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SOME DYNAMIC CHARACTERISTICS OF ROCKS

by

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and

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ABSTRACT. This investigation consists of a study of the transmission and decay of pulses produced both by impact and explosive loading in a rock classified as a diorite. The samples were chosen and prepared with sufficient care and tested under identical conditions so that reproducibility of results comparable to that expected in metallic systems was obtained, indicating that the concept of nonreproducibility in geologic materials is not well founded.

Ballistically suspended Hopkinson bars of diorite of 3/4-inch diameter and approximately 22 inches long were subjected to longitudinal impact by spherical and flat-ended cylindrical projectiles of hardened steel at an initial velocity of about 3,300 in/sec. Strain gages attached to the specimens at various stations permitted a recording of the shape and velocity of propagation of the resultant wave. Similar experiments were performed on an aluminum alloy bar of identical size to assess the magnitude of the dispersion resulting from the three-dimensional character of the rod. The nature of the transformation of the pulse during passage permits an assessment of the validity of various models proposed for geologic substances in the field of seismology. A further detailed study of the internal response of the samples to such pulse passage was accomplished by means of microscopy and static tests, which correlated very well with the dynamic results. The average propagation velocity of a pulse generated by a contact explosion in a rectangular block of diorite was also determined.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

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U. S. NAVAL ORDNANCE TEST STATION

AN ACTIVITY OF THE BUREAU OF NAVAL WEAPONS

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FOREWORD

The material in this report represents part of a continuing applied research program in support of explosive ordnance problems at the U. S. Naval Ordnance Test Station.

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CONTENTS

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INTRODUCTION

In recent years, the propagation of waves in rocks and soils has assumed increasing technological importance, and the subject has thus received corresponding attention. Since the equations of motion and boundary and initial conditions are identical to those employed in problems involving more familiar materials, the difference in the analytical representation of the physical situation and results deduced therefrom must be attributed to the differences in the material behavior of the medium. Here, however, geological raw materials exhibit characteristics that are considerably at variance from those of the more conventional transmitting media. This report is concerned with some aspects of the response of a particular type of rock to dynamic loads, and the difference between this response and that of a common aluminum alloy subjected to identical loading conditions. The purpose of this study is a preliminary effort to gain an understanding of the nature of the dissipative process present in the transmission of waves in such a substance with the eventual objective of establishing a relation describing the material behavior that is of relatively simple form, yet sufficiently accurate so as to provide usable results in the prediction of wave phenomena.

A popular conception, commonly expressed in the literature, is that geologic materials such as rock are extremely inhomogeneous, and highly directional in behavior; also variable grain size and chemical composition present additional problems in testing. This notion is well founded when random samples are chosen from random locations, for a study of a single rock will yield widely divergent results if the criterion of the rock name is the sole basis for the selection of specimens. Thus a single rock name encompasses materials that can vary widely in composition, grain size, structure, alteration, the presence of inclusions, and related effects that cause significant differences in mechanical properties. On the other hand, careful selection of a single rock type, as in the present investigation, with attention to details of physical structure in all respects will give accurately reproducible data, regardless of the locality from which the samples are collected, indicating that the concept of the nonreproducibility of properties of geologic materials is a myth. In other words, when the same precautions are observed in the selection of natural specimens as in the composition, manufacturing procedure, processing and heat-treatment of a specified type of steel, aluminum alloy or plastic, the data derived from a number of samples subjected to identical experimental conditions are equally uniform.

In addition to the sample selection procedure per se, significant sources of variation in collected data for rocks commonly result from poor preparation techniques, which selectively damage the crystal structure or chemical composition of portions of sample suites, and from the poor choice of test methods. As an example of the latter, a pulse length shorter than the grain size in a given test material will lead to highly variable results and the need for interpretation based on statistical methods. In view of this, the methods of sample selection, preparation, and testing in a project must be carefully delineated in any meaningful discussion of both static and dynamic properties of such easily damaged materials as rocks or other similar brittle solids. However, when properly executed, such procedures permit interpretations of behavior and behavior changes to be drawn from relatively few experiments involving both macroscopic measurements of pulse metamorphosis and travel time and microscopic examination of the internal grain structure response of the materials to pulse passage, accomplished by careful thin section techniques.

