table 20.

TABLE 19.—*Abundance of elements in certain types of rocks*

[T and W, data from Turekian and Wedepohl (1961); V, data from Vinogradov (1962)]

Percent	*Code*
1 -9	X
.1 - .9	.X
.01 - .09	.0X
.001- .009	.00X

Atomic No.	Element	Ultramafic rocks		Basalts		Intermediate rocks (V)	Felsic granites and granodiorites (V)	Granites (T and W)		Syenites (T and W)	Clays and shales (V)	Shales (T and W)	Sandstones (T and W)	Carbonate rocks (T and W)	Deep-sea carbonate rocks (T and W)	Deep-sea clays (T and W)
		(T and W)	(V)	(T and W)	(V)			High calcium	Low calcium							
							Weight percent									
1	Hydrogen	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
8	Oxygen	---	42.5	---	43.5	46	48.7	---	---	---	52.8	---	---	---	---	---
11	Sodium	.42	.57	1.80	1.94	3	2.77	2.84	2.58	4.04	.66	.96	.33	.04	2	4
12	Magnesium	20.40	25.90	4.60	4.5	2.18	.56	.94	.16	.58	1.34	1.50	.70	4.70	.40	2.10
13	Aluminum	2	.45	7.80	8.76	8.85	7.7	8.20	7.20	8.80	10.45	8	2.50	.42	2	8.40
14	Silicon	20.50	19	23	24	26	32.3	31.40	34.70	29.10	23.8	7.30	36.80	2.40	3.20	25
15	Phosphorus	.022	.017	.11	.14	.16	.07	.092	.06	.08	.077	.07	.017	.04	.035	.15
19	Potassium	.004	.03	.83	.83	2.3	3.34	2.52	4.20	4.80	2.28	2.66	1.07	.27	.29	2.50
20	Calcium	2.5	.7	7.6	6.72	4.65	1.58	2.53	.51	1.80	2.53	2.21	3.91	30.23	31.24	2.90
22	Titanium	.03	.03	1.38	.9	.8	.23	.34	.12	.35	.45	.46	.15	.04	.077	.46
25	Manganese	.162	.15	.15	.2	.12	.06	.054	.039	.085	.067	.085	.00X	.11	.10	.67
26	Iron	9.43	9.85	8.65	8.56	5.85	2.7	2.96	1.42	3.67	3.33	4.72	.98	.38	.90	6.50
							Parts per million									
2	Helium	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
3	Lithium	.X	.5	17	15	20	40	24	40	28	60	66	15	5	5	57
4	Beryllium	.X	.2	1	.4	1.8	5.5	2	3	1	3	3	.X	.X	.X	2.6
5	Boron	3	1	5	5	15	15	9	10	9	100	100	35	20	55	230
6	Carbon	---	100	---	100	200	300	---	---	---	10000	---	---	---	---	---
7	Nitrogen	6	6	20	18	22	20	20	20	30	600	---	---	---	---	---
9	Fluorine	100	100	400	370	500	800	520	850	1200	500	740	270	330	540	1300
10	Neon	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
16	Sulfur	300	100	300	300	200	400	300	300	300	3000	2400	240	1200	1300	1300
17	Chlorine	85	50	60	50	100	240	130	200	520	160	180	10	150	21000	21000
18	Argon	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
21	Scandium	15	5	30	24	2.5	3	14	7	3	10	13	1	1	2	19
23	Vanadium	40	40	250	200	100	40	88	44	30	130	130	20	20	20	120
24	Chromium	1600	2000	170	200	50	25	22	4.1	2	100	90	35	11	11	90
27	Cobalt	150	200	48	45	10	5	7	1	1	20	19	.3	.1	7	74
28	Nickel	2000	2000	130	160	55	8	15	4.5	4	95	68	2	20	30	225
29	Copper	10	20	87	100	35	20	30	10	5	57	45	X	4	30	250
30	Zinc	50	30	105	130	72	60	60	39	130	80	95	16	20	35	165
31	Gallium	1.5	2	17	18	20	20	17	17	30	30	19	12	4	13	20
32	Germanium	1.5	1	1.3	1.5	1.5	1.4	1.3	1.3	1	2	1.6	.8	.2	.2	2
33	Arsenic	1	.5	2	2	2.4	1.5	1.9	1.5	1.4	6.6	13	1	1	1	13
34	Selenium	.05	.05	.05	.05	.05	.05	.05	.05	.05	.6	.6	.05	.08	.17	.17
35	Bromine	1	.5	3.6	3	4.5	1.7	4.5	1.3	2.7	6	4	1	6.2	70	70
36	Krypton	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
37	Rubidium	.2	2	30	45	100	200	110	170	110	200	140	60	3	10	100
38	Strontium	1	10	465	440	800	300	440	100	200	450	300	20	610	2000	180
39	Yttrium	.X	---	21	20	---	34	35	40	20	30	26	40	30	42	90
40	Zirconium	45	30	140	100	260	200	140	175	500	200	160	220	19	20	150
41	Niobium	16	1	19	20	20	20	20	21	35	20	11	.0X	.3	4.6	14
42	Molybdenum	.3	.2	1.5	1.4	.9	1	1	1.3	.6	2	2.6	.2	.4	3	27
43	Technetium	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
44	Ruthenium	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
45	Rhodium	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
46	Palladium	.12	.12	.02	.019	---	.01	.00X	.00X	---	---	---	---	---	---	---
47	Silver	.06	.05	.11	.1	.07	.05	.051	.037	.0X	.1	.07	.0X	.0X	.0X	.11
48	Cadmium	.X	.05	.22	.19	---	.1	.13	.13	.13	.3	.3	.0X	.035	.0X	.42
49	Indium	.01	.013	.22	.22	---	.26	.0X	.26	.0X	.05	.1	.0X	.0X	.0X	.08
50	Tin	.5	.5	1.5	1.5	---	3	1.5	3	X	10	6	.X	.X	.X	1.5
51	Antimony	.1	.1	.2	1	.2	.26	.2	.2	.X	2	1.5	.0X	.2	.15	1
52	Tellurium	---	.001	---	.001	.001	.001	---	---	---	.01	---	---	---	---	---
53	Iodine	.5	.01	.5	.5	.3	.4	.5	.5	.5	1	2.2	1.7	1.2	.05	.05
54	Xenon	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

