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ON THE MATERIALS IN THE EARTH'S MANTLE

BY

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ABSTRACT

Several figures of the stony portion of stony meteorites are discussed in point of elastic property as compared with the figure of the mantle.

After the conclusion that there is no ground to assume that the stony portion of meteorites is the constituent material in the mantle, it is considered that, as previously discussed, dunite is the most probable material as the constituent of the mantle.

1. Introduction

Owing to a rapid advance in geophysics, the problem of what material the Earth's mantle is composed has recently become more and more important for every branch of Earth Science. With regard to radioactivity, thermal conduction, plasticity, and rupture phenomena in the Earth's mantle, for example, no definite conclusion could be drawn without knowledge of the material which exists in the mantle. Information about the material below the crust is necessarily indirect, and it is impossible to reach a conclusion unless some restriction is placed on speculation. Chemistry on rocks, meteorites and solar atmosphere will also be able to reveal the restriction about the material in the mantle. Our present knowledge of the Earth's interior, however, is mainly confined to the physical properties—seismic waves, density, moment of inertia, etc. Then, it is more natural to draw a definite conclusion that physical properties of rocks and meteorites constitute a conclusive factor. In this paper, the elastic property of stony meteorites and the variation of elasticity with metallic contents will be compared with that of the mantle by means of high pressure experiments.

2. Statistical analysis of stony meteorites

The study on chemical analysis of meteorites began a long time ago, and the data of the field of this branch have been accumulated year after year. Several authors (**1, 2, 3, 4**) have published interesting results as to the statistical consideration of the accumulated chemical analyses. But, there is no conclusive theory of meteorites derived from statistical chemical analyses. It is supposed that the reason is mainly due to scarcity of data. In the following, three models for stony meteorites are tentatively chosen.

- i) *Model A.* Recently Urey (**4**) has chosen 94 superior analyses as being reliable representatives for chondrite meteorites. These Urey's chemical analyses are taken as model A.
- ii) *Model B.* Owing to the weight of overlying materials, pressure in the Earth's interior is very high, and consequently the transition to a high pressure form would be plausible. Since the mineral in the Earth's interior would be transformed into jadeites or garnets under high pressure, the model of transformed feldspars in meteorites will be referred to as model B.
- iii) *Model C.* Wahl (**3**) proposed an Earth's model and a meteorites' model. According to him, the Earth and mother body of meteorites are originally metals, and owing to oxidation both have turned into oxides (rocks). He has chosen the meteorites fitted in his figure. This model will be referred to as model C.

3. Physical property of the meteorites

In order to compare the physical quantities of the Earth's mantle with those of the stony portion of stony meteorites, the density, the bulk modulus, and the ratio of the bulk modulus to the density of the stony portion are calculated as follows. At first, the mineralogical compositions of the stony portion are calculated. Secondly, the density of the stony portion is calculated by the equation:

$$\rho = \frac{\sum \rho_i v_i}{\sum v_i}, \qquad (1)$$

where ρ_i and v_i are the density and volume for the ith mineral respectively. Thirdly, the bulk modulus k of the stony portion is derived from the equation:

$$\frac{1}{k} = \frac{\sum \kappa_i v_i}{\sum v_i}, \qquad (2)$$

where κ_i is the compressibility of the ith mineral. There are some doubts about calculation of mineralogical composition from its chemical analysis for rocks and meteorites, and so it is preferable to collect the mineralogical composition of the stony portion.

But data for measured mineralogical compositions of the stony portion are still rare and in the present paper the theoretical calculations of mineralogical composition are adopted.

There is little ambiguity about reliability of Eqs. (1) and (2). L. H. Adams (**5**) has pointed out that the accuracy of Eqs. (1) and (2) is very high and that error of calculation is within 2 per cent.

The density and the bulk modulus of the stony portion are not measured directly, because meteorites have a mosaic structure with iron, sulphide and stony portion.

It is necessary to obtain their densities and bulk modulus to calculate from suitable assumptions. At the present stage of the study on meteorites the above-mentioned method would offer a plausible one.

The outline of calculation of the density and the bulk modulus of the stony portion is just as above mentioned. The details are stated in the following.

