Reports

Granites: Relation of Properties in situ to Laboratory Measurements

Abstract. *The velocity of compressional waves and electrical resistivity in granite* in situ *measured in two 3-kilometer boreholes exhibits very little variation with depth, in contrast with the variation predicted from laboratory measurements on dry samples. These observations can be explained either by the absence of small open cracks in the rocks* in situ *or by the effects of complete saturation with water. The seismic velocities of many granites at shallow depths in the earth's crust may be significantly larger than was previously believed. Other properties are also affected; correction for the effect of cracks on thermal conductivity raises the average heat flow in shield areas by as much as 20 percent.*

The presence of open cracks (*1*) in crystalline material affects significantly such physical properties as electrical conductivity (*2*), thermal conductivity (*3*), velocities of both shear and compressional waves (*4*), compressibility (*5*), Poisson's ratio (*6*), and fluid permeability (*7*). These properties vary with stress because the cracks tend to close at high pressure. The electrical conductivity of a granite with fluid-filled cracks decreases by several orders of magnitude with the change of hydrostatic pressure from 1 bar to 2 kb even though the electrical conductivity of the individual minerals generally increases. The bulk elastic properties also change greatly over this pressure range. In granites, the velocity of compressional waves changes typically by 30 to 50 percent, and the compressibility changes by a factor of 3 to 10. Other properties exhibit correspondingly large changes (Table 1). Implicit in the use of these data in the interpretation of field observations on the earth's outer few kilometers is the assumption that the properties measured in the laboratory on small, crack-filled rock specimens at the appropriate pressures and temperatures are the same as the properties of the rock *in situ*. This assumption is incorrect for the granites investigated and, therefore, by inference may be incorrect for such other low-porosity rocks as most igneous rocks, some metamorphic rocks, and perhaps high-density carbonates. The large changes with pressure of the velocity of compressional waves measured in the laboratory on granites are not observed *in situ* in the granite penetrated by two deep wells.

Parts of the sonic logs for two wells are shown in Figs. 1 and 2. The No. 1 Matoy well (Fig. 1) in southeastern Oklahoma was drilled in 1955 to a total depth of 3814 m, and it represents the deepest penetration of granite in the world. The rocks exposed are granite, diorite, and diabase. Petrographic descriptions of the cuttings and cores are given by Ham *et al.* (*8*). The granite is similar to that found in the outcrop of the Tishomingo-Troy area of Oklahoma.

The Wind River hole (Fig. 2) was drilled in 1964 to a depth of about 3063 m. The petrography of the cores obtained in this borehole was reported by Ebens and Smithson (*9*).

Several remarkable features are displayed by the logs of these two wells. The velocity logs of Figs. 1 and 2 show high values near the surface when compared with the values predicted from laboratory data, and the change of velocity between the top and bottom of the wells is very small. (The lithostatic pressure at a depth of 3½ km in granite is approximately 1 kb.) The electrical resistivity also shows little change with depth. Measurements of the velocity of compressional waves in the laboratory on cores from the Wind River hole, at pressures of a few bars, show typical values for granite, that is, 4 to 5 km/sec. The value indicated by the sonic log was 6 km/sec for the rocks *in situ*.

Although the variation of velocity in the Wind River hole is somewhat larger than it is in the Matoy well, the general trend is clear. The data at shallow depths are particularly significant. At depths less than 1500 m, there seems to be no increase of velocity with depth, an observation contrary to the predictions based on laboratory data. Petrographic analysis of the cores (Fig. 2) shows that the various cores to depths of 1500 m are essentially constant mineralogically, and that the increase of velocity at depths greater than 1500 m is associated with an increase of mafic content (*9*). The chemical analyses of these same cores also show little variation to a depth of 1500 m (*10*).

The integrated travel times of seismic

Table 1. Properties of granite measured in the laboratory as a function of confining pressure. Thermal conductivities are for Casco granite; all other data are for Westerly granite. Abbreviations: P, confining pressure; V_p, velocity of compressional waves (*19*); V_s, velocity of shear waves (*19*); ρ, electrical resistivity, saturated with pore fluid of .3 ohm-m resistivity (*7*); k, permeability (*7*); K, thermal conductivity of dry Casco (B) granite (*3*); K_s, thermal conductivity of saturated Casco (B) granite (*3*); β, volume compressibility (*5*); and nd, nanodarcys.

