

THE GEOLOGICAL SOCIETY OF AMERICA, INC.

Memoir 97

Handbook of Physical Constants

Revised Edition

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Yale University, New Haven, Connecticut



PUBLISHED BY THE SOCIETY

1966

Copyright 1966, The Geological Society of America, Inc.
Library of Congress Catalog Card Number 66-19814

PUBLISHED BY
THE GEOLOGICAL SOCIETY OF AMERICA, INC.
231 East 46th Street, New York, New York 10017

Made in the United States of America

FOREWORD

In the "Handbook of Physical Constants," Special Paper Number 36, published by The Geological Society of America in 1942, the editors sought to compile for the first time a wide variety of physical constants needed for geological and geophysical calculations. The choices of data were necessarily arbitrary; the compilations were contributed by the labors of volunteers with little bibliographical assistance. Nevertheless, the usefulness of the Handbook has been demonstrated, both by the exhaustion of several editions and by many citations in subsequent literature.

For at least ten years, the desirability of a revised edition has been recognized: many sections are now badly out of date, and new kinds of measurements have appeared. As the amount of material has increased, however, so has the labor of dealing with it. A preliminary selection of chapters and compilers was drawn up in 1955, and a few manuscripts eventually appeared. It was apparent, however, that a vigorous effort was needed to push the work to completion, and Prof. Sydney P. Clark, Jr., agreed to assume the editorship. The present volume is the result.

A primary consideration has been brevity, on the assumption that a volume of moderate size would be most generally useful. The introductory sections of the chapters have consequently been kept to the minimum length consistent with clarity and usefulness. A critical attitude toward measurements has been encouraged by the inclusion, in many cases, of measurements of ostensibly the same physical property by different observers. Without this confrontation, the real uncertainties of measurements can seldom be judged, although grossly erroneous determinations may sometimes throw suspicion on better ones. The geologist is usually aware of the great possible variations of natural materials lumped in a single descriptive category, such as "shale," or "sandstone"; it is generally impossible to tabulate adequate descriptions of such materials, even when they are available in the original documents, and particular applications may require a return to the source for additional details.

Perhaps one of the most useful functions of such compilations is to draw attention to areas where more adequate data are needed. If a particular measurement cannot be found, it does not necessarily mean that it has never been made—the compiler may have missed a reference—but if a whole category of measurements is conspicuously undernourished, the fact will be evident. A plenitude of data in other categories may serve to discourage unnecessary repetition.

Prof. Clark and I wish to take this opportunity to express our gratitude to those who prepared or contributed to the individual sections. We are especially indebted to the editorial staff of The Geological Society of America for their care in preparing this difficult manuscript for publication, and to the Memoir Fund of The Geological Society of America which helped defray the cost of publication.

FRANCIS BIRCH

October 1965

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SECTION 1

COMPOSITION OF ROCKS

by SYDNEY P. CLARK, JR.

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This section deals mainly with petrological terminology and is intended primarily for the nongeologist. It is impossible to cover this subject adequately in a short space, and the reader is referred to standard textbooks on petrography for further details (1, 2, 3, 5). The problem of terminology is complicated by the fact that many samples which have been used for the determination of physical properties of rocks have come from quarries, and terms peculiar to quarrymen have crept into the literature. Since rocks are mixtures of different phases, they can, at least in principle, have a continuous range of composition and of physical properties. Any scheme of classification demands that this potentially continuous series be fitted into more or less distinct and arbitrary compartments.

Three main classes of rocks are recognized: igneous, metamorphic, and sedimentary. Igneous rocks are thought to be in large part the products of crystallization of a silicate melt. Sedimentary rocks result from deposition of material by wind or water at the earth's surface and its later solidification into rock. Metamorphic rocks result from the recrystallization of igneous or sedimentary rocks in the solid state at relatively high temperatures and pressures.

Much of the early effort of petrographers went into the classification of the igneous rocks. The result was a bewildering list of categories, most of which contained rocks of unusual compositions. Only the principal types of rock are mentioned here. The igneous rocks may be divided into plutonic and volcanic types. Plutonic rocks crystallized at depth in the earth and are characterized by relatively coarse grain size, low porosity, and low permeability. Volcanic rocks, which formed at the earth's surface, are commonly poorly aggregated, and some types, known as tuffs, may be very porous and friable. Volcanic rocks may also contain appreciable quantities of glass.

