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ELECTRICAL CONDUCTIVITY OF ROCKS UNDER SHOCK COMPRESSION

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The electrical conductivity of silicate rocks (quartzite, granite, and dry and wet tuffs) under single shock-wave loading is measured. It is shown that even at a shock-wave pressure of 20 GPa*, the conductivity of rocks changes by several orders of magnitude compared to the initial value* (10^{-9}–10^{-12} $\Omega^{-1} \cdot \mathrm{m}^{-1}$ *for dry rocks) and reaches* 0.01 $\Omega^{-1} \cdot \mathrm{m}^{-1}$ *for quartzite and granite and* 0.1–1.0 $\Omega^{-1} \cdot m^{-1}$ *for tuff. As the shock-wave amplitude increases from* 20 *to* 60 GPa*, the electrical conductivity increases by further one or two orders of magnitude. The experiments with rocks did not reveal a drastic change in electrical conductivity similar to the that observed for silicon dioxide (fused quartz) at a pressure of about* 40 GPa*.*

Studies of shock-induced changes of electrical conductivity of rocks involves developing calculation models for electromagnetic-pulse generation during underground explosions to control the comprehensive test ban treaty. Electrical conductivity data (as part of information on the properties of rocks in the Earth's interior) are also useful for solution of problem of geophysics [1].

The conductivity σ is a main electrical characteristic of media. The mechanism of electrical conduction of minerals and rocks are commonly determined using dependences of electrical conductivity on the temperature T and pressure p under static conditions [2]. The linear relations $\log\ \sigma = f(1/T)$ for silicate rocks have regions of abnormal variation of σ and bends at $T = 1200$–1400 K, which correspond to transfer from impurity conduction to intrinsic conduction. In the temperature range 470–1270 K, the electrical conductivity of the rocks of the granite–diorite series with 20–30% (by mass) quartz increases by five or six orders of magnitude. The dependences $\sigma(p)$ for rocks are nonlinear and reflect the additive effect of changes in the electrical conductivities of components. Thus, with increase in pressure to 2 GPa (in the temperature range 470–770 K), the conductivity of granites increases by not more than an order of magnitude, remains unchanged or even decreases, depending on the content of quartz and feldspars.

Under dynamic (shock-wave) loading, compression and increase in temperature of specimens proceed very fast. The shock-wave front is a powerful generator of defects, which facilitates increase in carrier concentration and electrical conductivity. High electrical conductivity during shock compression was recorded in experiments with various dielectrics. However, the papers on the electrical conductivity of rocks and minerals in shock waves are few in number. Of the available results, the data for fused quartz (SiO_2) and fayalite (Fe_2SiO_4) are of interest. For fused quartz at shock-wave pressure, the value of σ becomes several orders of magnitude larger, and at $p = 35$ GPa and a calculated temperature of 2800 K, it reaches 0.1 $\Omega^{-1} \cdot \mathrm{m}^{-1}$ [3]. In the range $p = 36$–40 GPa, a jumpwise (nearly two orders of magnitude) increase in σ was observed. An analysis of the properties of fayalite [4] showed that at a static pressure of 40 GPa, fayalite undergoes a structural transition (amorphization), which was also detected by a drastic change of σ in dynamic experiments [5]. Complex behavior of the electrical characteristics of quartz and other geological materials indicates that *a priori* estimation of the electrical conductivity of rocks under shock compression is unfeasible.

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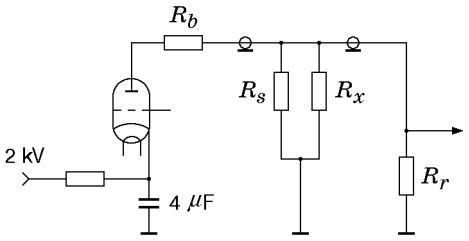

Fig. 1

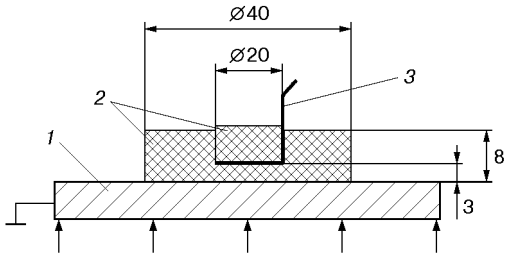

Fig. 2

Fig. 1. Circuit for resistance measurements.

