COMPRESSIBILITY AND ANISOTROPY OF ROCKS AT AND NEAR THE EARTH'S SURFACE*

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Purpose of the Investigation.—That remarkably active branch of geophysics, seismology, is dependent for theory and practice on accurate information regarding those physical properties of rocks that are most intimately related to the propagation of elastic waves in the earth. Most important of all for use in diagnosing the composition of hidden rocks is volume compressibility. Due to recent improvements in technique by Bridgman and others, it is now possible to measure the linear and cubic compressibility of a rock under hydrostatic pressures as high as 10,000 to 30,000 kilograms per square centimeter. This is the range of pressure at depths of roughly 35 to 100 kilometers in the earth. While Bridgman has supplied some data on the compressibility of rocks at high pressure, the greater part of the available information comes from the work of Adams and Williamson at the Geophysical Laboratory of the Carnegie Institution of Washington.[1]

Adams and Williamson worked in a pressure range of 2000 to 10,000 "megabars" (now sometimes called "bars"), a megabar being one million dynes per square centimeter and equal to about 1.02 kilograms per square centimeter or about ninety-nine per cent of one atmosphere. Their measurements were made under two different conditions. In the one case the rock specimens were exposed directly to the fluid transmitting the pressure; in the other case the air-dried specimens were covered with thin, impermeable tin-foil which prevented the direct access of the fluid. Adams and Williamson pointed out that the measured compressibility should be the greater in the second case, provided the rock carries cracks or pores in communication. For clearly, when the pressure goes on, the cracks and pores should be more easily closed if the specimen is "covered" than if the transmitting fluid is allowed to enter cracks and pores and so add to the resistance to closure. This theoretical expectation agreed with the results of the many experiments, except in the case of three rocks: marble, Westerly granite and Stone Mountain granite. These anomalies were not explained. During the experiments reported in the present paper, twenty-eight different specimens of rock were tested in both the covered and uncovered states; in every case the behavior was that foretold by Adams and Williamson.

Those authors showed that the compressibility of most rocks decreases rapidly as the pressure rises from an initial amount of three hundred atmospheres. This fact was discovered when they compared their values of compressibility at pressures over two thousand atmospheres with those obtained by Adams and Coker, who calculated the compressibilities of their rocks from measurements of Young's modulus and Poisson's ratio at a pressure range of about seventy to six hundred atmospheres.[2] From the two sets of results Adams and Williamson constructed curves of compressibility, reaching back to zero pressure, but their method for the lower pressures was by frank extrapolation. For seismological problems relating to rock formations at and close to the earth's surface there has been evident need of a direct experimental study of rocks in the pressure field below that occupied by Adams and Coker. The following paper presents the results of such a study.

Moreover, the geophysicist needs to know how far rocks, especially those at shallow depths, depart from isotropy. That the departure may be great has been shown by recent measurements of Young's modulus and Poisson's ratio at pressures reaching about fifty-six atmospheres.[3] The same fact has become evident in the course of the present research, when cubic compressibilities were determined by first measuring linear compressibility at a pressure range of one to about eight hundred atmospheres. The amount of the anisotropy in standard rocks can be gauged by study of the tables of data to be seen on later pages. It is clear that the seismologist must consider anisotropy when he is dealing with waves passing along the surface layer of the globe.

Description of Piezometer.—The piezometer designed for this work is on the same principle as Bridgman's well-known lever-piezometer used at pressures ranging up to twelve thousand atmospheres.[4] For research in that field of pressure the instrument could manifestly accommodate only short columns of the solids to be investigated. To secure reliable results at low pressures it was necessary to use columns six or eight times as long, the length actually favored being eight inches (twenty centimeters). The width was regularly five-eighths of an inch (1.6 centimeters). Such great lengths and actual thicknesses secured against errors due to the excessive influence of specially large crystals in the rocks, and also assured high sensitivity for the apparatus.