TABLE 19.—*Abundance of elements in certain types of rocks*—Continued

Atomic No.	Element	Ultramafic rocks		Basalts		Intermediate rocks (V)	Felsic granites and granodiorites (V)	Granites (T and W)		Syenites (T and W)	Clays and shales (V)	Shales (T and W)	Sandstones (T and W)	Carbonate rocks (T and W)	Deep-sea carbonate rocks (T and W)	Deep-sea clays (T and W)
		(T and W)	(V)	(T and W)	(V)			High calcium	Low calcium							
								Parts per million—Continued								
55	Cesium	.X	.1	1.1	1	-----	.5	2	4	.6	12	5	.X	.X	.4	6
56	Barium	.4	1	330	300	650	830	420	840	1600	800	580	X0	10	190	2300
57	Lanthanum	.X	-----	15	27	-----	60	45	55	70	40	92	30	X	10	115
58	Cerium	.X	-----	48	45	-----	100	81	92	161	50	59	92	11.5	35	345
59	Praseodymium	.X	-----	4.6	4	-----	12	7.7	8.8	15	5	5.6	8.8	1.1	3.3	33
60	Neodymium	.X	-----	20	20	-----	46	33	37	65	23	24	37	4.7	14	140
61	Promethium	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
62	Samarium	.X	-----	5.3	5	-----	9	8.8	10	18	6.5	6.4	10	1.3	3.8	38
63	Europium	.X	.01	.8	1	-----	1.5	1.4	1.6	2.8	1	1	1.6	.2	.6	6
64	Gadolinium	.X	-----	5.3	5	-----	9	8.8	10	18	6.5	6.4	10	1.3	3.8	38
65	Terbium	.X	-----	.8	.8	-----	2.5	1.4	1.6	2.8	.9	1	1.6	.2	.6	6
66	Dysprosium	.X	.05	3.8	2	-----	6.7	6.3	7.2	13	4.5	4.6	7.2	.9	2.7	27
67	Holmium	.X	-----	1.1	1	-----	2	1.8	2	3.5	1	1.2	2	.3	.8	7.5
68	Erbium	.X	-----	2.1	2	-----	4	3.5	4	7	2.5	2.5	4	.5	1.5	15
69	Thulium	.X	-----	.2	.2	-----	.3	.3	.3	.6	.25	.2	.3	.04	.1	1.2
70	Ytterbium	.X	-----	2.1	2	-----	4	3.5	4	7	3	2.6	4	.5	1.5	15
71	Lutetium	.X	-----	.6	.6	-----	1	1.1	1.2	2.1	.7	.7	1.2	.2	.5	4.5
72	Hafnium	.6	.1	2	1	1	1	2.3	3.9	11	6	2.8	3.9	.3	.41	4.1
73	Tantalum	1	.018	1.1	.48	.7	3.5	3.6	4.2	2.1	3.5	.8	.0X	.0X	.0X	.X
74	Tungsten	.77	.1	.7	1	1	1.5	1.3	2.2	1.3	2	1.8	1.5	.6	.X	X
75	Rhenium	-----	-----	-----	.00071	-----	.00067	-----	-----	-----	-----	-----	-----	-----	-----	-----
76	Osmium	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
77	Iridium	-----	-----	-----	-----	-----	.0063	-----	-----	-----	-----	-----	-----	-----	-----	-----
78	Platinum	-----	.2	-----	.1	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
79	Gold	.006	.005	.004	.004	-----	.0045	.004	.004	.00X	.001	.00X	.00X	.00X	.00X	.00X
80	Mercury	.0X	.01	.09	.09	-----	.08	.08	.08	.0X	.4	.4	.03	.04	.0X	.X
81	Thallium	.06	.01	.21	.2	.5	1.5	.72	2.3	1.4	1	1.4	.82	.0X	.16	.8
82	Lead	1	.1	6	8	15	20	15	19	12	20	20	7	9	9	80
83	Bismuth	-----	.001	.007	.007	.01	.01	-----	.01	-----	.01	-----	-----	-----	-----	-----
84	Polonium	-----	-----	-----	-----	.01	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
85	Astatine	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
86	Radon	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
87	Francium	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
88	Radium	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
89	Actinium	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
90	Thorium	.004	.005	4	3	7	18	8.5	17	13	11	12	1.7	1.7	X	7
91	Protactinium	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
92	Uranium	.001	.003	1	.5	1.8	3.5	3	3	3	3.2	3.7	.45	2.2	.X	1.3

PROBLEMS IN ESTIMATION OF ELEMENT ABUNDANCE

Some of the problems in the estimation of the abundance of elements, both in specific types of rocks and in the crust of the earth, are outlined by Fleischer and Chao (1960). These problems indicate some of the limitations and weaknesses imposed on abundance data, not only from the analytical standpoint, but from the standpoint of compilation and interpretation as well.

ABUNDANCE IN SPECIFIC ROCKS

The estimation of abundance in specific rock types is affected by the availability of analytical data, adequacy of sampling, and accuracy of results of analytical procedures. In recent years the analysis of rock samples for minor elements by X-ray fluorescence and optical spectrographic methods, in addition to routine analysis for the major elements, has added a wealth of data over the entire spectrum of rock compositions. Elements usually determined are barium, beryllium, cobalt, copper, chromium, gallium, molybdenum, nickel, lead, scandium, strontium, vanadium, and zirconium. In addition many analyses give data for silver, boron, lanthanum, lithium, niobium, rubidium, tin, yttrium, and ytterbium. Nevertheless, some elements in ordinary rocks exist below the threshold of detection by most analytical methods, and unless special preenrichment techniques or special analytical techniques are used, these elements are not determinable. Tantalum, indium, germanium, rhenium, and some platinum metals belong to this group. Some of these elements are amenable to detection by activation analyses of various types, but most laboratories at the present time do not have ready access to special isotope-activated instruments or atomic reactors. Such elements, because of analytical difficulty, are not determined routinely; therefore, far fewer analyses exist for these elements than for the more easily determined elements.