Model A. Urey has chosen 94 superior analyses as being reliable representatives for chondrite meteorites. This figure is assigned as model A. Brown (**2**) also collected the data for both stony and iron meteorites. His figure is very similar to that by Urey. For statistical analysis, the 94 chemical compositions are placed as ascending series of free metal contents, at which the free metal contents range from 2 per cent to 27 per cent. The 94 analyses are grouped into 28 groups in arrangement of every one per cent metal content. Among these 28 groups, the groups which contain smaller than ten analyses are discarded, because of the scarcity of members in the group. There are five groups which contain more than ten analyses among 28 groups. For these five groups, the means of chemical analyses are taken, from which the density and the bulk modulus of the stony portion are derived.

From the five mean chemical analyses, the mineralogical compositions can be calculated by the method proposed by Wahl (**3**). In Table I, the mineralogical compositions for five mean chemical analyses thus obtained are shown.

The calculation of mineralogical compositions (norm) from chemical compositions for meteorites have some uncertainty, though for rocks the norm calculation is established. And so the accuracy of the data shown in Table I is still unjustified. But the mineralogical compositions of the stony portion of stony meteorites are very simple compared with those of rocks, and the above figure in Table I is not so much different from those of the means of actual mineralogical compositions.

The densities of the stony portion for the five groups are derived from Eq. (1). The densities thus obtained for the five groups are shown in Table II.

It should be noted that the density of the stony portion is free from sulphide, because this procedure comes from taking account of the Earth's mantle free from sulphides.

There is another method of calculation of the density of the stony portion of stony meteorites. The method will be adopted in the following in order to ascertain the limit of error of calculation of the density.

The actual density of stony meteorites consists of the weighted means of contribution of metal, sulphide and stony portion, because actual stony meteorites consist of metal, sulphide and stony portion. Then the density of the stony portion has a value which is obtained by subtracting the contribution of the both parts of metal and sulphides from the original. The density ρ of the stony portion is obtained from the equation:

Table I. Average mineral compositions of stony meteorites.

Mineral	Density[1] (g/cm^3)	Mean weight %				
		Group 1	Group 2	Group 3	Group 4	Group 5
$Na_2OAl_2O_36SiO_2$	2.62	8.09	7.82	7.97	7.92	7.02
$K_2OAl_2O_36SiO_2$	2.56	1.20	1.32	0.84	1.17	0.71
$CaOA_2O_32SiO_2$	2.76	0.82	2.31	2.79	0.33	2.30
$FeOSiO_2$	3.9	7.44	7.62	6.53	5.43	6.36
$FeOTiO_2$	4.75	0.38	0.27	0.15	0.27	0.27
$MnOSiO_2$	3.67	0.31	0.36	0.84	0.44	0.46
$CaOSiO_2$	3.33[2]	3.25	2.33	2.23	4.19	2.26
$MgOSiO_2$	3.19	17.71	17.63	15.76	17.68	21.20
$2FeOSiO_2$	4.07	14.45	14.47	14.62	9.96	8.63
$2MgOSiO_2$	3.21	31.76	30.45	32.09	29.02	26.07
$FeOCr_2O_3$	4.5	0.55	0.90	0.58	0.38	0.41
$3CaONa_2OP_2O_5$	3.10	0.65	0.21	0.62	0.64	0.48
Metal	7.7[3]	7.42	8.43	9.44	16.77	18.86
FeS	4.73[3]	5.40	5.92	6.12	5.38	5.10

Name of meteorites

Group 1. Bjnrbole, Chandakapur, Forksville, Lundsgard, Modoc, Moorleah, Rakovka, Rich Mountain, Tuan Tuc, Warbreccan.

Group 2. Baroti, Chantonnay, Girgenti, Grossliebenthal, MacKinney, Meuselbach, Perpeti, Saint Deniswestrem, Saratov, Shelburne, Strathmore, Tieschitz, Tourinnesla-Grosse, Varpaisjarvi, Wittekrantz.

Group 3. Coon Butte, Crumlin, Lanzenkirchen, Launton, Lesves, Lissa, Mezo-madaras, Narellan, Ojuelos Altos, Phuoc-binh, Prambachkirchen, Rangara, Saint Christophe, Saint Michel, Sazovice.

Group 4. Bowden, Estacado, Linum, Oakley, Phu-Long, Salt Lake City, Seldebourak, Suwahib, Tabor, Tanezrouft.