Fig. 2. Diagram of experimental cell: 1) shield electrode; 2) specimen; 3) upper electrode end.

The present paper describes an experimental study of the conductivity of three silicate rocks: quartzite, granite, and tuff at shock-compression pressures of 20–60 GPa.

1. The electrical resistance of a rock subjected to shock-wave compression was measured by the electrocontact method of [6]. Pulsed current was supplied to the electrodes located in the test specimen, and a voltage drop was recorded. A diagram of the measurements is given in Fig. 1. The current supply is a charged capacitor. Capacitor discharge is initiated by a triggering signal a few microseconds before arrival of the shock wave at the specimen. At that time, the recorder (SUR-1 oscillograph) records the voltage drop V_s across the shunt resistance R_s, and with arrival of the shock wave at the specimen, it records the voltage drop V across the total resistance $R = R_s R_x/(R_s + R_x)$, where R_x is the measured resistance of the specimen. If the ballast resistance R_b and the input resistance R_r of the recorder are much higher than R_s, then the measured resistance is

$$R_x = R_s V/(V_s - V). \tag{1}$$

The experimental cell shown schematically in Fig. 2 is similar to the cells used previously in studies of the electrical conductivity of semiconductors and dielectrics (see, for example, [7]). The test specimen is located on the aluminum disk -like shield of an explosive device that produces a plane shock wave of constant amplitude in the specimen. The shield serves as the first electrode, and the second (upper) electrode having the shape of a 20-mm-diameter circle made of a 10 μm aluminum foil is located inside the rock. In the experiments on one-dimensional shock loading of the rock in the interelectrode gap, additional shock waves or rarefaction waves did not arise for a time of not less than 0.7 μsec. In the experiments, we measured the time dependence of the resistance of the specimen after arrival of the shock-wave front at the upper electrode. The electrical conductivity was calculated from the measured resistance and geometrical dimensions of shock-compressed specimen taking account of the edge effects:

$$\sigma = hf/(\varepsilon S R_x). \tag{2}$$

Here h is the initial height of the specimen, ε is the shock-induced compression of the specimen, S is the area of the upper electrode, R_x is the measured resistance, and f is a correction coefficient that depends on the ratio of the specimen height to the diameter of the upper electrode. For the chosen geometry of the experiments, $f = 0.8$ [8].

We studied the following most abundant silicate rocks:

1) Quartzite — a fine-crystalline quartz rock with 98% (by mass) silicon dioxide (SiO_2);

2) Medium-grained granite containing predominantly quartz, feldspars, and micas (73% SiO_2, 13% Al_2O_3, 4% Na_2O, and 3% K_2O);

3) Tuff — rhyolitic tuff lava containing 70% SiO_2, 15% Al_2O_3, 5% Na_2O, and 5% K_2O.

The rock specimens were prepared by turning. For better contact with the electrodes, the working areas of the specimens were ground, and the irregularities were not more than 10 μm high. Some tuff specimens were saturated with water, and for maintenance of moisture, the specimens were sealed in the experimental assembly by plasticine. Characteristics of the specimens are given in Table 1.