We turn first to the plutonic igneous rocks. *Granite* contains roughly equal amounts of quartz, sodic plagioclase, and potassium feldspar. Dark minerals (amphibole, biotite, or both) rarely exceed 10 per cent. In *diorites*, sodic plagioclase greatly predominates over potassium feldspar. Dark minerals (in most cases amphibole, although biotite is also found) may constitute up to 25 per cent of the rock. Little or no quartz is present. If quartz occurs as a major constituent of such a rock, the term *quartz diorite* or *granodiorite* is used. *Gabbro* consists almost entirely of calcic plagioclase and dark minerals (amphibole, pyroxene, or both). If either quartz or olivine is present in appreciable quantities the term *quartz gabbro* or *olivine gabbro* is used.

Diabase is a fine-grained rock consisting almost entirely of calcic plagioclase and pyroxene. Its composition may be similar to some gabbros. This type of rock occurs as dikes or sills, and it is usually relatively fine-grained. Ultramafic rocks have a low content of silica and are characterized by the almost complete absence of feldspar. *Pyroxenite* consists almost entirely of pyroxene. *Peridotites* are mixtures of pyroxene and olivine, and *dunites* are almost entirely olivine. Rocks consisting almost entirely of calcic plagioclase are termed *anorthosites*.

Only four types of volcanic rocks need be considered here. The more siliceous types, the rhyolites and dacites, tend to be largely glassy and commonly very porous. *Rhyolites* contain about 70 per cent silica and are mainly composed of glass with crystals of quartz, alkali feldspar, and in some cases sodic plagioclase. *Dacites* are less siliceous and more sodic than rhyolites, and crystals of pyroxene are commonly found in the glass. Basalts and andesites are considerably less siliceous than dacites and apparently were extruded at considerably higher temperatures. The resulting liquid is much more fluid and crystallizes more readily. *Basalts* invariably contain calcic plagioclase and pyroxene, and commonly also olivine, nepheline, or small amounts of quartz. *Andesites* are more siliceous than basalts and commonly contain amphibole. Glass is usually a

relatively minor constituent of basalts and andesites. All volcanic rocks may show considerable porosity, and this as well as the nature of the constituent minerals may influence the physical properties.

Table 1-1 gives average chemical compositions of these and some other types of igneous rocks. Figure 1-1 shows in a generalized way the variation in mineralogical constitution of igneous rocks. It must be realized that any particular rock of a given type may depart markedly from the indicated compositions, although many rocks are well represented in a general way by the diagram.

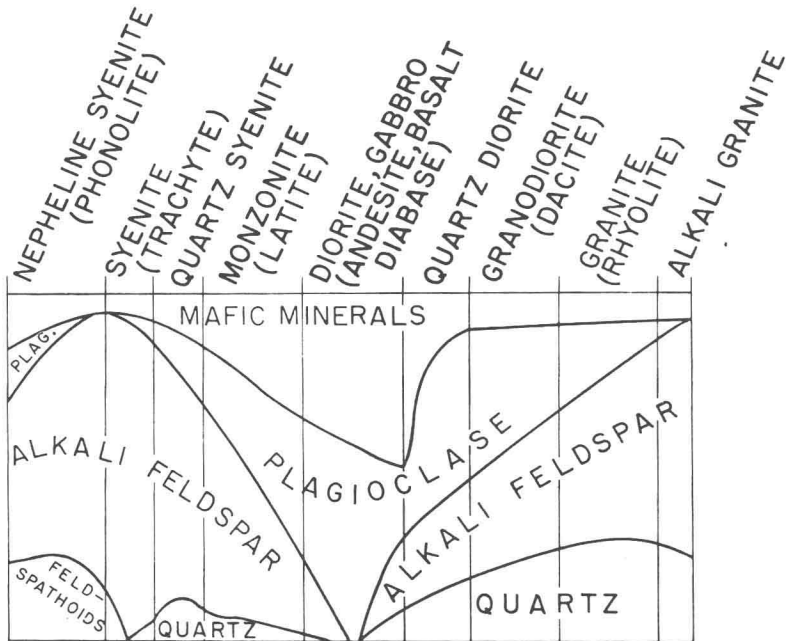


Figure 1-1. Generalized mineralogical constitutions of igneous rocks (after 4)

Sedimentary and metamorphic rocks have not been nearly as extensively studied by petrographers and have not been classified in as much detail as the igneous rocks.

