Tectonophysics - Elsevier Publishing Company, Amsterdam
Printed in The Netherlands

COMPOSITION AND EVOLUTION OF THE CONTINENTAL CRUST AS SUGGESTED BY SEISMIC OBSERVATIONS[1]

L.C. PAKISER and RHODA ROBINSON

U.S. Geological Survey, Menlo Park, Calif. (U.S.A.);
U.S. Geological Survey, Denver, Colo. (U.S.A.)

(Received April 14, 1966)

SUMMARY

The average composition of the continental crust is more mafic than hitherto supposed. The conterminous United States can be divided, on the basis of seismic structure, into ten regions. The seven western and the three eastern regions can be termed western and eastern superprovinces. Seismic studies show that the crust is thinner and more silicic in tectonically active regions (western superprovince - average crustal thickness 34 km), than in stable regions (eastern superprovince - average crustal thickness 44 km). Mafic rocks are estimated to average 55% of the continental crust: 45% in the western and 59% in the eastern superprovince. These results express quantitatively the ideas expressed qualitatively by Pakiser and Zietz (1965). The computations of percentages of major oxides in the crust associate seismic velocities with rock compositions.

INTRODUCTION

During the past four decades, several attempts have been made to estimate the average composition of the continental crust. The early estimates–including those by Clarke and Washington (1924) and Goldschmidt (1933)–were based on sampling of surface rocks only, and therefore do not represent adequately the composition of the total continental crust. Surprisingly, these estimates do not differ greatly from more recent estimates (Poldervaart, 1955; Vinogradov, 1962; Taylor, 1964), which attempted to represent the composition of the whole crust.

During the past two decades, an immense amount of information has been accumulated on the seismic structure of the continental crust of the United States (Tatel and Tuve, 1955; Steinhart and Meyer, 1961; Pakiser and Steinhart, 1964; McConnell et al., 1966) and this information makes possible a more reliable estimate of the composition of the continental crust, provided some way can be found to associate seismic velocities with rock compositions. Such an association, which contains many uncertainties, can be made from laboratory studies of seismic velocities of rocks by Birch (1960, 1961) and others and from more recent correlations of seismic velocities and rock types by Christensen (1965). The general implications

[1]Publication authorized by the Director, U.S. Geological Survey.

of these studies, in terms of crustal composition, have been discussed by Pakiser (1965) and by Pakiser and Zietz (1965). Pakiser and Zietz also considered aeromagnetic indications of crustal composition.

In this paper, we attempt to estimate the composition of the continental crust of the United States using seismic results, laboratory measurements of rock velocities, and average compositions of silicic and mafic igneous rocks as determined by Nockolds (1954).

ROCK VELOCITIES

Compressional-wave velocities of rocks can be measured directly in the laboratory or calculated from the velocities and volume (in percent) of their mineral constituents. Christensen (1965) has calculated velocities for various types of igneous rocks from their mineral compositions and compared these velocities directly with velocities measured in the laboratory at 1.5 kbar of pressure (equivalent depth of burial, ca. 0.5 km) by Birch (1960) and by Hughes and Maurette (1956, 1957). Christensen's results show satisfactory agreement between calculated and observed velocities (Fig.1). Veloc-

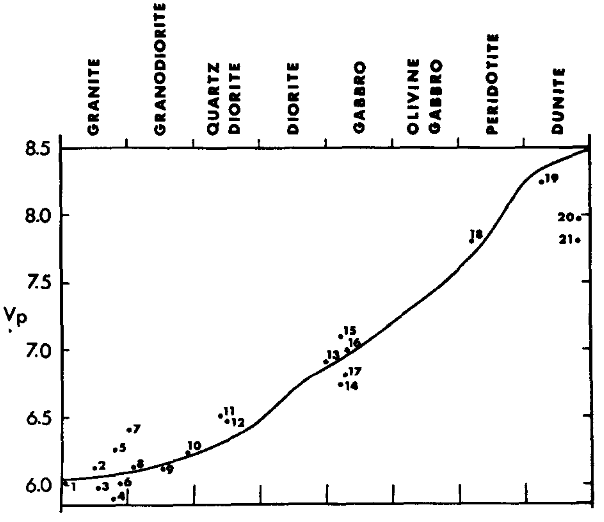

Fig.1. Diagram showing the variation of calculated velocity with composition. Dots refer to observed velocities at 1.5 kbar.