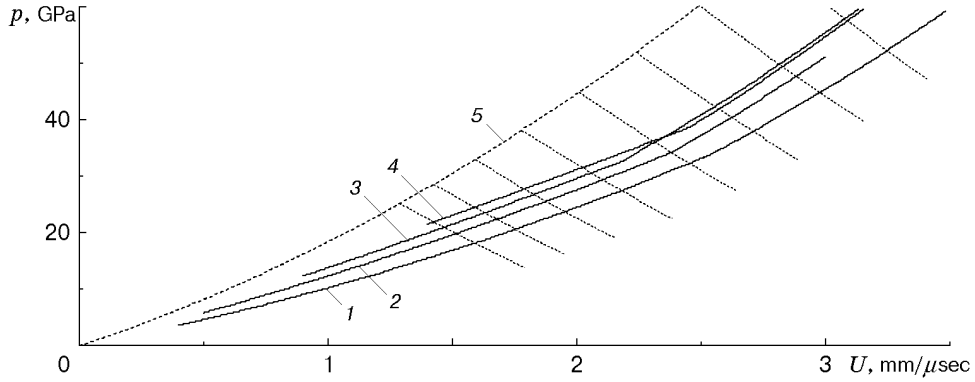

Fig. 3. Shock adiabats for dry tuff (1), wet tuff (2), granite (3), and quartzite (4) and shock adiabat and release isentropes of aluminum (5).

TABLE 1

Specimen	ρ_0, g/cm^3	Volume fraction, %	
		water	air
Tuff:			
dry	2.31	<0.1	11
wet	2.42	11	<0.5
Granite	2.62	<0.1	<0.5
Quartzite	2.65	<0.1	<0.1

2. Shock waves were produced by explosive launching and contact devices with aluminum shields. For known shock-wave parameters in the shield [9], the pressure p and mass velocity U are determined in the (p–U) coordinates by intersection of the release isentrope of aluminum with the shock adiabat of the rock (Fig. 3). The compression of the specimen is determined from the laws of conservation of momentum and mass at the shock front:

$$p = \rho_0 DU, \qquad \varepsilon = D/(D - U)$$

(ρ_0 is the initial density and D is the wave-front velocity).

For rocks with a high elastic Hugoniot limit (granite and quartzite, for which a two-wave structure is observed at loading pressures below 30–35 GPa), we used shock-compression parameters corresponding to the final state behind the plastic-wave front.

In determining the state of quartzite specimens, we used the shock adiabat of monocrystalline quartz [10]. Data for shock compressibility of granite are taken from [11]. For dry tuff, we used our previous experimental data.The pressure and compression of the specimens of wet (water-saturated) tuff were estimated from the a shock adiabat calculated in an additive approximation [12]. Water-saturated tuff was treated as a mixture of particles of the rock and water. For the rock, we used the shock adiabat of granite (tuff and granite are close in elemental composition and particle density), and the data on shock compressibility of water are taken from [13].

3. The time dependences of the resistance of the specimen calculated from formula (1) are given in Fig. 4. In determining the conductivity, we used the average resistance in the range $t = 0.1$–0.3 μsec after arrival of the wave front at the upper electrode ($t = 0$). These values of the resistance R_x, the electrical conductivity σ calculated from formula (2), and the pressure p and compression ε are given in Table 2.

It should be noted that the resistances determined in the experiments are not strictly constant in time. Thus, for dry tuff in the range $p = 20.5$–44.5 GPa, a small (about two-fold) increase in resistance (less pronounced at $p = 44.5$ GPa) is detected in 0.3 μsec after the beginning of recording (Fig. 4a), and at $p = 18$ and 52.5 GPa, there is no such an increase (Fig. 4b). We note that the pressures at which a change in the