Group 5. Beaver Creek, Benld, Benoni, Cape Girardeau, Collescipoli, Cronstad, Ekeby, Elsinora, Gopalpur, Hessle, Khairpur, Khetri, Mount Browne, Olmedilla di Alarcon, Plantersville.

1) from Reference (10)
2) assumed as diopside
3) from Reference (11)

Table II. Average density of silicate portion of stony meteorites.

Mineral	Mean weight %				
	Group 1	Group 2	Group 3	Group 4	Group 5
Feldspars	11.60	13.37	13.75	12.09	12.23
Pyroxenes	33.36	32.94	30.22	35.98	40.20
Olivine	53.28	52.46	55.33	50.08	45.64
Chromite	0.63	1.05	0.69	0.49	0.54
Merrillite	0.74	0.24	0.74	0.82	0.63
Total	99.61	100.16	100.73	99.46	100.24
Metal content (%)	7.42	8.43	9.44	16.77	18.86
Density[1] (g/cm^3)	3.3_0	3.3_0	3.2_9	3.2_6	3.2_6

1) Density of silicate portion of stony meteorite (mean value)

$$\rho=\frac{100-c_M-c_S}{100/\rho_0-c_M/\rho_M-c_S/\rho_S}, \tag{3}$$

where ρ_0 is the measured density of actual stony meteorites, and c_M, c_S, ρ_M and ρ_S are the volume percentage of metal portion, the volume percentage of sulphide portion, the density of metal portion and the density of sulphide portion respectively.

In Table III, the densities of the stony portion of stony meteorites for given groups are shown.

Table III.

Component	Density (g/cm³)	Mean weight %				
		Group 1	Group 2	Group 3	Group 4	Group 5
Metal	7.7	7.42	8.43	9.44	16.77	18.86
FeS	4.73	5.40	5.92	6.12	5.38	5.10
Silicate		87.18	85.65	84.44	77.85	76.04
Measured density¹⁾ (g/cm³)		3.50	3.51	3.52	3.59	3.66
Density of silicate portion²⁾ (g/cm³)		3.3_0	3.3_0	3.2_9	3.2_6	3.2_6
Density of silicate portion³⁾ (g/cm³)		3.2_9	3.2_7	3.2_6	3.1_7	3.1_9

1) Density of stony meteorite (mean value)
2) Density from Table II.
3) Calculated density from Eq. (3) for comparison.

The densities in Table III offer the indication of the limit of error of densities calculated in Table II. The values obtained in Table III are all in good agreement with those in Table II within errors of about 3 per cent. Therefore, the figures shown in Table II will have an accuracy smaller than about 3 per cent. As seen in Tables II and III, the figures obtained in Table III are all smaller than those in Table II. This is no doubt due to porosity of actual meteorites.

The bulk modulus (incompressibility) of the stony portion is derived from Eq. (2).

Among the minerals found in stony meteorites, the compressibilities for almost all of them were measured. But a few are not measured yet, $3CaO \cdot Na_2O \cdot P_2O_5$, for example, and so for such materials calculations were made without them. Total amount of the materials for which the compressibility is still unknown does not exceed 1 per cent. In Table IV, the bulk modulus for the stony portion (without sulphide) is shown.

It should be noted that the error of calculated figures in Table IV will be within 5 per cent, because the error comes from the uncertainty of Eq. (2) and the unknown factor of compressibility which is not yet measured.

Model B. Owing to the weight of overlying materials, pressure in the Earth's mantle is extraordinarily large, and under such high pressure the transition of minerals

Table IV. Average elasticity of silicate portion of stony meteorites.

Mineral	κ 1) $(10^{-13}$C.G.S.)	Mean volume %				
		Group 1	Group 2	Group 3	Group 4	Group 5
$Na_2OAl_2O_3 6SiO_2$	19	11.75	11.48	11.77	12.73	11.44
$K_2OAl_2O_3 6SiO_2$	21	1.75	1.98	1.27	1.90	1.17
$CaOAl_2O_3 2SiO_2$	11	1.13	3.23	3.92	0.49	3.54
$FeOSiO_2$	10	7.26	7.52	6.47	5.87	6.95
$FeOTiO_2$	5.6	0.30	0.23	0.13	0.23	0.23
$MnOSiO_2$		0.30	0.36	0.88	0.52	0.52
$CaOSiO_2$	11	3.72	2.67	2.58	5.28	2.89
$MgOSiO_2$	10	21.11	21.25	19.09	23.33	28.41
$2FeOSiO_2$	9.1	13.74	13.69	13.89	10.30	9.07
$2MgOSiO_2$	7.9	37.64	36.53	38.70	38.10	34.71
$FeOCr_2O_3$		0.46	0.76	0.49	0.36	0.39
$3CaONa_2OP_2O_5$		0.79	0.26	0.78	0.85	0.65
κ $(10^{-13}$C.G.S.)		$10._4$	$10._4$	$10._3$	$10._5$	$10._4$
k/ρ $(10^{11}$C.G.S.)		2.9	2.9	2.9	2.9	2.9