Type of rock: *1* = graphic granite; *2* = gneiss, Barre; *3* = gneiss 2; *4* = granite, Westerley; *5* = granite, Sacred Heart; *6* = granite, Chelmsford; *7* = granite, Texas Pink; *8* = granite, Texas Gray; *9* = granodiorite, Betlehem *10* = gneiss 3; *11* = quartz diorite, San Luis Rey; *12* = quartz diorite, Dedham *13* = gabbro, San Marcos; *14* = diabase, Centreville; *15* = norite, Bushveld; *16* = gabbro, French Creek; *17* = diabase, Frederick; *18* = Harzburgite; *19* = dunite, Twin Sisters; *20* = dunite, Balsam Gap; *21* = dunite, Mount Dun.

References: *1, 4, 5, 6, 9, 11, 12, 14, 16, 17, 18, 19, 20, 21*, from Birch (1960); *3, 10*, from Christensen (1965); *7, 8*, from Hughes and Maurette (1956); *13*, from Hughes and Maurette (1957).

(Reprinted from Christensen, 1965, fig.12.)

ities for silicic igneous rocks average about 6.2 km/sec, and velocities for mafic igneous rocks average about 7.0 km/sec.

Rock velocities, therefore, can be adopted, with reservations, as a general guide to rock compositions. Velocity cannot be used to distinguish igneous rocks from their metamorphic equivalents, unless high-pressure phase transformations are involved. Christensen noted, for example, that granitic gneiss and homogeneous granite of similar chemical, but different mineral, composition have similar seismic velocities; mafic rocks such as amphibolite and gabbro are similar chemically and have similar velocities, but different mineral compositions. In the calculations it is immaterial whether the rocks we identify as "silicic" and "mafic" are igneous or metamorphic rocks. A conclusion that the silicic rocks of the upper crust are "granite" and the mafic rocks of the lower crust are "basalt" or "gabbro" is not justified, however.

Certain metasedimentary rocks, such as quartzite and marble, have seismic velocities similar to those of typical silicic rocks, although they are chemically different. The unacknowledged presence of large quantities of such rocks in the upper part of the crust would introduce errors into the calculations that follow. If the proportions of metasedimentary rocks are similar to those of unmetamorphosed sedimentary rocks (about 56% shale, 22% sandstone, and 22% limestone) and if only about 5–10% of the upper part of the crust consists of sedimentary of metasedimentary rocks, the effects of their presence on composition can probably be ignored (see Pettijohn, 1957, pp.7–11, for discussion of volumes and abundances of sedimentary rocks).

Anorthosites and some altered dunites have seismic velocities similar to those of typical mafic rocks (Birch, 1960), although they have greatly different average chemical compositions. If such rocks are present in quantity in the deep crust, the results of this study may be significantly in error. Minor amounts of anorthosite or altered dunite could be tolerated, however, without modifying the assumptions of this study.

SEISMIC STRUCTURE OF THE CONTINENT

The continental crust in this study is represented for computational purposes as consisting of two units, or zones, having different seismic velocities: an upper unit with velocities generally ranging from 5.8 to 6.4 km/sec and a lower unit with velocities generally ranging from 6.7 to perhaps as much as 7.5 km/sec. If the effects on velocity of depth of burial are taken into account, velocities in the upper unit are appropriate for rocks of silicic composition, and velocities in the lower unit are appropriate for rocks of mafic composition (Pakiser, 1965). The implied assumption of layering into two units is open to doubt in many and perhaps most areas, but it is a convenient way to classify the gross seismic properties of the crust to estimate the average crustal composition. We do not mean to imply, however, that the silicic and mafic crustal units are necessarily or even probably separated by a discontinuity.