The principle of the Bridgman instrument, built with specifications to match the new kind of investigation, may be briefly reviewed (see Fig. 1). One end of the rock cylinder rests on the piezometer case at the point A. The other end is in contact at B with the short arm CB of a lever ECB whose fulcrum is at C, the end of the pointed screw DC. The arm EC is about fourteen times longer than arm CB. A spring JI maintains CB in firm contact with the upper end B of the specimen. At EH is a stiff straight piece of manganin resistance wire about one centimeter long. This is in gentle, sliding contact with a blade of manganin, G, which is supported but electrically insulated from the main body of the piezometer $M_3M_2M_1$. At F and H are soldered wire connections for the electrical circuit. When the hydrostatic pressure is increased on the liquid in the steel cylinder into which the piezometer is screwed, the specimen shortens in all its dimensions. Point A is fixed, but point B moves downward. Then the lever arm ECB rocks about the fulcrum at C and point E moves to the right. Therefore, the distance FG decreases as the result of the sliding of the manganin wire over the fixed knife-edge contact at G. By measuring the consequent change in electrical resistance of FG, we can, from our knowledge of the resistance per unit length of the wire, calculate the decrease in length of the rock under pressure.

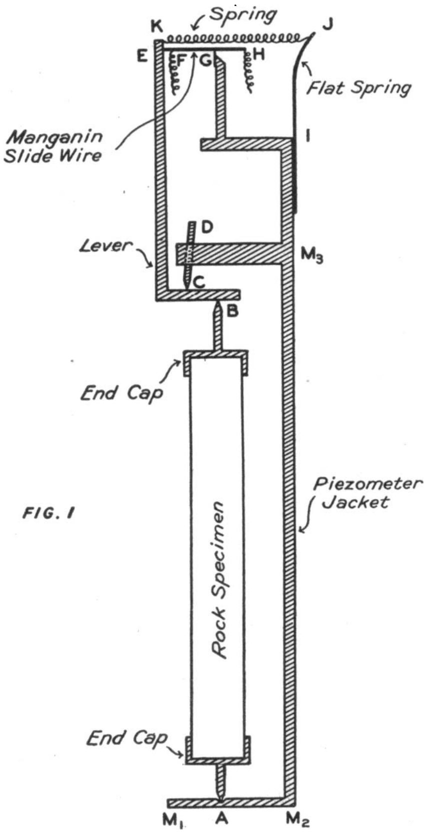


FIG. 1

SCHEMATIC DIAGRAM OF PIEZOMETER

In order to eliminate troubles from the contact resistance at G, the resistance of FG is measured by a potentiometer bridge method described in Bridgman's papers. For this method F and G serve as potential and E and H as current connections.

It is apparent that such an instrument measures only the difference in the hydrostatic linear compressibilities of the rock and the steel of the piezometer case, for when the length of the specimen shortens so does the distance M_2M_3, due to the compressibility of the steel. The true compressibility of the rock is obtained by allowing for that of the steel, for which Bridgman's value, 2.00×10^{-13} cm.^{2}/dyne, was used.

In order to test the reliability of the instrument, a cylinder of soft steel of the same kind as in the piezometer jacket was used in place of the rock specimen. No change in resistance under pressure was observed that could be due to relative motion of the specimen and the jacket, such as would occur if distortion took place in the instrument when the high pressure permitted any internal stresses in the steel to exhibit their presence.

If a specimen of some homogeneous substance free from internal strains and cavities is used, the graph of shortening of the specimen as a function of pressure will be a smooth curve free from hysteresis. This is the most reliable test for the existence of slipping at the bearing points *B* and *C*. A cylinder of pure cast lead was used for such a test. Several independent runs gave the same result and proved the absence of hysteresis. At thirty degrees centigrade the linear compressibility of lead was found to be 8.40×10^{-13} cm.^{2}/dyne. Bridgman[5] obtained 8.07×10^{-13} cm.^{2}/dyne. This difference may be due to the lack of perfect annealing in my specimen.