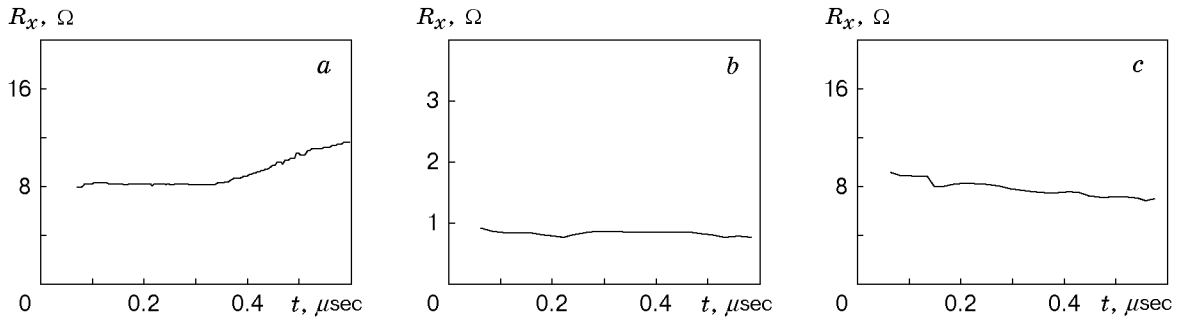

Fig. 4. Resistance of specimen versus time: (a) dry tuff ($p = 20.5$ GPa); (b) dry tuff ($p = 52.5$ GPa); (c) granite ($p = 58$ GPa).

TABLE 2

Specimen	p, GPa	ε	R_x, Ω	σ, $\Omega^{-1} \cdot \mathrm{m}^{-1}$
Dry tuff	18	1.46	85	0.06
	20.5	1.53	8	0.6
	20.5	1.53	30	0.2
	23.5	1.61	1.7	2.8
	27	1.70	2	2.3
	27	1.70	1.25	3.6
	32.5	1.74	0.6	7.3
	38	1.80	0.75	5.6
	44.5	1.85	0.5	8.1
	52.5	1.87	0.8	5.1
Wet tuff	19.5	1.40	4.1	1.3
	23.5	1.44	6.4	0.8
	25.5	1.50	2.4	2.1
	34	1.68	1.3	3.5
Granite	23.5	1.42	≈600	≈0.01
	30.5	1.58	28	0.2
	58	1.76	8	0.5
	58	1.76	10	0.4
Quartzite	24.5	1.38	≈700	≈0.01
	31.5	1.52	≈100	≈0.05
	31.5	1.52	220	0.02
	41.5	1.73	180	0.03
	49	1.76	65	0.07
	57.5	1.79	19	0.2
	57.5	1.79	16	0.3

resistance is observed corresponds to the region of phase transition in silicon dioxide [9, 10, 14]. The changes in the resistances of quartzite and granite specimens are of irregular nature, as might be expected for rock granular rock (Fig. 4c).

The dependence of log σ on shock pressure is given in Fig. 5 (the values of σ are taken from Table 2). The error in determining the conductivity of a particular specimen was expected to be less than 20%. As follows from results of repeated measurements, the experimental error far exceeds this value, which is apparently due to the difference in structure between specimens of the same rock and imperfection of the contact of the specimen with the electrodes. Figure 5 gives an approximation of the experimental data: the solid curve refers to quartzite and granite, which have close electrical conductivity, and the dashed curve corresponds to dry and wet tuff. The figure also gives the results of the experiments of Kondo et al. [3] for fused quartz