Clastic sediments are commonly classified according to the median diameter of their constituent grains. The mineralogical composition of these materials proves to be fairly closely related to the median diameter. *Sandstones*, which form from coarse clastic sediments, are predominantly composed of quartz and feldspar, whereas *shales*, which form from the finest-grained sediments, contain important quantities of clay minerals as well. The grains comprising these types of rock were shaped by weathering, piled together, and then more or less tightly cemented. The result is that the rocks are relatively porous; this porosity is very important in influencing physical properties. The second important category of sedimentary rocks is that of the so-called chemical sediments. Examples are *limestone* (dominantly CaCO_3), *dolomite* (dominantly

TABLE 1-1. AVERAGE CHEMICAL ANALYSES OF CERTAIN TYPES OF PLUTONIC IGNEOUS ROCKS
(Totals reduced to 100.00)
(Compiled by R. A. Daly)

	Granite	Syenite	Granodiorite	Quartz diorite	Diorite	Gabbro	Olivine diorite	Diabase	Dunite	Lherzolite (peridotite)	Plateau basalt
	546	50	40	55	70	41	12	90	10	13	43
	Number of Analyses Averaged										
SiO ₂	70.18	60.19	65.01	61.59	56.77	48.24	48.54	50.48	40.49	43.95	48.80
TiO ₂	.39	.67	.57	.66	.84	.97	1.31	1.45	.02	.10	2.19
Al ₂ O ₃	14.47	16.28	15.94	16.21	16.67	17.88	15.24	15.34	.86	4.82	13.98
Fe ₂ O ₃	1.57	2.74	1.74	2.54	3.16	3.16	3.06	3.84	2.84	2.20	3.59
FeO	1.78	3.28	2.65	3.77	4.40	5.95	8.88	7.78	5.54	6.34	9.78
MnO	.12	.14	.07	.10	.13	.13	.21	.20	.16	.19	.17
MgO	.88	2.49	1.91	2.80	4.17	7.51	8.08	5.79	46.32	36.81	6.70
CaO	1.99	4.30	4.42	5.38	6.74	10.99	9.38	8.94	.70	3.57	9.38
Na ₂ O	3.48	3.98	3.70	3.37	3.39	2.55	2.69	3.07	.10	.63	2.59
K ₂ O	4.11	4.49	2.75	2.10	2.12	.89	.98	.97	.04	.21	.69
H ₂ O*	.84	1.16	1.04	1.22	1.36	1.45	1.35	1.89	2.88	1.08	1.80
P ₂ O ₅	.19	.28	.20	.26	.25	.28	.28	.25	.05	.10	.33

* Since most of the analysts neglected the effect of the adsorption of water by their specimens when pulverized, the proportion given for this oxide is in general somewhat too high. On the whole, about three fourths of the total water indicated was driven off at temperatures no higher than 105° C.

$\text{CaMg}(\text{CO}_3)_2$, and *rock salt* (NaCl). These rocks were laid down under water by chemical or biochemical agencies. They tend to be dense and of low porosity, and in this respect resemble the metamorphic and igneous rocks.

Metamorphic rocks result from the recrystallization of pre-existing sedimentary and igneous rocks. They are reconstituted essentially in the solid state, perhaps with the aid of interstitial aqueous fluids. Changes in the bulk composition of the rock may be caused by metamorphism. The most conspicuous is the dehydration of the rock as higher grades of metamorphism are attained. Metamorphic rocks are generally of low porosity and permeability, and hence their physical properties are mainly determined by the properties of the constituent minerals. They are commonly anisotropic owing to a foliation which is caused by parallel arrangement of plates of micas and by planar orientation of rodlike minerals, such as amphiboles. The principal types of metamorphic rocks are *gneisses* and *schists*. They are distinguished by their content of micaceous minerals: gneisses commonly contain less than about 15 per cent, and schists have more than 15 per cent. *Gneisses* may be formed from a variety of rocks, such as granites, rhyolites, and impure sandstones. *Schists* result mainly from the metamorphism of shales. *Slate* is intermediate between shale and schist. The names applied to gneisses and schists may be modified by the names of prominent minerals, as for example hornblende gneiss, or quartz-mica schist.