The adequacy of sampling varies from element to element and depends on the number of determinations, the scope of the sampling, the description of the samples, and the petrologic classification of the samples. Hundreds of determinations are available for elements such as zirconium and gallium, whereas few exist for such elements as tellurium and bismuth. Some elements have been adequately analyzed in only a few types of rocks and geographic areas, greatly limiting our knowledge of their occurrence and regional distribution. Some analyzed samples have been so incompletely described as to leave doubt as to the petrologic classification of the sample, or whether the sample is

TABLE 20.—*Abundance of elements in the earth's crust and in igneous rocks*

Percent	*Code*
1 -9	X
.1 -.9	.X
.01 -.09	.0X
.001 -.009	.00X
.0001 -.0009	.000X
.00001- .00009	.0000X

Atomic No.	Element	Continental crust [1]	Earth's crust [2]	Earth's crust	Igneous rocks		
		Taylor (1964)	Vinogradov (1962)	Mason (1958)	Rankama (1954)	Goldschmidt (1937)	Clarke and Washington (1924)
	Weight percent						
1	Hydrogen	---	---	0.14	---	---	0.13
8	Oxygen	46.4	47	46.6	46.6	46.6	46.59
11	Sodium	2.36	2.50	2.83	2.83	2.83	2.85
12	Magnesium	2.33	1.87	2.09	2.09	2.09	2.09
13	Aluminum	8.23	8.05	8.13	8.13	8.13	8.13
14	Silicon	28.15	29.5	27.72	27.72	27.72	27.72
15	Phosphorus	.105	.093	.118	.118	.08	.13
19	Potassium	2.09	2.5	2.59	2.59	2.59	2.60
20	Calcium	4.15	2.96	3.63	3.63	3.63	3.63
22	Titanium	.57	.45	.44	.44	.44	.63
25	Manganese	.095	.10	.10	.10	.10	.10
26	Iron	5.63	4.65	5	5	5	5.01
	Parts per million						
2	Helium	---	---	0.003	0.003	---	---
3	Lithium	20	32	30	22	65	40
4	Beryllium	2.8	3.8	2	2	6	10
5	Boron	10	12	3	3	3	10
6	Carbon	200	230	320	320	320	320
7	Nitrogen	20	19	46	46.3	---	---
9	Fluorine	625	660	700	700	300	300
10	Neon	---	---	---	.00007	---	---
16	Sulfur	260	470	520	520	520	520
17	Chlorine	130	170	200	314	480	480
18	Argon	---	---	.04	.04	---	X
21	Scandium	22	10	5	20	5	.X
23	Vanadium	135	90	110	150	150	170
24	Chromium	100	83	200	200	200	370
27	Cobalt	25	18	23	23	40	10
28	Nickel	75	58	80	80	100	200
29	Copper	55	47	45	55	100	100
30	Zinc	70	83	65	111	40	40
31	Gallium	15	19	15	16	15	.0000X