The present investigation is concerned with the determination of various properties of a specific type of rock, a diorite. Specimens were subjected to standard static compressive tests and to impulsive loading by two types of projectiles. The changes in wave form and the velocity of pulse propagation between measuring stations were observed, some of the results being compared to data obtained under identical conditions in a 2024-T4 aluminum bar. Microscopic examinations were conducted of the crystal structure of both virgin and shocked rock specimens. Finally, the average velocity of shock propagation of a high-amplitude pulse produced by a contact explosion was determined. Corresponding properties of the rock and the aluminum alloy are presented to indicate the nature of the difference of behavior of the two materials under these loading conditions. The results of the pulse propagation tests were compared to the predicted performance of various analytical models proposed for geologic substances.

SUMMARY OF PREVIOUS INVESTIGATIONS

The propagation of seismic waves and interpretation of seismograms have been analyzed most frequently on the basis of a homogeneous, isotropic, albeit layered elastic medium (Ref. 1 and 2). In the case of underground explosions, the investigation of the transient generated at "moderate" pressures has been pursued on the same basis in a continuous medium (Ref. 3-10), extending even to an explanation of fracture processes (Ref. 9-14). The partial success of such an approach to the failure phenomenon is attributable to the high ratio of compressive to tensile strength of rocks that permits an incident compressive pulse small in comparison with the breaking strength to produce spalling upon reflection from a free surface as a tensile wave. This concept has been utilized in a recent investigation of the dynamic tensile strengths of basalt and sandstone determined from measurements in a Hopkinson bar and the use of a one-dimensional theory of elastic wave propagation (Ref. 15).

The propagation of pulses at high pressures has been universally described on the basis of hydrodynamic theory involving the Rankine-Hugoniot shock front conditions that assume a negligible rigidity of the medium and a state of thermodynamic equilibrium. Experiments seem to confirm that both of these conditions are fairly well satisfied for a sufficiently high shock pressure and short rise time. It has been suggested that an elastic analysis of the propagation phenomenon would be appropriate in the region beyond the fracture zone (Ref. 16), that is, at pressures below the crushing strength of the material. However, the scattered investigations of the transition of the pulse from one regime to the other have been inconclusive.

Consideration has also been given to the nature (Ref. 17 and 18) and mathematical representation of dissipative mechanisms in the analysis of pulse propagation in the earth, primarily in an attempt to explain discrepancies appearing in seismographic records interpreted on a purely elastic basis. This effort has proceeded in two directions: (1) laboratory determinations of the attenuation of waves in rock specimens, ascertained from the measured decay of ultrasonic pulses (Ref. 19–21) and the energy dissipated per cycle in the transverse vibrations of beams (Ref. 22), or field measurements of the propagation characteristics of waves initiated by explosive sources, and (2) an analysis of several theoretical models based upon incorporation of various simple frictional processes. The latter approach is complicated by conflicting experimental evidence. Attenuation factors have been determined experimentally that vary as different powers of the frequency of harmonic components present; alternatively, in a number of cases, the dissipation function appears to be independent of frequency (Ref. 20, 23 and 24). In particular, the ratio of energy loss per cycle to maximum elastic energy stored, $\Delta E/E$, in transverse vibration tests was found to be independent of frequency in the range from 40 to 120 cps for specimens of sandstone, oolitic and shelly limestone, granite, dolerite and diorite specimens, the latter exhibiting the lowest of the values at 5% (Ref. 22).

A corollary controversy in geophysical circles has developed around the question as to whether this attenuation is accompanied by dispersion. It has even been suggested that internal friction for consolidated rock appears to have a negligible effect at frequencies up to 100 cps (Ref. 1) --in contradiction to the results cited above--and would thus not significantly affect seismic phenomena, though it might be of considerable importance in the propagation of explosively or impact generated waves. Only Pierre shale of Eastern Colorado appears to conform experimentally to the attenuation and dispersion requirements of a simple, viscoelastic solid, namely the Kelvin-Voigt model (Ref. 25–27).