1) from Reference (**10**)

Table V. Elasticity of the stony portion of stony meteorites in hypothetical high pressure form.

Mineral	Density (g/cm^3)	κ $(10^{-13}$ C.G.S.)	Mean weight %				
			Group 1	Group 2	Group 3	Group 4	Group 5
$Na_2OAl_2O_3 4SiO_2$	3.33 1)	7.8 1)	8.17	7.80	8.00	8.93	7.80
$3CaOAl_2O_3 3SiO_2$	3.54 1)	6.3 1)	1.53	4.36	5.22	0.67	4.91
$3FeOAl_2O_3 3SiO_2$	4.16 1)	6.0 1)	—	—	0.15	5.02	—
$CaOSiO_2$	3.33	11	2.93	0.46	—	—	0.45
$FeOTiO_2$	4.75	5.6	0.44	0.32	0.18	5.02	0.36
$FeOCr_2O_3$	4.5		0.63	1.05	0.69	0.49	0.54
$MnOSiO_2$	3.67		0.35	0.42	1.00	0.57	0.61
$2FeOSiO_2$	4.07	9.1	14.73	14.45	14.73	10.82	9.47
$2MgOSiO_2$	3.21	7.9	31.82	30.47	32.42	31.90	28.90
$FeOSiO_2$	3.9	10	11.31	12.11	10.99	9.24	10.80
$MgOSiO_2$	3.19	10	26.95	27.84	26.65	30.02	35.97
$3CaONa_2OP_2O_3$	3.10		0.74	0.89	0.74	0.82	0.63
Density (g/cm^3)			3.4	3.4	3.4	3.4	3.4
κ $(10^{-13}$C.G.S.)			8.9	8.8	8.7	8.8	8.9
k/ρ $(10^{+11}$C.G.S.)			3.3	3.3	3.4	3.3	3.3

1) Reference (**12**)

will be undergone. Recent experiments (**6**) show that feldspars are transformed into jadeites and garnets in such case of high pressure. It is plausible that under high pressure, a part of the stony portion will be transformed into a high pressure form. If it happens, the figures in model A will lose their reliability. In model B, whole feldspars will be transformed into high pressure forms and other minerals still remain unchanged as in model A.

The method of calculation of both the density and the bulk modulus is the same except feldspars. In Table V, the bulk modulus of a hypothetical high pressure form of the stony portion is shown.

The limit of errors in the figures in Table V cannot be estimated because of uncertainty of the fundamental postulation.

Model C. Recently, Wahl (**3**) proposed an Earth's model and meteorites. According to him, the Earth and the mother body of meteorites consist originally of metals. Owing to oxidation, the planets are oxided gradually from their surface to deeper part. The planets become two-layer planets composed of oxides layer (rocks layer) and metal layer (core). According to him, it must be concluded that for meteorites the larger their metal content is, the smaller FeO content. He has chosen four representative groups for stony meteorites fitted with the figure. In Table VI, the ratio of the bulk modulus to the density of his figures is shown.

Table VI. Mineralogical composition; After W. Wahl.