An *amphibolite* is a metamorphic rock consisting mainly of amphibole with subordinate plagioclase. It is thought to result from the metamorphism of basalt. *Quartzite* results from the metamorphism of sandstone, *marble* from the metamorphism of limestone or dolomite. *Eclogite* is a dense rock consisting mainly of a pink garnet rich in CaO and MgO and a green pyroxene containing Na_2O and Al_2O_3 . Most eclogites also contain minor amounts of biotite and amphibole.

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SECTION 2

ABUNDANCES OF THE ELEMENTS

by A. G. W. CAMERON

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Table 2-1. Compilations of abundances

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Table 2-1 contains a compilation of abundances of the elements derived from various sources. The basic purpose behind most of these determinations of abundances has been to attempt to find the over-all composition of the solar system. Some of the volatile elements can be found from the solar spectrum; others must be determined from the spectra of type-B stars, which are believed to be similar in composition to the sun. Some of the nonvolatile elements can also be determined from the solar spectrum, usually with rather low accuracy. Commonly the relative abundances of these elements are better determined from chondritic meteorites, in which not much fractionation of the nonvolatile elements appears to have taken place. Elements in the earth's crust seem to have been fractionated and concentrated to such an extent that it is exceedingly difficult to determine the average abundances and virtually impossible to draw any useful conclusions about the unfractionated abundances, except in a few cases. Meteorites other than chondrites, and certain peculiar classes of stars, may have very different compositions from those listed in Table 2-1.

TABLE 2-1. COMPILATIONS OF ABUNDANCES

Atomic no.	.. Element	Suess- Urey	Cameron	Clayton- Fowler	Chondrites	Sun	B stars
1	H	4.00×10^{10}	3.2×10^{10}	..	..	3.2×10^{10}	3.6×10^{10}
2	He	3.08×10^9	2.6×10^9	..	..	..	5.7×10^9
3	Li	100	38	..	38	..29	..
4	Be	20	7	..	.64*	7.2	..
5	B	24	6	..	..	..	..
6	C	3.5×10^6	1.66×10^7	..	..	1.66×10^7	7.1×10^6
7	N	6.6×10^6	3.0×10^6	..	..	3.0×10^6	5.4×10^6
8	O	2.15×10^7	2.9×10^7	..	..	2.9×10^7	2.1×10^7
9	F	1600	$\sim 10^3$	..	..	..	1.2×10^5
10	Ne	8.6×10^6	2.9×10^6	..	..	..	1.9×10^7
11	Na	4.38×10^4	4.18×10^4	..	..	6.3×10^4	..
12	Mg	9.12×10^4	1.046×10^6	..	..	7.9×10^5	3.1×10^6
13	Al	9.48×10^4	8.93×10^4	..	..	5.0×10^4	5.8×10^4
14	Si	1.00×10^6	1.00×10^6	..	..	1.00×10^6	1.00×10^6
15	P	1.00×10^4	9320	..	..	6900	1.08×10^4
16	S	3.75×10^5	6.0×10^5	..	..	6.3×10^5	1.08×10^6
17	Cl	8850	1836	..	..	..	5.8×10^4
18	Ar	1.5×10^5	2.4×10^5	..	..	..	2.9×10^5
19	K	3160	2970	..	3290	1580	..
20	Ca	4.90×10^4	7.28×10^4	..	4.5×10^4	4.5×10^4	..
21	Sc	28	29	..	32	21	..
22	Ti	2440	3140	..	2090	1510	..
23	V	220	590	..	..	158	..
24	Cr	7800	1.20×10^4	..	6400	5000	..
25	Mn	6850	6320	..	7200	2500	..
26	Fe	6.00×10^5	8.50×10^4	..	..	1.17×10^5	..
27	Co	1800	750	..	1190	1380	..
28	Ni	2.74×10^4	1.5×10^4	..	2.48×10^4	2.6×10^4	..
29	Cu	212	39	316	186	3500	..
30	Zn	486	202	360	..	800	..
31	Ga	11.4	9.05	32	..	7.2	..
32	Ge	50.5	134	49.1	18.7	62	..
33	As	4.0	4.4	2.18	..	..	..
34	Se	67.6	18.8	30.9	18.8	..	..
35	Br	13.4	3.95	6.9	..	..	..
36	Kr	51.3	20	17.9	..	..	..
37	Rb	6.5	5.0	4.24	4.6-5.8	9.5	..
38	Sr	18.9	21	17.55	..	13.5	..
39	Y	8.9	3.6	11.35	..	5.6	..
40	Zr	54.5	23	39.8	..	54	..
41	Nb	1.00	.81	3.5	..	2.8	..
42	Mo	2.42	2.42	2.77	..	2.5	..