This solid has been employed as the most common anelastic model for the earth, and its specification leads to the one-dimensional differential equation of motion

$$\left[1 + \frac{\eta}{E}\frac{\partial}{\partial t}\right]\frac{\partial^2 u}{\partial x^2} = \frac{1}{c_o^2}\frac{\partial^2 u}{\partial t^2} \tag{1}$$

where u is the displacement in the direction of propagation x, t is time, η is the Stokes' viscosity term, E is Young's modulus, and

$$c_o = (E/\rho)^{\frac{1}{2}} \tag{2}$$

is the "rod" wave velocity, with ρ as the density of the material. Numerous theoretical investigations applying to seismic phenomena have been conducted with the aid of Eq. 1 (Ref. 1, 24-35). It has been shown that the propagation of a plane harmonic compression wave through such a medium, characterized by frequency ω and wave number k, can be described by the component

$$u = u_o\, e^{-\alpha x}\, e^{i(\omega t - kx)} \tag{3}$$

provided the frequency-dependent phase velocity $c \equiv \omega/k$ and attenuation coefficient α are determined by the relations

$$\frac{c}{c_o} = \left[-\left(\frac{1 + \sqrt{1 + \zeta^2}}{\zeta}\right)^2 + 2\left(1 + \sqrt{1 + \zeta^2}\right) + 1\right]^{\frac{1}{2}} \quad \text{with} \quad \zeta \equiv \frac{\omega\eta}{E} \tag{4}$$

and

$$\alpha = \frac{\omega}{\zeta c}\left[-1 + \sqrt{1 + \zeta^2}\right] \tag{5}$$

The decay constant can also be expressed in terms of the logarithmic decrement δ and hence as a function of $\Delta E/E$ by

$$\alpha = \frac{\delta\omega}{2\pi c} \quad \text{and} \quad \frac{\Delta E}{E} = 1 - e^{-2\delta} \tag{6}$$

Among many well-known solutions of Eq. 3, the case of a step pulse of displacement at the origin has been determined in the vicinity of the principal part of the disturbance (Ref. 31).

To obtain a better fit with a large body of experimental data, a solid friction type of mechanism has been attributed to rock-like materials, so that the wave propagation equation for rods is given by (Ref. 23 and 24)

$$\left[1 + \frac{1}{|\omega| Q_o} \frac{\partial}{\partial t}\right] \frac{\partial^2 u}{\partial x^2} = \frac{1}{c_o^2} \frac{\partial^2 u}{\partial t^2} \tag{7}$$

where Q_o is assumed to be a dimensionless constant that is connected to the energy loss per cycle through the relation (Ref. 36)

$$\frac{1}{Q_o} = \frac{1}{2\pi} \frac{c}{c_o} (1 - e^{-2\delta}) \tag{8}$$

The absolute value of the angular frequency, $|\omega|$, is included in Eq. 7 to assure absorption of both positive and negative frequency terms of the Fourier spectrum of the pulse. The dissipative quantity in this relation corresponds to the well-known structural damping factor frequently used in vibration analysis. A harmonic component $e^{i(\omega t - kx)}$ will propagate in such a medium with a frequency-independent phase velocity c given by

$$c = \frac{c_o}{\gamma} \left[1 + \frac{1}{Q_o^2}\right]^{\frac{1}{2}} \quad \text{where} \quad \gamma \equiv \left[\tfrac{1}{2}\left(1 + \sqrt{1 + \frac{1}{Q_o^2}}\right)\right]^{\frac{1}{2}} \tag{9}$$

and a frequency-dependent absorption coefficient α specified as

$$\alpha = \frac{\phi\omega}{c} \left[1 + \frac{1}{Q_o^2}\right]^{\frac{1}{2}} \quad \text{with} \quad \phi \equiv \left[\tfrac{1}{2}\left(-1 + \sqrt{1 + \frac{1}{Q_o^2}}\right)\right]^{\frac{1}{2}} \tag{10}$$