We have divided the conterminous United States into ten regions, on the basis of seismic properties (Fig.2). The continent is more finely divided in and west of the Rocky Mountains, where a dense network of seismic-

TABLE I

Proportions of major crustal units

Region (Fig.2)	Area ($km^2 \cdot 10^{-4}$)	Silicic crust		Mafic crust		Total crust	Mafic rocks	
		thickness (km)	volume ($km^3 \cdot 10^{-4}$)	thickness (km)	volume ($km^3 \cdot 10^{-4}$)	volume ($km^3 \cdot 10^{-4}$)	volume (%)	weight[1] (%)
Western superprovince								
(1) California coastal region	43	15	645	5	215	860	25.0	26.3
(2) Sierra Nevada	7	25	175	25	175	350	50.0	51.7
(3) Pacific northwest coastal region	29	10	290	25	725	1,015	71.4	72.8
(4) Columbia Plateaus	30	10	300	35	1,050	1.350	77.7	78.8
(5) Basin and Range province	121	20	2,420	10	1,210	3,630	33.3	34.8
(6) Colorado Plateaus	34	25	850	15	510	1,360	37.5	39.1
(7) Rocky Mountains	61	25	1,525	15	915	2,440	37.5	39.1
Subtotal	325	-	6,205	-	4,800	11,005	-	-
Average	-	19[2]	-	15[2]	-	-	43.6	45.3
Eastern superprovince								
(8) Interior Plains and Highlands	358	20	7,160	30	10,740	17,900	60.0	61.6
(9) Coastal Plain	154	20	3,080	15	2,310	5,390	42.8	44.4
(10) 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	-	19*	-	25*	-	-	57.4	59.2

Continental crust,								
conterminous U.S.:								
Total	999	-	18,875	-	21,900	40,775	-	-
Average	-	19*	-	22*	-	-	53.7	55.4

[1]Average weight percent of mafic rocks based on average densities of 2.8 g/cm^3 and 3.0 g/cm^3 for silicic crust and mafic crust, respectively.
*Average thicknesses of total crust: western superprovince, 34 km; eastern superprovince, 44 km; all regions, 41 km.

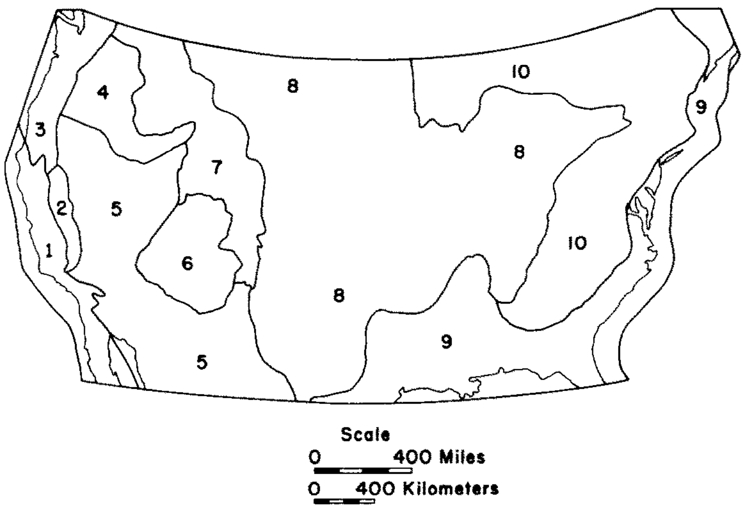

Fig.2. Regions used for estimates of crustal volumes. See Table I for identification of regions and their crustal properties.

refraction profiles has been completed, than it is farther east (Stuart et al., 1964; Pakiser and Steinhart, 1964; Healy et al., 1965; McConnell et al., 1966). We group the seven regions in and west of the Rocky Mountains into a western superprovince, and the three regions east of the Rocky Mountains into an eastern superprovince, following the previous suggestions by Pakiser and Steinhart (1964), Pakiser (1965), and Pakiser and Zietz (1965). Such a twofold grouping is, of course, somewhat arbitrary, but it does distinguish, on a broad scale, the tectonically active (western) region from the stable (eastern) region.