P (bar)	V_p (km/sec)	V_s (km/sec)	ρ (ohm-m)	k (nd)	K (cal/cm sec °C)	K_s (cal/cm sec °C)	β (Mb^{-1})
0	4.15	2.69			7.11	7.70	8.3
50			310	350	7.31	7.75	
100	4.82	3.02	420	230	7.43	7.78	5.4
250			650	118	7.62	7.81	
500			930	63	7.73	7.84	2.89
1000	5.71	3.38	1400	35	7.81	7.89	2.46
2000	5.83	3.48	2500	15			2.16
4000			4900	4.2			2.03
6000							1.96
10000	6.21	3.59					1.84

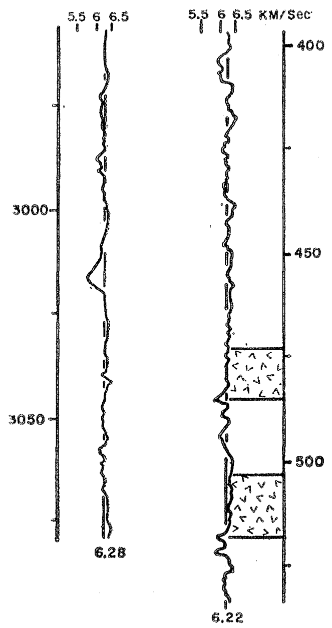


Fig. 1. Sonic log for two intervals of the Phillips No. 1 Matoy well in southeastern Oklahoma (Section 24, Township 5S, Range 11E, Bryan County). The horizontal scale is in kilometers per second, vertical scale in meters. Most of the rock in these intervals is identified as granite from petrographic observations on cuttings; the rock in the section indicated by a checked pattern is diabase.

waves in each well were verified by obtaining the total travel times to a borehole seismometer lowered to various depths. The differences were consistently less than 0.1 percent.

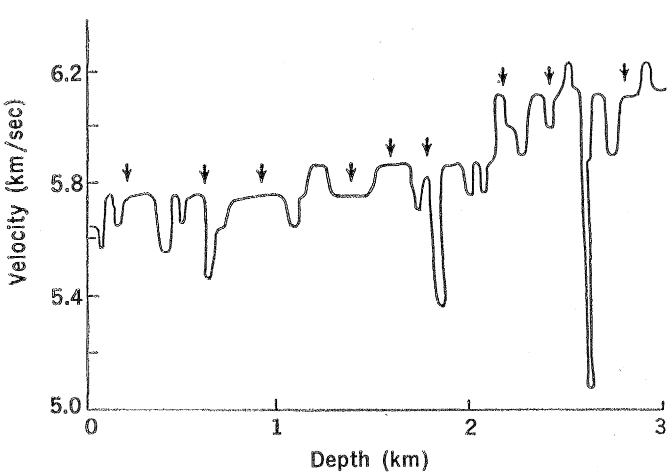
Cores were not obtained from the Matoy well, but Ham *et al.* (*8*) state that the Tishomingo-Troy granite, which is exposed at the surface several miles from the well, is similar. The compressional velocities, determined by ultrasonic technique (*11*) on samples for the Troy granite quarry, are shown in Fig. 3 (curve marked *T*) together with similar data for other granites and the velocities *in situ* for the Matoy well. Values of the three orthogonal Troy samples differed by less than 1 percent at all pressures above 50 bars. Several features are noteworthy—the small change of velocity of the rocks in place (as compared with the laboratory measurements), the relatively high (for granite) velocity of the rock *in situ*, and the fact that the laboratory values approach asymptotically with pressure the values *in situ*. The velocities in the rocks *in situ* coincide with the linear extrapolation of velocities measured at higher pressures.