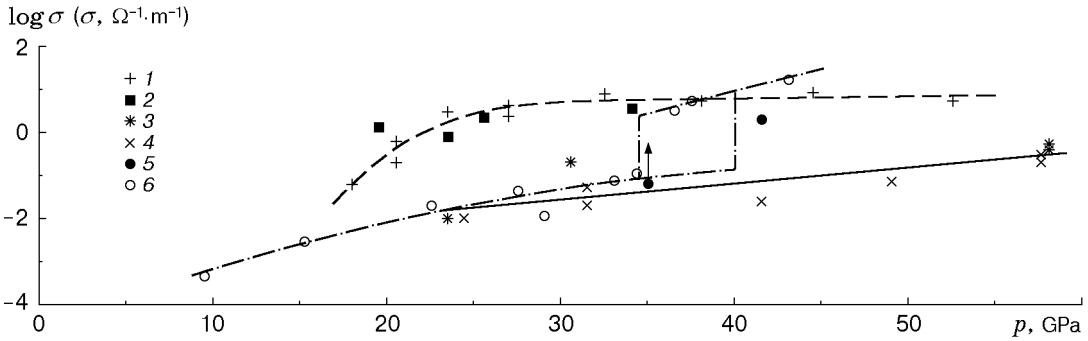

Fig. 5. Dependence of the logarithm of electrical conductivity of rocks on shock-wave pressure: the solid curve refers to granite and quartzite, the dashed curve refers to dry and wet tuffs, and the dot-and-dashed curve refers to fused quartz; points 1 and 2 refer to dry and wet tuffs, respectively, points 3 to granite, points 4 to quartzite, points 5 to fused quartz, and 6 to fused quartz [3].

(dot-and-dashed curve). Kondo et al. [3] noted the absence of changes in the (ionic) conduction characteristics in transition to the pressure region of the quartz–stishovite phase transformation. At higher pressures (36–40 GPa), a "jump" of electrical conductivity is detected. The change of electrical properties is confirmed by occurrence of a strong polarization signal. It is assumed that the drastic change in electrical conductivity is due to the previously unknown transformation. In the measurements of [3], the resistance of a specimen under single compression was determined at the moment the wave front arrived at the upper electrode, and the change in resistance with time was not recorded. In our experiments, we performed measurements in fused quartz (according to the diagram of Fig. 2) near the "jump" of electrical conductivity at pressures of 35 and 41.5 GPa. At $p = 35$ GPa, low conductivity of $\sigma = 0.06\ \Omega^{-1} \cdot \mathrm{m}^{-1}$ is recorded for about 0.12 μsec. In the subsequent 0.3 μsec, the value of σ increases by an order of magnitude (shown by an arrow in Fig. 5), which agrees with the assumption of [3] that the electrical properties of fused quartz may depend on time with approach to the "critical" pressure 40 GPa. At $p = 41.5$ GPa, a high value of $\sigma = 2\ \Omega^{-1} \cdot \mathrm{m}^{-1}$ is recorded, which confirms the conclusions of [3]. It should be noted that Postnov et al. [15] also observed a jumpwise increase in σ for fused quartz; in this case the transition pressure was $p = 29$ GPa.

In the region of the quartz–stishovite transition pressures, the electrical conductivity of dense rocks (granite and quartzite) is close in order of magnitude to the value of σ for fused quartz. At higher pressure, a difference is observed: for the rocks there is a smooth increase in σ. To estimate the activation energy of current carriers, it is necessary to consider the dependence $\sigma(T)$ for quartzite. In the literature, however, experimental and calculated temperatures on the shock adiabat of quartz are available only for pressures above 60 GPa [16, 17].

It is evident from Fig. 5, that the conductivity of the porous rocks (dry and wet tuff) is two orders of magnitude higher than that for dense rocks. For dry tuff, this difference is determined by the influence of air ionization in pores and an increase in conductivity of the skeleton due to the higher temperatures of shock compression for tuff (as a porous media [18]). The high electrical conductivity of wet tuff is due to dissociation of interstitial water. As follows from [19], at a shock pressure above 20 GPa, water is almost completely dissociated and its conductivity reaches $10^3\ \Omega^{-1} \cdot \mathrm{m}^{-1}$.

From results of the measurements performed, it is possible to calculate the conductivity of silicate rocks of various initial phase composition (porosity and moisture content). Calculation schemes should allow for structural changes in the pore space due to shock compression (volume occupied by the pore material, the presence and shape of current-conducting channels, etc.). Obviously, additional experiments are required for more reliable prediction of electrical conductivity.