32	Germanium	1.5	1.4	2	7	7	.0000X
33	Arsenic	1.8	1.7	2	5	5	X
34	Selenium	.05	.05	.09	.09	.09	.0X
35	Bromine	2.5	2.1	3	1.62	---	X
36	Krypton	---	---	---	---	---	---
37	Rubidium	90	150	120	350	310	X
38	Strontium	375	340	450	220	150	190
39	Yttrium	33	29	40	28.1	28.1	[3]150
40	Zirconium	165	170	160	185	220	260
41	Niobium	20	20	24	24	20	[4]30
42	Molybdenum	1.5	1.1	1	2.5	1.5	X
43	Technetium	---	---	---	---	---	---
44	Ruthenium	---	---	.001	---	---	.0000X
	Parts per million—Continued						
45	Rhodium	---	---	.001	.001	.001	.0000X
46	Palladium	---	.013	.01	.01	.01	.0000X
47	Silver	.07	.07	.1	.1	.1	.0X
48	Cadmium	.2	.13	.2	.15	.5	.X
49	Indium	.1	.25	.1	.11	.1	.0000X
50	Tin	2	2.5	3	40	40	X
51	Antimony	.2	.5	.2	1(?)	1	.X
52	Tellurium	---	.001	.002	.0018(?)	.0018(?)	.00X
53	Iodine	.5	.4	.3	.3	.3	.X
54	Xenon	---	---	---	---	---	---
55	Cesium	3	3.7	1	6	7	.X
56	Barium	425	650	400	1000	250	500
57	Lanthanum	30	29	18	18.3	18.3	---
58	Cerium	60	70	46	46.1	46.1	---
59	Praseodymium	8.2	9	6	5.53	5.53	---
60	Neodymium	28	37	24	23.9	23.9	---
61	Promethium	---	---	---	---	---	---
62	Samarium	6	8	7	6.47	6.47	---
63	Europium	1.2	1.3	1	1.06	1.06	---
64	Gadolinium	5.4	8	6	6.36	6.36	---
65	Terbium	.9	4.3	.9	.91	.91	---
66	Dysprosium	3	5	5	4.47	4.47	---
67	Holmium	1.2	1.7	1	1.15	1.15	---
68	Erbium	2.8	3.3	3	2.47	2.47	---
69	Thulium	.48	.27	.2	.20	.20	---
70	Ytterbium	3	.33	3	2.66	2.66	---
71	Lutetium	.5	.8	.8	.75	.75	---
72	Hafnium	3	1	5	4.5	4.5	30
73	Tantalum	2	2.5	2	2.1	15(?)	---
74	Tungsten	1.5	1.3	1	1.5	69	50
75	Rhenium	---	.0007	.001	.05	.001	---
76	Osmium	---	---	.001	---	---	.000X
77	Iridium	---	---	.001	.001	.001	.000X
78	Platinum	---	---	.005	.005	.005	.00X
79	Gold	.004	.0043	.005	.005	.005	.00X
80	Mercury	.08	.083	.5	.077	.5	.X
81	Thallium	.45	1	1	1.3	.3	.000X
82	Lead	12.5	16	15	15	16	20
83	Bismuth	.17	.009	.2	.2	.2	.0X
84	Polonium	---	---	---	3×10^{-10}	3×10^{-10}	---
85	Astatine	---	---	---	---	---	---
86	Radon	---	---	---	---	---	---
87	Francium	---	---	---	---	---	---
88	Radium	---	---	---	1.3×10^{-6}	1.3×10^{-6}	$X\times10^{-6}$
89	Actinium	---	---	---	3×10^{-10}	3×10^{-10}	---
90	Thorium	9.6	13	10	11.5	12	20
91	Protactinium	---	---	---	8×10^{-7}	8×10^{-7}	---
92	Uranium	2.7	2.5	2	4	4	80