The area of each region (Fig.2) and the thickness of the upper low-velocity (silicic) unit and the deeper high-velocity (mafic) unit were estimated and tabulated (Table I). The thicknesses are from published results summarized by Steinhart and Meyer (1961), Pakiser and Steinhart (1964), and from McConnell et al. (1966), and from recent unpublished results of the U.S. Geological Survey as analyzed by J.C. Roller (personal commun., 1965) and his coworkers. Crustal models from these sources were arbitrarily reconstructed into their two-unit equivalents and averaged in each region to the nearest 5 km of thickness. From the areas and crustal thicknesses of the regions, the volumes of the silicic and mafic parts of the crust and the volume and weight percents of mafic rocks were computed (Table I).

Two results emerge from the data in Table I:

(1) The average crust is thinner in the western superprovince (34 km) than in the eastern superprovince (44 km). The thickening occurs in the lower, predominantly mafic part of the crust, which, from west to east, increases in average thickness from 15 to 25 km; the average thickness of the predominantly silicic part of the crust remains constant at 19 km. The average thickness of the entire continental crust is 41 km.

(2) The mafic crust in the western superprovince ranges by weight from 26% in the California coastal region to 79% in the Columbia Plateaus, and averages 45%. The mafic crust in the eastern superprovince ranges

from 44% in the coastal plain to 64% in the Appalachian Highlands and Superior Upland, and averages 59%; locally, mafic rocks constitute practically the entire crust in the eastern superprovince. The mafic rocks of the entire continental crust average 55%.

These results express quantitatively the ideas expressed qualitatively by Pakiser and Zietz (1965).

CHEMICAL COMPOSITION OF THE CONTINENT

To estimate the composition of the continental crust from the amount of mafic rocks (in weight %), we adopt Nockolds' (1954) averages of 794 silicic igneous rocks and of 637 mafic igneous rocks as representative, respectively, of the silicic upper crust and the mafic lower crust (Table II). These averages are consistent with the velocities of the various rock types reported by Birch (1960, 1961) and discussed by Christensen (1965).

We ignore the likelihood of a possibly thick transition zone of gradually varying intermediate composition and velocity at intermediate depths in the crust. A line drawn through the middle of such a transition zone would assign roughly half of these rocks to the silicic upper crust and half to the mafic lower crust; therefore existence of a transitional zone, rather than twofold separation into units, would probably not affect the results significantly.

We include the veneer of sedimentary and metasedimentary rocks in the silicic upper crust. The total volume of these rocks is small, and their average composition differs from the average composition of near-surface igneous rocks too insignificantly to affect our results.

We ignore the possibility of the presence in the lower crust of significant quantities of ultramafic rocks, such as altered dunite, or feldspathic rocks, such as anorthosite. We believe, however, that such rocks are probably relatively rare, and that representatives of common mafic rocks exposed (in many places by deep erosion) at the surface are more likely to occur in the lower crust.

The abundances of major oxides in the crust of the western superprovince indicate that the crust there is significantly more silicic than the crust of the eastern superprovince. The western crust is significantly richer in silica, and poorer in the oxides of iron, magnesium, and calcium. The quantities of the major oxides in the entire continental crust are most similar to those of monzonites and latites as reported by Nockolds (1954).

The continental crust is significantly more mafic than the continental crust suggested by Vinogradov (1962) and Taylor (1964) and most similar to that reported by Poldervaart (1955), when the estimates of this study are compared with earlier estimates. However, we reverse Poldervaart's results by finding the crust of the western superprovince slightly more silicic than his analogous crust for young folded belts, whereas our crust of the eastern superprovince is significantly more mafic than his analogous crust for continental shields (Table II). These differences arise from the new seismic results, which suggest that the crust is thinner and more silicic in tectonically active regions than in stable regions, rather than the reverse relation assumed in Poldervaart's estimates.