The hydrostatic pressure was measured with a manganin resistance coil by inserting a 250-ohm coil of well seasoned manganin wire in the pressure chamber and measuring its change of resistance under pressure with a Carey-Foster bridge. The pressure calibration of this type of secondary gauge is simple. The resistance of manganin was shown by Bridgman to change linearly with pressure in the range 0–10,000 kg./cm.^{2}. Therefore it is necessary only to measure the resistance of the coil at atmospheric pressure and again at some higher known pressure, such as that at which mercury freezes at zero centigrade (7640 kg./cm.^{2}). There was no change in the calibration of the coil used during the year needed for these measurements.

Preparation of Specimens.—The rock cylinders were core-drilled from the same blocks as those from which were cut the two-inch-diameter cylinders used for the measurement of Young's modulus and Poisson's ratio described in a previous paper.[3] The same method of indicating the directions of coring of the cylinder for compressibility tests was used. The cores were ground carefully to form accurate right cylinders.

The compressibility of the specimen was measured when immersed in kerosene, the fluid transmitting the pressure. This will be referred to as the compressibility of the "uncovered" rock. In contrast is the compressibility of the "covered" rock, the cylinder in this case having been enclosed in an impermeable sheath of 0.002-inch annealed copper foil. This covering was strong enough to prevent entrance of the kerosene into the rock and flexible enough to transmit the pressure freely to the rock within.

The method of preparing these covers may be indicated. The rock cylinder was rolled in a sheet of foil, much as the tobacco of a cigarette is rolled in its paper cover. The end of the rolled sheet of foil then formed a seam running the length of the cylinder. This seam was soft-soldered, and to facilitate the operation the foil edge was tinned before rolling. Thin caps were made for covering the ends of the cylinder, by spinning a sheet of copper into a cap whose inside diameter was five-eighths of an inch and whose length was from a quarter to three-eighths of an inch. The cap fitted snugly over the end of the specimen and the rim was soft-soldered to the copper covering beneath. When hydrostatic pressure was applied, the excess foil present was forced into the surface cavities in the rock, making an extremely close fit like that of the skin of an onion.

After being covered, the rock was exposed to a pressure of 1000 kg./cm.[2] for five minutes. Then a small hole was made in the cover. If there had been a leak, it was detected by the issuing of small bubbles of kerosene from this hole. After some practice in the technique it was found that few covers leaked. After this test, the small hole was sealed with soft solder, and the specimen was ready for a compressibility measurement. Upon

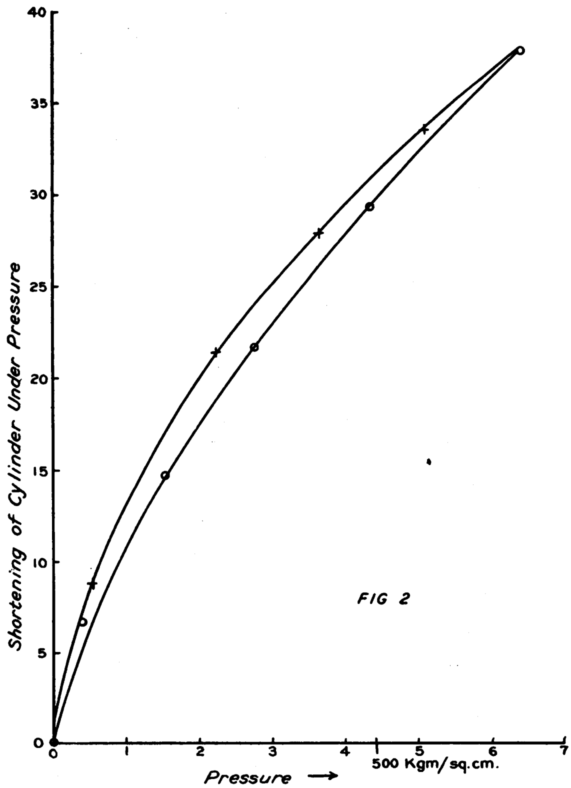
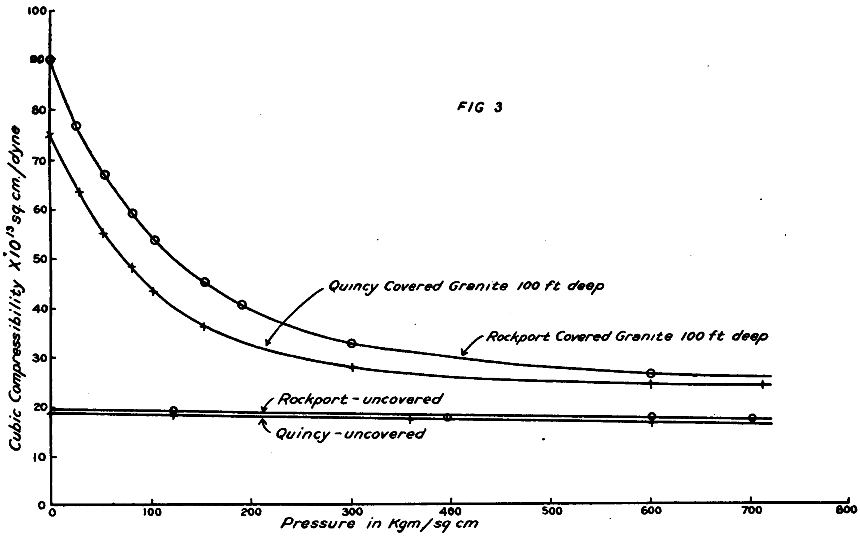