Most of the difference between the velocity of rocks *in situ* and in the laboratory might be due to the effect of saturation (*12*). The velocity of the Troy granite, at atmospheric pressure, dry is 5.30; fully saturated, 5.95; and *in situ* (extrapolated to atmospheric pressure), 6.2 km/sec. Our measurements on other granites show that the effect on velocity of saturation is significant. The change of V_p with pressure observed in the saturated Troy granite may be due to incomplete saturation.

The electrical resistivity of the granite in the Matoy well is shown in Fig. 4. The resistivities, as measured in the laboratory (*2*), are shown also for several granites. The laboratory values have been corrected for temperature. The change with depth of electrical resistivity in the well is less than the laboratory values would indicate. Because the salinity of the connate water in the granite *in situ* is unknown we emphasize the lack of change of resistivity with depth.

There are two possible explanations of these observations. The cracks inferred from laboratory data may not be present in the granites *in situ* (they were introduced into the rock during its removal from the earth), or cracks may be present *in situ* and the high velocities are due to complete saturation with water. Preliminary check of velocities of several rocks (at room conditions) that had been saturated with water by the procedure of Brace *et al.* (*2*) shows that the velocity of some rocks is near the value predicted by linear extrapolation from high pressures.

The data from short (less than 20 km) refraction surveys over granites typically show values of compressional velocity near 5.0 km/sec (*13*). For the Tishomingo-Troy granite Weatherby *et al.* (*14*) observed over a 120-m profile values that increased from 4.54 at the surface to 5.23 km/sec at an estimated penetration of 9 m.



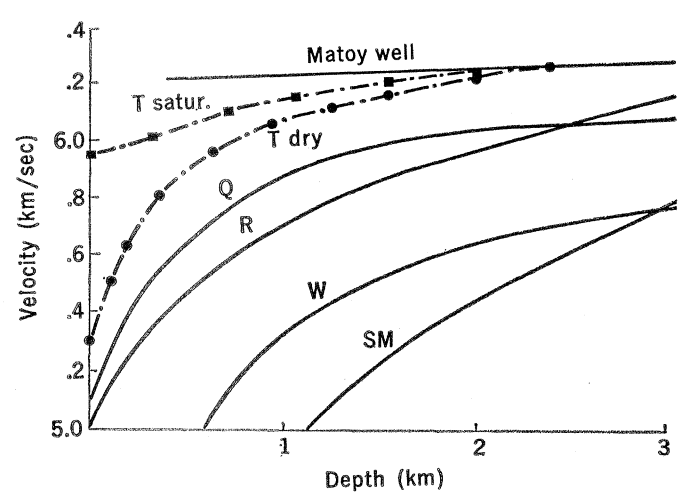


Fig. 2 (left). Compressional velocities of rocks penetrated by the drill hole in Wind River, Wyoming (Section 2, Township 32N, Range 107W, Sublette County). Values were obtained from the sonic log by averaging values over intervals of 33 m. Arrows indicate depths at which cores were obtained (*9*) and that chemical analyses are available (*10*). Fig. 3 (right). Velocities of compressional waves in several granites, as a function of depth, and in granite penetrated by the Matoy well. Pressures measured in the laboratory were converted to depths on the assumption that confining pressure equals lithostatic pressure; no corrections were made for pore fluid pressures. Departures of the velocity on the Matoy log from the mean value shown here, for granite sections, throughout the total well depth were about the same as in Fig. 1. Abbreviations: *T*, Troy granite; *Q*, Quincy; *R*, Rockport; *W*, Westerly; *SM*, granite from Stone Mountain.

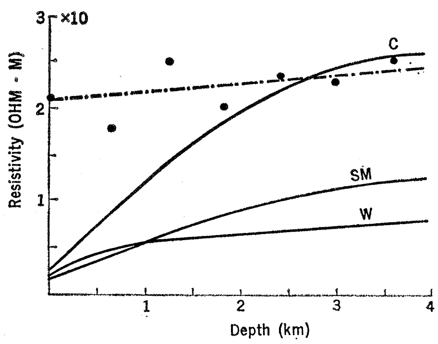


Fig. 4. Electrical resistivity of granite in the Phillips No. 1 Matoy well, southeastern Oklahoma, indicated by the black circles. Shown also are typical curves for several granites, saturated with 0.1*N* NaCl solution, as measured in the laboratory (*2*). The values have been corrected to borehole temperatures. Abbreviations: *C*, Casco granite; *SM*, Stone Mountain granite; *W*, Westerly granite.