TABLE 2-1. *Continued*

Atomic no.	Element	Suess-Urey	Cameron	Clayton-Fowler	Chondrites	Sun	B stars
44	Ru	1.49	1.58	.83	1.3†	.93	
45	Rh	.214	.26	.13	.27	.19	
46	Pd	.675	1.00	.601	..	.51	
47	Ag	.26	.26	.166	.131	.044	
48	Cd	.89	.89	.804	..	.91	
49	In	.11	.11	.071	.0013	.46	
50	Sn	1.33	1.33	1.88	..	1.10	
51	Sb	.246	.15	.091	..	2.8	
52	Te	4.67	3.00	1.86	.5-2**	..	
53	I	.80	.46	.21	.02-.3**	..	
54	Xe	4.0	3.15	2.61	..	..
55	Cs	.456	.25	.13	.10, .14	..	
56	Ba	3.66	4.0	3.68	3.96, 6.44	4.0	
57	La	2.00	.38	.70	.40	..	
58	Ce	2.26	1.08	1.17	.62	..	
59	Pr	.40	.16	.176	.15	..	
60	Nd	1.44	.69	.777	.74	..	
62	Sm	.664	.24	.595	.25	..	
63	Eu	.187	.083	.149	.078, .097	..	
64	Gd	.684	.33	.410	.36	..	
65	Tb	.0956	.054	.083	.056	..	
66	Dy	.556	.33	.449	.39	..	
67	Ho	.118	.076	.084	.078	..	
68	Er	.316	.21	.359	.21	..	
69	Tm	.0318	.032	.060	.039	..	
70	Yb	.220	.18	.387	.19	1.07	
71	Lu	.050	.031	.035	.036	..	
72	Hf	.438	.16	.236	..	..
73	Ta	.065	.021	.030	.017, .019	..	
74	W	.49	.11	.184	.11	..	
75	Re	.135	.054	.052	..	..
76	Os	1.00	.73	.511	.73†	..	
77	Ir	.821	.500	.39	.38	..	
78	Pt	1.625	1.157	.80	..	..
79	Au	.145	.13	.13	.13	..	
80	Hg	.284	.27	.62	.04-8.4	..	
81	Tl	.108	.11	.74	$(3.8-10) \times 10^{-4}$..	
82	Pb	.47	2.2	6.5	.05-.28	2.5††	
83	Bi	.144	.14	.92	.0016	..	
90	Th	..	.069	..	.026	..	
92	U	..	.042	..	$(7.2-7.9) \times 10^{-8}$..	

* Sill and Willis, *Geochim. Cosmochim. Acta*, **26**, 1209, 1962.

† Bate and Huizenga, *Geochim. Cosmochim. Acta*, **27**, 345, 1963

** Goles and Anders, *Jour. Geophys. Res.*, **66**, 3075, 1961

†† Helliwell, 1961, *Astrophys. Jour.*, **133**, 566, 1961

The first two columns of Table 2-1 contain the atomic number and symbol of the naturally occurring elements. The following paragraphs describe the nature of the abundance information in the remaining columns of the table.

Column three gives the Suess-Urey (1) compilation of abundances. This represents an important pioneering attempt to reconcile astronomical abundance information with abundance analyses of the chondritic meteorites, on the assumption that chondritic meteorites are good samples of solar system nonvolatile material. The results of meteoritic abundance analyses available by 1955 were adjusted by Suess and Urey to give smooth variations in the abundances of the nuclides of odd mass number. The abundance compilation is, therefore, best termed a semiempirical one. This compilation

was of very great importance to nuclear physicists when they attempted to deduce the types of nuclear reactions that had been responsible for the synthesis of the elements.