Mineral	Density (g/cm^3)	κ 2) (10^{-13}C.G.S.)	Weight %			
			Sample 1	Sample 2 1)	Sample 3	Sample 4
$Na_2OAl_2O_36SiO_2$	2.62	19	5.72	9.92	7.18	8.14
$K_2OAl_2O_36SiO_2$	2.56	21	1.50	1.37	1.51	1.37
$CaOAl_2O_32SiO_2$	2.76	11	2.86	2.60	2.20	2.36
$FeOSiO_2$	3.9	10	0.13	8.71	8.23	0.04
$FeOTiO_2$	4.75	5.6	0.31	0.28	0.43	0.36
$MnOSiO_2$	3.67		0.41	0.60	0.59	0.06
$CaOSiO_2$	3.33	11	3.33	2.67	4.67	3.41
$MgOSiO_2$	3.19	10	0.18	19.53	26.93	83.20
$2FeOSiO_2$	4.07	9.1	37.98	16.40	11.68	—
$2MgOSiO_2$	3.21	7.9	46.06	36.30	34.55	—
$FeOCr_2O_3$	4.5		0.95	0.84	1.00	0.51
$3CaONa_2OP_2O_5$	3.1		0.58	0.74	1.03	—
SiO_2	2.6	27	—	—	—	0.53
Metal content %			5.54	9.08	17.16	25.60
k/ρ (10^{11}C.G.S.)			3.0	2.9	2.9	2.8

1) Mean value of 12 stony meteorites.
2) Reference (**10**)

To obtain the figure in Table VI, the employed procedure is exactly the same as those for model A, except the difference in mineralogical compositions.

4. Comparison with the Earth's mantle

Meteorites are only rocks which come from outside the Earth. Chemical properties of meteorites are studied in many respects and are shown similiar to those for rocks on the surface of the Earth. It is often said from this point of view that the Earth's mantle consists of materials very similar to the stony portion of stony meteorites. But little has been done of their elastic properties in comparison with the Earth's mantle. The physical properties of meteorites are only tools to compare with those of the mantle. In Table VII, are shown the values of the ratio of the bulk modulus to the density for models A, B, and C respectively, together with that in the mantle (**7**).

Table VII. Average k/ρ from models A, B and C together with that from seismic observation in the Earth's mantle.

	Model A	Model B	Model C	Mantle[1]
$\frac{k}{\rho}$ (10^{11}C.G.S.)	29	33	29	36~37

[1] from Reference (6)

The ratio of the bulk modulus to the density in the Earth's mantle can be calculated without introducing any assumptions about seismic wave velocities. In Table VII the said ratio at the surface of the mantle is given for comparison with the figures obtained in §3.

As will be seen in Table VII, the ratios of the bulk modulus to the density of the stony portion of stony meteorites from models A, B and C are all smaller than that obtained from seismic observation.

If we assume that the ratio of the bulk modulus to the rigidity for meteorites is nearly 2, just as in the case of both rocks and the Earth's interior, the dilatational wave velocities for figures of models A, B and C are 7.1, 7.5 and 7.4 km/sec respectively. From seismic observation, it is shown that the dilatational wave velocity just below the so-called Mohorovičić discontinuity is nearly equal to 8.0 km/sec (**6**). The discrepancy will exceed the limit of error of calculation.

For figures of model A the discrepancy is very large, and so there is no ground to assume that the Earth's mantle consists of the minerals similar to those of meteorites.

Usually, minerals have very complex crustal lattice structure, and so occurrence of polymorphic transitions under high pressure are very plausible in the Earth's mantle.

In this sense, the figure of model B will be reasonable for the figures proposed in the mantle. As shown in Table VII, however, this figure of model B is qualitatively unsatisfactory.

It will be pointed out that if stony meteorites contained more sodium oxide and alumina, the figure of meteorites would be fitted with that in the Earth's mantle. For model C, the calculated figure is still lower than that in the Earth's mantle. It will be pointed out that FeO is too much to interpret the figure of meteorites as that of the mantle in this case.

With regard to the variation of elasticity of the stony portion with metallic contents, the variation is very small, as seen in tables, and there is no correlation of the existence of layers in the mantle with the variation of elasticity of the stony portion of meteorites with their metallic contents.

Adams (8) has pointed out that the Earth's mantle consists mailny of olivine and dunite. His figure fits the observational fact in the mantle with regard to seismic wave velocities. There is no ground for altering Adam's postulation for figures of meteorites.

5. Conclusion

Several models of figures of the stony portion of stony meteorites were taken for the sake of comparison with the figure in the Earth's mantle. Calculated bulk modulus, and the ratio of the bulk modulus to the density for the stony portion of stony meteorites cannot interpret the value in the mantle obtained from seismic observations. The present writer tried to examine physical properties of dunite in the previous paper (9) and confirmed that the mantle consists mainly of dunite. This assumption was ascertained also in the present paper.

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