The scatter in arrival times at larger distances is usually too large to distinguish between velocity-depth relations that reach 6 km/sec at a few kilometers and those that reach 6 km/sec at depths of only tens of meters. Velocities in granites of about 5 km/sec very near the surface are well substantiated and are due probably to weathering effects.

The absence of small, open cracks that close due to lithostatic pressure with depth in the earth's crust holds serious implications for geophysics. Although Gutenberg, Landisman, and Mueller (*15*) suggested the possibility of low velocity zones in the crust, their suggestion has not gained wide acceptance among seismologists. If rocks *in situ* do not exhibit the rather large increase of velocity due to pressure shown by unsaturated crack-filled rocks in the laboratory, the effects of pressure and temperature on the properties of rocks *in situ* are more nearly equal and the existence of low-velocity layers at shallow depth in the crust now appears to be more likely. For example, in the western high-heat-flow province of the United States (*16*), the gradients are probably sufficiently high to produce a low-velocity zone in the crust throughout much of the region.

The problem of duplicating conditions *in situ* for measurements in the laboratory is also important to heat-flow determinations. Walsh and Decker (*3*) demonstrated the necessity of measuring thermal conductivity on water-saturated specimens. Our observations emphasize their conclusions. On the basis of our set of heat-flow data (*17*), several authors noted that the heat flow beneath the Precambrian shields (Canadian, Australian, and Baltic, and the others by inference) is about 20 percent lower than the "normal" heat flow beneath continental areas. The "measured" heat flow is the product of the thermal gradient, which is measured in place, and the thermal conductivity, which is measured in the laboratory on small specimens. It is possible that the thermal conductivities reported and used to calculate the heat flow for rocks from the Precambrian shield areas are too low by as much as 10 to 15 percent, roughly the difference in apparent heat flow beneath Precambrian shields and "normal" heat flow beneath continental areas.

The importance of the electrical properties of the crust for the possibility of the propagation of electromagnetic waves in the earth for the purposes of communication as well as exploration has been noted (*18*). All of the determinations in the laboratory of the electrical properties of rocks as models of crustal rocks have been made on specimens in which cracks are present. The effect of these cracks, and especially their behavior as a function of pressure, together with the nature of the fluids that fill the cracks are the main parameters that control the electrical properties of rocks. If the cracks do not exist in the rocks *in situ* then the estimates based on laboratory data may be different by several orders of magnitude from the true values of the properties *in situ*.

In conclusion, the state of granites *in situ* in the outer few kilometers of the earth's crust cannot be duplicated in the laboratory by the application of temperature and pressure only, if crack porosity is the same as it is *in situ*. The presence of these cracks, pore fluids, pore pressure, and pore configuration affect the velocity and electrical resistivity significantly.

The velocity of compressional waves in two granite bodies extending from the surface to about 3½ km, as measured in the borehole, is much larger and changes much less than would be predicted from laboratory measurements on dry samples. The velocity *in situ* corresponds to the intrinsic properties of the rock obtained by extrapolating to lower pressures the properties measured in the laboratory as a function of pressure from 4 to 10 kb. The electrical resistivity of the granites *in situ*, as determined from the logs, changes less with depth than would be predicted on the basis of laboratory data obtained on similar rocks.

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References and Notes

1. The term crack is used to describe the very small openings that are believed to occur in granite rocks which have, in general, porosities less than 0.01 or 0.02. These cracks might be several tens of microns wide by a few millimeters long. Jointing, cleavage, and fracture are not cracks in this sense. See (*5*) and (*6*) for detailed discussion.
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20. We thank W. F. Brace, T. R. Madden, and S. Solomon for discussions; and F. Birch, W. F. Brace, F. Press, and S. Solomon for reviewing our manuscript. Without the use of the well logs for the Wind River hole and the Phillips Petroleum Company's Matoy well, this study would have been impossible. Supported by NASA contract NGR-22-009-176.

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