[1] Average 1 part mafic and 1 part felsic rocks.
[2] Average 1 part mafic and 2 parts felsic rocks.
[3] Yttrium plus cerium plus all other rare-earth elements.
[4] Niobium plus tantalum.

representative. Fortunately these undesirable trends are being stemmed in modern studies.

The accuracy of analyses is a factor that is difficult to assess. Some progress toward standardization among laboratories has been made by using standard samples. The fact that some laboratories produce analyses of high precision does not necessarily mean their analyses are of high accuracy, as has been pointed out by Ahrens (1957). Two rocks—granite G-1 from Westerly, R.I., and diabase W-1 from Centerville, Va.—were submitted to different laboratories to obtain comparative results (Fairbairn and others, 1951). The results showed serious disagreement among different laboratories, the disclosure of which has led to considerable improvement in techniques and accuracy. The results of analyses of these standards have been summarized by Ahrens and Fleischer (1960), Fleischer and Stevens (1962), and Fleischer (1965). Differences in the dependability of the analytical results are exemplified by data on zirconium and strontium, for which selected determinations by major laboratories are listed in table 21.

The results for zirconium are in close agreement, only 5 of 24 determinations falling outside the range 210±30 ppm. The results for strontium, however, are considerably divergent in the group done prior to 1951, and even those since 1954 range from 200 to 350 ppm. Such variations in determinations must be considered in establishing or interpreting abundance figures.