The fourth column of Table 2-1 gives the abundance compilation of Cameron (2). This compilation represents a re-adjustment of that of Suess and Urey, intended to take into account some additional astronomical and meteoritic abundance data and to readjust the abundances of the heavier elements on the basis of specific theories of individual mechanisms of nucleosynthesis.

The fifth column of Table 2-1 lists the abundances of the heavy elements predicted by Clayton and Fowler (3) from an analysis of the formation of heavy elements by the processes of neutron capture on both slow and fast time scales in stellar interiors. These authors emphasize that many of the predicted values are very uncertain.

Column six of Table 2-1 contains new abundance analyses of chondritic meteorites that have been carried out since the compilation of Suess and Urey. Except where noted, these abundances have been taken from the compilation of Ehmann (4). Most of the values usually represent an average of several analyses; in some cases, averages obtained by different analysts are given, separated by a comma; in other cases, where there is a wide variation in the abundances in different chondrites, the range of these values is given. Most of the abundances have been determined by radiochemical analysis and are subject to considerably greater error and intrinsic variation than is indicated by the significant figures that are listed.

The seventh column of Table 2-1 gives a compilation of abundances in the sun, as deduced at the University of Michigan by analysis of the solar spectrum by a method of model atmospheres, and summarized by Aller (5). Some of these abundance values are subject to very great error, owing to some considerable remaining uncertainties in the oscillator strengths of many of the elements. The abundance value given for lead comes from a recent calculation of the oscillator strength of one of the lines in that element by Helliwell (6).

Similar analyses for abundances of the lighter elements in B stars, also summarized by Aller (5), are given in the last column of Table 2-1.

Inspection of Table 2-1 shows that very great uncertainties exist in the relative abundances of many of the elements. It may also be seen that for many elements, such as indium, thallium, lead, and bismuth, the abundance levels in the chondrites are very much lower than would be expected on the basis of nucleosynthesis and on the basis of the solar analyses. The reasons for some of these discrepancies are not at present understood. A great deal of research in many fields remains to be done to improve our knowledge of elemental abundances.

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SECTION 3

ISOTOPIC ABUNDANCES AND 1961 ATOMIC WEIGHTS

by SYDNEY P. CLARK, JR.

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Isotopic abundances have been taken from the compilation by Strominger, Hollander, and Seaborg (Revs. Modern Physics, **30**, 585, 1958). Their values have been rounded to the nearest 0.1 per cent, except in cases of very rare isotopes. The natural isotopic variation may exceed this. Atomic weights are on the carbon-12 scale.

TABLE 3-1. ISOTOPIC ABUNDANCES AND ATOMIC WEIGHTS

Atomic no.	Symbol	Mass no.	Abundance (per cent)	1961 Atomic weight
1	H	1	99.99	1.00797
		2	.01	
2	He	3	10^{-4} – 10^{-5}	4.0026
		4	100	
3	Li	6	7.4	6.939
		7	92.6	
4	Be	9	100	9.0133
5	B	10	~19	10.811
		11	~81	
6	C	12	98.9	12.01115
		13	1.1	
7	N	14	99.6	14.0067
		15	.4	
8	O	16	99.8	15.9994
		17	.04	
		18	.2	
9	F	19	100	18.9984
10	Ne	20	90.9	20.183
		21	.3	
		22	8.8	
11	Na	23	100	22.9898
12	Mg	24	78.8	24.312
		25	10.2	
		26	11.1	
13	Al	27	100	26.9815
14	Si	28	92.2	28.086
		29	4.7	
		30	3.1	
15	P	31	100	30.9738
16	S	32	95.0	32.064
		33	.8	
		34	4.2	
		36	.02	
17	Cl	35	75.5	35.453
		37	24.5	
18	A	36	.3	39.948
		38	.06	
		40	99.6	
19	K	39	93.1	39.102
		40	.01	
		41	6.9	
20	Ca	40	97.0	40.08
		42	.6	
		43	.1	
		44	2.1	
		46	.003	
		48	.2	