TABLE II

Estimates of abundances (in percent) of major oxides in continental crust

This study						Earlier estimates			
oxides	silicic rocks*1	mafic rocks*1	western super-province*2	eastern super-province*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	7.2	6.0	4.8	5.1
MnO	0.1	0.2	0.1	0.2	0.2	0.1*7	0.1*7	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	0.2*7	0.2*7	0.3	0.2
Totals	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 ifneous rocks.
*2 Based on weight percent of mafic crust, this study and Nockolds' (1954) averages.
*3 Taylor's (1964) averages based on one part mafic and one part silicic rocks.
*4 Vinogradov's (1962) averages based on one part mafic and two parts silicic rocks.
*5 Poldervaart's (1955) averages based on assumed crustal models.
*6 Total Fe expressed as FeO.
*7 Estimated to complete table.

DISCUSSION

The validity of the assumptions and the reliability of the data used to obtain these crustal compositions may be questioned. Several compromises and approximations are, of course, involved:

(1) Individual crustal models may be somewhat inaccurate. The model for the Columbia Plateaus, for example, was assumed from actual measurements in the Snake River plain; other models from a few measurements in the eastern superprovince were extended to broad regions. Undoubtedly these models will be refined by current and future seismic work, but we do not believe that the average volumes we used will be changed by more than a few percent. The effect of these changes on estimates of rock compositions will be minor.

(2) The possible errors resulting from the assumption that the crust is separated into silicic and mafic units and from including the sedimentary rocks in the silicic upper crust have been discussed and judged probably to be minor.

(3) It is not entirely valid to relate compositions to seismic velocities, as Birch (1960) has shown and as discussed in the section on rock velocities. Large errors might result if individual velocity measurements were related to individual chemical analyses of rock samples. However, the seismic-refraction method averages the velocities of large volume of rocks, and Nockolds (1954) averaged chemical compositions of many hundreds of silicic and mafic rocks. These average chemical compositions were compared with average velocities obtained from scores of samples subjected to a large range of pressures. This process gives us some confidence in the results of our computations, provided that our assumption that large volumes of the rocks of the deep crust are predominantly representatives of common mafic rocks is correct.

(4) The particular averages selected from Nockolds' (1954) findings may not be the best available. Without significantly changing the results, we could have selected the average composition of granodiorites or their metamorphic equivalents as representative of the silicic crust, or the average composition of gabbros or their metamorphic equivalents as representative of the mafic crust. The inclusion of altered ultramafic rocks in the samples, however, would result in higher percentages of the oxides of iron and magnesium, and lower percentages of silica, alumina, and the oxides of calcium, sodium, and potassium. A selection had to be made, and Nockolds' averages seemed the most reliably based.

(5) The crust of the part of the United States selected for analysis may not truly represent North America. Nevertheless, we believe that it does. What few data we have from Alaska and recent results from Canada and the conterminous United States are very similar, when comparable regions are examined.

(6) The effects of temperature on velocities of deeply buried rocks were ignored. Evaluation of these effects must await the results of current and future research in the laboratory and in the field, but we doubt that consideration of temperatures well below the rock melting points will require significant modification of our results. In the west, where the average heat flow is high, the deepest crustal rocks are relatively near the surface and therefore presumably relatively cool. In the east, the average heat flow is lower, and temperature effects on the deep crustal rocks are probably not great.

CRUSTAL EVOLUTION

In two previous papers, Pakiser (1965) and Pakiser and Zietz (1965) speculated that the primitive crust that evolved from the mantle was predominantly silicic and was made slowly more mafic by the addition of mafic material from the mantle accompanied by removal of silicic material by erosion. The primitive silicic crust may have evolved from the mantle about 3 1/2 billion years ago, as is suggested by radiogenic dating of the oldest crustal rocks. The implied crustal thickening by addition of mafic material probably is accompanied by the addition of new silicic material from the mantle. The process of crustal evolution essentially is completed in the eastern superprovince, while it still goes on in the western superprovince

The processes of crustal evolution envisaged are largely the ordinary geologic processes of plutonism and volcanism; the process of evolving silicic material directly from the mantle deserves special study. Eardly (1963) has proposed that the Rocky Mountain uplifts are caused by intrusions of mafic megasills or megalacoliths into the deep crust from the mantle. With modifications and additions, his explanation of how the uplift of individual mountain ranges took place reasonably could explain the general process of crustal evolution. Such a general explanation for the transfer of mafic magma within the mantle and from the mantle to the crust was proposed by Pakiser and Zietz (1965).