FIG 2

completion of an experiment the foil was stripped from the rock to permit detection of further evidence of a leak.

A blank run on the compressibility of a cylinder of soft steel covered with foil was made, and it was thus possible to prove that there was no contribution to the observed compressibility attributable to the existence of air spaces between the foil and the flat ends of the rock. When the compressibility of the covered rock was measured, the smallness of the permanent set found after each pressure run was considered good reason for believing the observed pressure effect to be due to the change in length of the rock rather than to the squeezing of the foil covering against the ends of the specimen. This conclusion was strengthened by the fact that successive runs on the same rock using entirely new covers gave the same compressibility within a few per cent. Moreover, the compressibility of covered and uncovered obsidian glass was found to agree, as it should, since such material is non-porous.

Description of Results.—Figure 2 is the graph of the shortening of a cylinder of covered Rockport granite against pressure. There is a permanent set amounting to about three per cent of the total shortening. The uncovered rocks show somewhat smaller amounts of permanent set. From such a graph it is not difficult to obtain measurements of the compressibility as a function of pressure by reading off the slope for, say, eight values of the pressure.



Just before taking a compressibility measurement to 800 kg./cm.[2] a ten-minute pressure seasoning to 1000 atmospheres was given the apparatus and specimen. A repetition of the compressibility measurement was found unnecessary. Even when the pressure seasoning lasted as long as five hours, the compressibility was unchanged.

The permanent set was found greatest for the rocks exhibiting the largest change in compressibility with pressure, that is, for the most porous rocks. On the other hand, pronounced hysteresis, as indicated by a great width for the hysteresis loop, was not always easily linked with high porosity. It is quite possible that most of the hysteresis was due to the presence of internal strains in the rocks, such as there must always be in a rock essentially composed of non-cubic crystals.

In the following tables the linear (α) and cubic compressibilities (β) at thirty degrees centigrade are given as a function of pressure for both the covered and uncovered rocks. The cubic compressibility was computed by tripling the mean value of the linear compressibilities. In figure 3 is presented the cubic compressibility of granite as a function of pressure.

The difference in behavior of each rock with and without cover is striking. The values for the uncovered rocks should be considered as the more accurately determined, chiefly because the small change in compressibility with pressure then observed made it easier to obtain from the graphs accurate values of shortening with pressure. The values of the compressibilities for the compact rocks are good to two per cent, while for the rocks showing rapid changes in compressibility with pressure, the error may rise as high as five per cent for the initial compressibility and two to three per cent at 840 kg./cm.^{2}.

Throughout the whole series of measurements the compressibility of each covered rock is greater than its value when uncovered. The difference between the two becomes smaller as the pressure is raised. This is what one would expect, for at high pressures the looseness of texture in the rock due to the presence of cavities and cracks is substantially removed. Thus we find the two values almost equal at 840 kg./cm.^{2}.