An initial impulse of displacement at x = 0, represented by I, leads to displacement

$$u = \frac{I\phi c_o x}{\pi} \left[\frac{\left(1 + \frac{1}{Q_o^2}\right)^{\frac{1}{2}}}{\tau^2 c_o^2 \left(1 + \frac{1}{Q_o^2}\right) + x^2 \phi^2}\right] \quad \text{with} \quad \tau \equiv t - \frac{\gamma x}{c_o \left[1 + \frac{1}{Q_o^2}\right]^{\frac{1}{2}}} \tag{11}$$

with a peak value u_{max} of

$$u_{max} = \frac{I c_o \left[1 + \frac{1}{Q_o^2}\right]^{\frac{1}{2}}}{\pi \phi x} \tag{12}$$

A similar impulse of stress S results in the displacement

$$u(x,\tau) = \frac{S}{\pi\rho}\left[\frac{\frac{x}{2Q_o} - \phi c_o\tau}{x^2\phi^2 + \tau^2 c_o^2\left(1 + \frac{1}{Q_o^2}\right)}\right] \qquad (13)$$

With the aid of Lighthill's method of characteristics, the variation of peak strain with distance for an impressed exponentially decaying strain pulse at the origin, given by $\epsilon_o\, e^{-\beta t}$ for $t \geq 0$, can be derived to first order in $1/Q_o$ as

$$\epsilon = \epsilon_o\, e^{-\frac{\pi\beta x}{Q_o}} \qquad (14)$$

A closed form solution has also been obtained using the method of superposition for a pulse $\psi(0,t)$ impressed at $x = 0$ in a medium, whose attenuation coefficient can be expressed as (Ref. 37)

$$\alpha(\omega) = b|\omega|^{\frac{1}{2}} \qquad \text{where} \qquad b = \text{constant} \qquad (15)$$

In this case, the disturbance propagated from the exponentially decaying source $\psi(0,t) = A_o\, e^{-\beta t}$ for $t \geq 0$ can be represented as

$$\psi(x,t) = A_o\, e^{-\beta(\tau - \frac{x}{c_o})}\ \mathrm{Re}\left| e^{ibx\sqrt{2\beta}}\ \mathrm{Erfc}\left(\frac{bx}{\sqrt{2(t - \frac{x}{c_o})}} + i\sqrt{\beta(t - \frac{x}{c_o})}\right)\right| \qquad (16)$$

A similar method has been employed to permit the retention of a linear form of the wave equation, and hence the validity of the superposition principle, by a suitable choice of frequency dependence of the adsorption coefficients, based on a first-power law of attenuation (Ref. 36). However, it is not claimed that such a procedure will shed light on the actual mechanism of propagation in geologic materials.

Available information concerning the mechanical behavior of rocks can be classified as data specifying either elastic, attenuating, or hydrodynamic properties. Although such sources are not abundant, the use and interpretation of results in these categories must be approached with caution including due regard for the problems of reproducibility. Furthermore, much of these data have been obtained under static, quasi-static, or ultrasonic conditions in the laboratory, with the notable exception of Ref. 15 and 22, the latter reporting a slight increase in the value of Young's modulus of 2.5% over the frequency range from 40 to 120 cps for seven rocks, including diorite. However, no variation was found in this parameter over the range from 140 to 4,500 cps in another study (Ref. 38). Most dynamic determinations have been performed in situ using seismic exploration techniques, where knowledge of the character of the medium is virtually absent.

Some data concerning the elastic constants and density of rocks may be found in Ref. 39–43, while an exhaustive investigation of the mechanical properties of randomly selected rocks has been undertaken (Ref. 44–46) using standardized testing and sampling techniques on laboratory specimens. Longitudinal bar velocities were obtained by calculation from the observed fundamental mode of longitudinal vibration and the measured length and density of the specimen. Results of this type have also been compared to field measurements of the arrival times of pulses generated by shallow underground explosions (Ref. 47). Furthermore, a host of experiment have been performed to determine the velocity of propagation in rocks by ultrasonic techniques (Ref. 21, 48–50).