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REFERENCES

1. M. A. Sadovskii, "Topical problems of geophysics in the complex of Earth sciences," *Vestn. Akad. Nauk SSSR*, No. 1, 60–63 (1968).
2. É. I. Parkhomenko and A. T. Bondarenko, *Electrical Conductivity of Rocks at High Pressures and Temperatures* [in Russian], Nauka, Moscow (1972).
3. K. I. Kondo, A. Sawaoka, and T. J. Ahrens, "Electrical measurements on fused quartz under shock compression," *J. Appl. Phys.*, **52**, No. 8, 5084–5089 (1981).
4. Q. Williams, E. Knittle, R. Reichlin, et al., "Structural and electronic properties of Fe $_2SiO_4$-fayalite at ultrahigh pressures: Amorphization and gap closure," *J. Geophys. Res.*, **95**, No. B13, 21.549–21.563 (1990).
5. T. Mashimo, K. I. Kondo, A. Sawaoka, et al., "Electrical conductivity measurement of fayalite under shock compression up to 56 GPa," *J. Geophys. Res.*, **85**, 1876–1881 (1980).
6. A. A. Brish, M. S. Tarasov, and V. A. Tsukerman, "Electrical conductivity of explosion products of condensed explosives," *Zh. Éksp. Teor. Fiz.*, **37**, No. 6, 1543–1550 (1959).
7. K. Kani, T. Yamada, and M. Abe, "Hugoniot and electric resistivity measurement on amorphous Se," in: *Proc. of the 4th Amer. Phys. Soc. Conf. on Shock Waves in Condensed Matter* (Spokane, Washington, July 22–25, 1985), Plenum Press, New York (1986), pp. 477–482.
8. A. C. Mitchell and R. N. Keeler, "Technique for accurate measurement of the electrical conductivity of shocked fluids," *Rev. Sci. Instrum.*, **39**, No. 4, 513–522 (1968).
9. Yu. N. Zhugin, K. K. Krupnikov, N. A. Ovechkin, et al., "Some features of the dynamic compressibility of quartz," *Fiz. Zemli*, No. 10, 16–21 (1994).
10. J. Wackerle, "Shock-wave compression of quartz," *J. Appl. Phys.*, **33**, No. 2, 922–937 (1962).
11. S. P. Marsh (ed.), *LASL Shock Hugoniot Data*, Univ. California Press, Berkely, CA (1980).
12. A. N. Dremin and I. A. Karpukhin, "Method for determining the shock adiabats of dispersed materials," *Prikl. Mekh. Tekh. Fiz.*, No. 3, 184–189 (1960).
13. I. I. Sharipdhzanov, L. V. Al'tshuler, and S. E. Brusnikin, "Anomalies of the shock and isentropic compressibility of water," *Fiz. Goreniya Vzryva*, **19**, No. 5, 149–153 (1983).
14. T. J. Ahrens and J. T. Rosenberg, "Shock metamorphism: Experiments on quartz and plagioclase," in: *Shock Metamorphism of Natural Materials*, Mono Book Co., Baltimore (1968), pp. 59–81.
15. V. I. Postnov, S. S. Nabatov, and V. V. Yuakishev, "Investigation of the behavior of fused quartz behind the shock-wave front by measuring electrical conductivity," in: *High-Energy Action on Materials*, Proc. IX Int. Conf. (Novosibirsk, August 18–22, 1986), Institute of Hydrodynamics, Novosibirsk (1986), pp. 106–110.
16. G. A. Lyzenga and T. J. Ahrens, "Shock temperatures of SiO_2 and their geophysical implications," *J. Geophys. Res.*, **88**, No. B3, 2431–2444 (1983).
17. L. V. Al'tshuler and I. I. Sharipdzhanov, "Additive equations of state for silicates at high pressures," *Izv. Akad. Nauk SSSR, Fiz. Zemli*, No. 3, 11–28 (1971).
18. Ya. B. Zel'dovich amd Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Magnetohydrodynamic Phenomena* [in Russian], Nauka, Moscow (1966).
19. S. D. Hamann and M. Linton, "Electrical conductivity of water in shock compression," *Trans. Farad. Soc.*, **62**, 2234–2241 (1966).