The change in the linear compressibility with direction parallels the vectorial change of E and σ. This is a natural relation, the cylinders having been cut respectively from the same blocks of rock and in the same directions. The results for French Creek norite will serve as an example. Of the three directions studied, the greatest linear compressibility occurs in specimen No. 2, and the least in No. 1. The measurements of E and σ show number two to have the smallest value and number one the greatest. Thus, as we should expect, a large E and σ accompany a small linear compressibility.

Description of Rocks Used.—Most of the rocks used in these experiments were described in a previous publication.[3] The following descriptions of additional rocks studied here are due to the kindness of H. J. Fraser, E. B. Dane, Jr., and C. S. Hurlbut, of the Department of Geology of Harvard University.

Obsidian, Lipari Islands.—This well-known material is essentially an unstrained rhyolitic glass, containing thread-like crystallites of iron oxide and minute feldspars totaling about two per cent of the volume. Alignment of the crystallites indicates a definite flow structure, which is macroscopically not conspicuous. A chemical analysis of this glass is to be found in Washington's Tables.

Peridotite (Dunite), North Carolina.—A large block of this astonishingly fresh, ultrabasic rock was generously supplied by Mr. A. W. Hyatt of Balsam (Balsam Gap), North Carolina. A sugary, holocrystalline, allo-

TABLE 1

LINEAR (α) AND CUBIC COMPRESSIBILITIES (β) AT 30°C. ($CM.^2$/DYNE)
(Cylinders numbered, mutually at right angles to one another)

	PRESSURE ($KG./CM.^2$)	$\alpha \times 10^{13}$ CYL. 1	$\alpha \times 10^{13}$ CYL. 2	$\alpha \times 10^{13}$ CYL. 3	$\beta \times 10^{13}$ MEAN
Quincy granite at surface (uncovered)	0	6.92	9.42	8.32	24.7
	60	6.76	9.05	8.12	24.0
	120	6.62	8.69	7.93	23.2
	240	6.30	8.27	7.62	22.2
	360	6.10	7.95	7.40	21.4
	480	5.93	7.78	7.25	21.0
	600	5.89	7.74	7.15	20.8
	720	...	7.73	7.09	20.7
	840	...	7.72	7.07	...
Quincy granite, 100 feet deep (covered)	0	20.9	31.1	23.6	75.6
	24	18.9	25.3	20.4	64.5
	48	17.1	21.1	17.4	55.6
	72	15.8	17.4	15.5	48.7
	96	14.7	15.1	14.2	43.9
	120	13.6	13.7	13.0	40.2
	144	12.7	12.7	12.1	37.6
	180	11.5	11.6	11.2	34.4
	300	9.52	9.81	9.51	28.8
	600	8.26	8.54	8.44	25.3
	720	8.18	8.22	...	24.6
Quincy granite, 100 feet deep (uncovered)	0		6.50	6.23	19.2
	60		6.35	6.15	18.8
	120		6.20	6.07	18.5
	240		5.88	5.93	17.7
	360		5.72	5.82	17.3
	480		5.58	5.72	17.0
	600		5.51	5.65	16.7
	720		5.49	5.63	16.7
	840		5.48	5.61	16.6
Quincy granite, 235 feet deep (covered)	0	30.0			89.9
	24	26.3			78.8
	48	23.2			69.7
	72	20.8			62.3
	96	18.7			56.0
	120	16.9			50.8
	144	15.5			46.5
	180	13.8			41.3
	300	10.4			31.2
	600	8.32			25.0
	720	7.84			23.6
Quincy granite, 235 feet deep (uncovered)	0	7.68	6.35		21.1

TABLE 1 (*Continued*)