REFERENCES

Birch, F., 1960. The velocity of compressional waves in rocks to 10 kbar, 1. J. Geophys. Res., 65: 1083–1102.

Birch, F., 1961. The velocity of compressional waves in rocks to 10 kbar, 2. J. Geophys. Res., 66: 2199–2224.

Christensen, N.I., 1965. Compressional wave velocities in metamorphic rocks at pressures to 10 kbar. J. Geophys. Res., 70: 6147–6164.

Clarke, F.W. and Washington, H.D., 1924. The composition of the earth's crust. U.S. Geol. Surv., Prof. Papers, 127: 117 pp.

Eardly, A.J., 1963. Relation of uplift to thrusts in Rocky Mountains. Am. Assoc. Petrol. Geologists, Mem., 1963 (2): 209–219.

Goldschmidt, V.M., 1933. Grundlagen der quantitativen Geochemie. Fortschr. Mineral. Krist. Petrog., 17: 112–156.

Healy, J.H., Steinhart, J.S. and Meyer, R.P., 1965. Seismic-refraction studies in the transcontinental geophysical survey. Trans., Am. Geophys. Union, 46: 383–384.

Hughes, D.S. and Maurette, C., 1956. Variation of elastic wave velocities in granites with pressure and temperature. Geophysics, 21: 277–284.

Hughes, D.S. and Maurette, C., 1957. Variation of elastic wave velocities in basic igneous rocks with pressure and temperature. Geophysics, 22: 23–31.

McConnell, R.K., Gupta, R.N. and Wilson, J.T., 1966. Compilation of deep crustal seismic refraction profiles. Rev. Geophys., 4: 41–100.

Nockolds, S.R., 1954. Average chemical compositions of some igneous rocks: Bull. Geol. Soc. Am., 65: 1007–1032.

Pakiser, L.C., 1965. The basalt–eclogite transformation and crustal structure in the western United States. U.S. Geol. Surv., Prof. Papers, 525-B: B1–B8.

Pakiser, L.C. and Steinhart, J.S., 1964. Explosion seismology in the Western Hemisphere. In: H. Odishaw (Editor), Research in Geophysics. 2. Solid Earth and Interface Phenomena. Cambridge Mass. Inst. Technol. Press, Cambridge, Mass., pp.123–147.

Pakiser, L.C. and Zietz, I., 1965. Transcontinental crustal and upper-mantle structure. Rev. Geophys., 3: 505–520.

Pettijohn, F.J., 1957. Sedimentary Rocks, 2nd ed. Harper, New York, N.Y.,718 pp.
Poldervaart, A., 1955. The chemistry of the earth's crust. In: A. Poldervaart (Editor), Crust of the Earth, a Symposium - Geol. Soc. Am., Spec. Papers, 62: 119–144.
Steinhart, J.S. and Meyer, R.P., 1961. Explosion studies of continental structure. Carnegie Inst. Wash., Publ., 622: 409 pp.
Stuart, D.J., Roller, J.C., Jackson, W.H. and Mangan, G.B., 1964. Seismic propagation paths, regional traveltimes, and crustal structure in the western United States. Geophysics, 29: 178–187.
Tatel, H.E. and Tuve, M.A., 1955. Seismic exploration of a continental crust. In: A. Poldervaart (Editor), Crust of the Earth, a Symposium - Geol. Soc. Am., Spec. Papers, 62: 35–50.
Taylor, S.R., 1964. Abundance of chemical elements in the continental crust; a new table. Geochim. Cosmochim. Acta, 28: 1273–1285.
Vinogradov, A.P., 1962. Average contents of chemical elements in the principal types of igneous rocks of the earth's crust. Geokhimiya, 1962: 641–664.