TABLE 21.—*Selected determinations of zirconium and strontium in granite G–1*

Year reported	Method used	Zirconium (ppm)	Strontium (ppm)	Name of laboratory
1951	Chemical	200	450	British Museum of Natural History, London.
	Spectrographic	280	250	Massachusetts Inst. Technology, Cambridge, Mass.
	do	200	900	Macauley Inst. Soil Research, Aberdeen, Scotland.
	do	190	120	U.S. Geol. Survey, Washington, D.C.
1954	do	----------	200	Great Britain Geol. Survey.
	do	180	280	Cambridge Univ., England.
	do	130	----------	McMaster Univ., Hamilton, Ontario.
1955	do	----------	225	Columbia Univ., New York.
	do	200	----------	U.S. Geol. Survey, Denver, Colo.
	Isotope dilution	----------	233	Massachusetts Inst. Technology, Cambridge, Mass.
1956	X-ray fluorescence.	220	----------	Queen's Univ., Kingston, Ontario.
	Spectrographic	----------	218	Columbia Univ., New York.
1957	Isotope dilution	----------	262	Columbia Univ., New York.
	do	----------	252	Atomic Energy Research Establishment, Harwell, England.
	Colorimetric	162	----------	Göttingen Univ., Germany.
	Fluorimetric	200	----------	Minnesota Univ., Minneapolis.
	Spectrographic	220	200	California Inst. Technology, Pasadena, Calif.
	do	200	----------	Indiana Geol. Survey, Bloomington, Ind.
	do	180	----------	Yale Univ., New Haven, Conn.
1958	do	190	----------	U.S. Geol. Survey, Denver, Colo.
	do	----------	250	McMaster Univ., Hamilton, Ontario.
	X-ray fluorescence.	213	----------	Div. Soils, Commonwealth Sci. and Indus. Research Organization, Adelaide, Australia.
1961	Spectrographic	233	----------	McMaster Univ., Hamilton, Ontario.
	do	230	300	Leeds Univ., England.
	do	250	350	Div. Coal Research, Commonwealth Sci. and Indus. Research Organization, Chatswood, Australia.
	Flame photometer.	----------	270	Vernadskii Inst., Moscow.
1963	do	----------	307	Bologna Univ., Italy.
	Spectrographic	210	262	Pennsylvania State Univ., University Park, Pa.
1964	do	185	250	Australian National Univ., Canberra, Australia.
	do	155	----------	Olso Univ., Norway.
	X-ray fluorescence.	220	265	Olso Univ., Norway.
1965	do	214	271	Oxford Univ., England.
	do	239	265	Durham Univ., England.

ABUNDANCE IN THE CRUST

An accurate estimate of the abundance of elements in the crust requires an accurate knowledge of the proportions of specific rock types, their spatial distribution, and accurate analytical data on the concentration of the elements in these rocks. The works of Poldervaart (1955) and Pakiser and Robinson (1967) have come closest to this ideal, but even these outstanding works are limited to the few major elements. Furthermore the accuracy of computations are limited by the inadequate(?) geologic and chemical data available. It should be pointed out, however, that the average composition computed by Clarke and Washington (1924) corresponds rather closely with those of Poldervaart and Pakiser and Robinson even though the validity of the method of computing crustal composition of Clarke and Washington has been the subject of considerable controversy and doubt.

Estimation of the abundance of some of the minor elements in the lithosphere is hampered not only by a lack of precise analytical data, but by the compilation methods that are employed as well. Many of these estimates are computed on the basis of ratios of certain minor elements to geochemically similar elements that are more easily determined analytically. Such ratios, however, for some elements have been shown to vary considerably among different rock types and comagmatic suites. Many abundance figures are established from averages of standard mafic and felsic rocks that are combined in various proportions to approximate the major element composition of the average crustal rock. The recent compilations by Vinogradov (1962) and Taylor (1964) are examples of this approach. Minor elements that are more or less uniformly distributed in the crust can be fairly accurately established by this method; however, those elements that are unequally distributed and are more abundant in or closely tied to certain types of rocks can be quite erroneously computed. Inasmuch as most of the standard rocks used for such computations are continental rocks, such averages cannot be truly said to represent the entire crust, including the more than half of the crust lying beneath the oceans.

Derivation of accurate crustal abundance figures for both major and minor elements is hampered by our limited knowledge of (1) the sediments and underlying rocks in the oceanic regions not exposed to direct observation, (2) the proportions of different rocks in the exposed areas of the earth, and especially (3) the actual distribution and composition of materials at depth in the crust. As the wealth of geologic data accumulates, our knowledge of these factors can be expected to improve. The constantly increasing coverage of geologic mapping affords data for determining volumetric distribution and proportion of rocks through geologic interpretation and projection. Accelerated research in oceanography and geophysics is adding measurably to the data on the nature of the vast areas beneath the oceans and at depths within the crust.

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