	PRESSURE (KG./CM.²)	CYL. 1 $\alpha \times 10^{13}$	CYL. 2 $\alpha \times 10^{13}$	CYL. 3 $\alpha \times 10^{13}$	$\beta \times 10^{13}$ MEAN
	24	7.44	...		...
	60	7.09	6.26		20.1
	120	6.71	...		...
	180	6.38	...		...
	240	6.22	5.91		18.2
	360	6.15	5.71		17.8
	480	...	5.49		...
	600	...	5.31		...
	720	...	5.13		...
Rockport granite, 100 feet deep (covered)	0	33.0	28.2		91.7
	24	26.7	25.5		78.2
	48	22.1	23.4		68.2
	72	18.8	21.3		60.2
	96	16.8	19.6		54.6
	120	15.3	18.3		50.4
	144	14.2	17.1		47.0
	180	12.7	15.4		42.2
	300	10.6	11.5		33.2
	600	8.45	9.29		26.6
Rockport granite, 100 feet deep (uncovered)	0	6.46	6.53		19.5
	60	6.33	6.35		19.1
	120	6.22	6.22		18.7
	240	5.99	6.02		18.0
	360	5.92	5.91		17.7
	480	5.86	5.87		17.5
	720	5.79	5.75		17.3
French Creek norite (covered)	0	17.7	22.1	19.1	59.0
	24	16.1	21.1	17.4	54.6
	48	14.7	20.2	15.9	50.8
	72	13.5	19.1	14.6	47.1
	96	12.5	17.9	13.5	43.9
	120	11.5	17.0	12.5	41.1
	144	10.8	15.9	11.7	38.4
	180	9.74	14.4	10.6	34.8
	300	7.24	10.9	7.82	25.9
	600	4.74	6.42	5.40	16.6
	720	4.48	5.78	4.93	15.2
French Creek norite (uncovered)	0	4.58	4.94	4.43	14.0
	60	4.54	4.60	4.42	13.6
	120	4.52	4.42	4.38	13.4
	240	4.45	4.30	4.33	12.9
	360	4.39	4.22	4.30	12.9
	480	4.33	4.19	4.26	12.7
	600	4.26	4.17	4.24	12.6
	720	4.18	4.16	4.22	12.5
	840	4.12	4.15	4.20	12.5

TABLE 1 (*Continued*)

	PRESSURE (KG./CM.^{2})	CYL. 1 $\alpha \times 10^{13}$	CYL. 2 $\alpha \times 10^{13}$	CYL. 3 $\alpha \times 10^{13}$	$\beta \times 10^{13}$ MEAN
Sudbury norite (covered)	0	10.2	10.8		31.5
	24	9.58	10.16		29.6
	48	8.97	9.41		27.6
	72	8.38	8.80		25.8
	96	7.77	8.22		24.0
	120	7.17	7.75		22.4
	144	6.69	7.40		21.1
	180	6.07	6.93		19.5
	300	5.50	5.96		17.2
	600	5.40	5.57		16.5
	720	5.34	5.56		16.3
Sudbury norite (uncovered)	0	5.60	5.42*		16.5
	60	5.51	5.42*		16.4
	120	5.44	5.42*		16.3
	240	5.33	5.42*		16.1
	360	5.26	5.42*		16.0
	480	5.20	5.42*		15.9
	600	5.18	5.42*		15.7
Olivine diabase (covered)	0				17.1
	120				15.9
	300				14.3
	480				13.3
	720				12.6
Olivine diabase (uncovered)	0–200				14.6
	400–720				13.3
Peridotite (uncovered)	0	4.50	2.98*		11.2
	60	4.32	2.98*		10.9
	120	4.20	2.98*		10.9
	240	3.89	2.98*		10.3
	360	3.68	2.98*		9.98
	480	3.48	2.98*		9.68
	600	3.36	2.98*		9.51
	720	3.28	2.98*		9.37
Orthogneiss (covered; cylinder No. 1 cut with axis at right angle to plane of schistosity)	0			48.5	
	120			27.4	
	300			14.3	
	600			9.61	
	720			9.06	
Orthogneiss (uncovered)	0	8.24	6.32	6.18*	20.7
	60	7.62	6.17	6.18*	20.0
	120	7.13	6.03	6.18*	19.3
	240	6.36	5.82	6.18*	18.4
	360	5.85	5.65	6.18*	17.7
	480	5.45	5.57	6.18*	17.2
	600	5.10	5.52	6.18*	16.8
	720	...	5.48	6.18*	...

* No sensible change of α in range of pressure.

TABLE 1 (*Continued*)

	PRESSURE (KG./CM.^{2})	CYL. 1 $\alpha \times 10^{13}$	CYL. 2 $\alpha \times 10^{13}$	CYL. 3 $\alpha \times 10^{13}$	$\beta \times 10^{13}$ MEAN
Quartzitic sandstone (covered; cylinder No. 1 cut with axis at right angle to bedding)	0	19.7	23.3	15.7	58.7
	24	18.3	21.5	14.3	54.1
	48	17.2	19.7	13.3	50.2
	72	16.3	18.3	12.4	47.1
	96	15.6	17.3	11.8	44.8
	120	15.0	16.5	11.3	42.8
	144	14.5	15.9	10.9	41.3
	180	13.8	15.1	10.4	39.2
	300	12.1	13.2	9.48	34.8
	600	10.9	11.0	8.92	30.9
	720	10.5	10.5	8.82	29.9
Quartzitic sandstone (uncovered)	0	8.39*	9.40	8.86*	26.7
	60	8.39*	9.31	8.86*	26.6
	120	8.39*	9.22	8.86*	26.5
	240	8.39*	9.07	8.86*	26.3
	360	8.39*	8.92	8.86*	26.2
	480	8.39*	8.82	8.86*	26.1
	600	8.39*	8.76	8.86*	26.0
	720	8.39*	8.74	8.86*	26.0
Vermont marble (covered cylinder No. 2 cut with axis at right angle to bedding)	0	58.8	75.0	46.5	180.0
	24	42.0	47.1	26.2	115.0
	48	24.0	26.1	18.0	68.2
	72	18.0	18.6	13.6	50.3
	96	14.2	15.9	10.9	40.9
	120	11.7	12.2	9.12	33.1
	144	10.2	10.6	8.32	29.2
	180	8.79	9.12	7.95	25.9
	300	6.67	7.25	6.59	20.5
	600	4.29	5.62	5.10	15.0
	720	...	5.46	...	...
Vermont marble (uncovered)	0	4.17	5.19*	4.53	13.9
	120	4.06	5.19*	4.47	13.8
	240	3.90	5.19*	4.40	13.5
	360	3.79	5.19*	4.28	13.3
	480	3.69	5.19*	4.09	12.9
	600	3.61	5.19*	3.82	12.6
	720	3.53	5.19*	3.50	12.2
	840	3.46	5.19*	...	...
Limestone (covered; cylinder No. 1 cut with axis at right angle to bedding)	0	14.5	6.20	8.49	29.2
	60	13.9	6.12	8.29	28.2
	120	13.4	6.02	8.09	27.5
	240	12.4	5.90	7.75	26.1

* No sensible change of α in the range of pressure.

TABLE 1 (*Continued*)

	PRESSURE (KG./CM.^{2})	CYL. 1 $\alpha \times 10^{13}$	CYL. 2 $\alpha \times 10^{13}$	CYL. 3 $\alpha \times 10^{13}$	$\beta \times 10^{13}$ MEAN
	360	11.6	5.79	7.44	24.9
	480	11.0	5.73	7.25	23.9
	600	10.7	5.68	7.10	23.5
	720	10.4	5.65	6.94	23.0
Limestone (uncovered)	0	11.6*	5.88*	7.22	24.7
	60	11.6*	5.88*	7.13	24.6
	120	11.6*	5.88*	7.06	24.5
	240	11.6*	5.88*	6.96	24.5
	360	11.6*	5.88*	6.81	24.2
	480	11.6*	5.88*	6.71	24.1
	600	11.6*	5.88*	6.58	24.1
	720	11.6*	5.88*	6.45	24.0
	840	11.6*	5.88*	6.32	23.7
Dolomite (massive; covered)	0	14.2	10.60		37.1
	24	13.0	10.2		34.8
	60	10.6	9.63		30.4
	120	8.28	8.65		25.4
	240	6.62	6.73		20.1
	360	5.88	5.37		16.9
	480	5.40	4.91		15.5
	600	5.18	4.70		14.8
	720	4.99	4.44		14.2
Dolomite (uncovered)	0	4.11	3.81		11.9
	360	4.11	3.81		11.9
	720	4.11	3.81		11.9

* No sensible change of α in range of pressure.

triomorphic mass of medium grain, it is composed of olivine (92 per cent Mg_2SiO_4 and 8 per cent Fe_2SiO_4, as measured optically), 97 per cent; serpentine, two per cent; with chromite, carbonate and hornblende totaling one per cent. The olivines reach 4.4 mm. in diameter, the average being 0.75 mm. The chemical composition of this dunite must approximate that of the olivine alone, as found by Gonyer.[6]

Dolomite, Pennsylvania.—This material of Cambrian age, obtained through the courtesy of Professor B. L. Miller of Lehigh University, came from the Bethlehem Mines Corporation quarry just east of Bethlehem, Pennsylvania (about 40° 37′ N. Lat., 75° 22′ W. Long., Allentown topographic sheet). The rock is massive, with obscure bedding in the block actually studied. The mineral data are as follows:

	VOLUME, PER CENT	MAXIMUM DIAMETER, MM.	AVERAGE DIAMETER, MM.
Calcite	98	0.25	0.01
Quartz	1	0.25	0.1
Feldspar	1	0.2	0.1

TABLE 2

SUMMARY OF COMPRESSIBILITY DATA

	PRESSURE (KG./CM.²)	COMPRESSIBILITY $\beta \times 10^{13}$ UNCOVERED	COVERED	DENSITY
Quincy granite, at surface	0	24.7	..	2.61
	720	20.7	..	
Quincy granite, from depth of 100 feet	0	19.2	76.6	2.59
	720	16.7	24.6	
Quincy granite, from depth of 235 feet	0	21.1	89.8	2.64
	720	17.8[1]	23.6	
Rockport granite	0	19.5	91.7	2.63
	720	17.3	26.6[1]	
French Creek norite	0	14.0	59.0	3.05
	720	12.5	15.2	
Sudbury norite	0	16.5	31.5	2.85
	720	15.7[1]	16.3	
Olivine diabase	0	14.6[2]	17.1	2.96
	720	13.3[3]	12.6	
Peridotite	0	11.2	..	3.27
	720	9.37	..	
Orthogneiss	0	20.7	..	2.64
	720	16.6	..	
Obsidian	0	29.6	29.5	2.34
	720	29.6	29.5	
Quartzitic sandstone	0	26.7	58.7	2.64
	720	26.0	29.9	
Marble	0	13.9	180.0	2.71
	720	12.2[1]	15.0	
Limestone	0	24.7	29.2	2.69
	720	24.0	23.0	
Dolomite	0	11.9	37.1	2.82
	720	11.9	14.2	
Soft steel	0	5.99	..	7.79

[1] Value at 600 kg./cm.².

[2] Mean for range of 0–200 kg./cm.².

[3] Mean for range of 400–720 kg./cm.².

Numerous cracks carry a limonitic stain and along them the calcite has been locally recrystallized, with an increase in the size of the crystals.

Summary.—The compressibilities of a number of rocks of geophysical interest have been measured at thirty degrees centigrade for pressures up to 840 kg./cm.². The prediction of Adams and Williamson of a rapid rise in compressibility as the pressure is decreased has been verified. It is a remarkable effect in the case of covered rocks, and a very much smaller one for uncovered rocks. The variation of the compressibility with pressure is greater for the more porous rocks. Thus, in order of decreasing magnitude of this effect, we have marble, granite, limestone, Sudbury norite and Vinal Haven diabase. The compressibility of the uncovered rock is always found to be less than that of the same rock when

covered. At pressures up to 300 kg./cm.[2] the difference may be large, but it rapidly approaches zero at higher pressures. In many cases the difference is already unimportant at 840 kg./cm.[2]. Simple explanations of these pressure effects can be given, based upon the existence of many easily compressed cracks and cavities between mineral grains. The linear compressibility often shows a large variation with direction in the rock; it is naturally most striking in layered or bedded rocks.

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