Although some earlier experiments have been performed to ascertain the static compressibility of rocks and minerals (Ref. 51 and 52)--where the compressibility of most igneous rocks, including diorite, was found to be essentially independent of pressure--the principal results concerning the high-pressure behavior of rocks have only been obtained very recently, employing the detonation of a high explosive in intimate contact with the specimen and the measurement of both shock and particle velocity. From these data, the stress and density extant in the material can be computed by means of the hydrodynamic theory (Ref. 53). Information has been obtained in this manner for gabbro, dunite, basalt, granite, marble, rock salt, limestone, tuff, greywhacke, shale, and concrete (Ref. 16, 54, and 55). Polymorphic transitions similar to those found in metals under similar circumstances have been observed in gabbro (Ref. 54); the effect of such changes on wave propagation phenomena is discussed in Ref. 53. Otherwise no effort seems to have been expended in correlating the microstructural behavior with the passage of pulses.

SELECTION AND PREPARATION OF TEST MATERIALS

The selection of a diorite, an igneous plutonic rock, for the examination of the behavioral characteristics of a rock was made on a twofold basis. The grain structure of the chosen material is typical of the medium- to coarse-grained crystalline or hypidiomorphic granular rocks of the world. Thus any useful data obtained concerning the properties of a diorite should be reasonably applicable to other common plutonic rocks with similar grain structure, such as granites, adamellites, and the syenites. A plutonic rock was chosen for these initial studies because such rocks are more uniform three-dimensionally than either sediments or metamorphics, both of which are usually planar in structure.

The use of a massive plutonic rock obviates many of the problems of reproducibility and validity of sampling commonly encountered in studies of the layered or planar geologic materials.

The specific choice of diorite as a representative plutonic rock was based on the chemistry of the constituent minerals and on the over-all internal structure as well as on the form of available field occurrences. The first feature is optimal since the rock lacks potash feldspar, a mineral that weathers rapidly to clays upon exposure in outcrop and that is also readily attacked by deuteric fluids during the cooling history of the rock. Selection of a diorite free of potash feldspar implies that small, easily handled joint blocks from field occurrence could serve as specimens and still be free of the weakening effects of chemical alteration due to weathering. The use of small joint blocks from the outcrop was required to prevent pre-test damage to the grain structure by sledging or blasting, a serious problem in many commercially quarried rock samples. The material selected was further checked for possible internal grain boundary damage as the result of geologic processes by means of petrographic techniques. No measurable grain-boundary crushing or deformation was noted, though some constituent minerals (interstitial quartz) exhibited considerable strain. To investigate the possibility of nonuniform behavior of the test diorite as a result of this or other unnoted strains, a set of cores were drilled in three mutually perpendicular directions. Specimens from these cores did not exhibit any directional properties.

The test diorite, like many plutonic rocks, contains scattered inhomogeneities in grain size, though not in mineralogy. These areas of inhomogeneity are fine-grained diorite that forms small xenoliths. The presence of xenoliths in the test specimens was minimized by the small size plus visual inspection and rejection of suspect samples. On the basis of internal structure, mineralogy, uniformity of composition, lack of preferred orientation of either minerals or internal stress, and the presence of blocks of practical size for handling, the diorite chosen was considered a valid and worthwhile sample. This material was found in Wilson Canyon at this Station and forms a surface exposure measurable in terms of miles.

The preparation of the specimens to be employed in the static and dynamic tests was performed in such a fashion as to minimize possible damage to the structure of the sample. The material collected at the field outcrop consisted of naturally occurring joint blocks. Only boulders of proper size were utilized in order to prevent shock damage from sledging or blasting. The use of these small samples from the surface of the ground does admit of the possibility of general grain bond weakening through the process of temperature cycling, as the sample site air temperature often fluctuates in excess of 50°F daily. After transport to the laboratory, all material conceivably damaged by weathering was removed and the ends of the sample blocks were cut parallel by trimming with a large diamond saw to a 12- by 12- by 24-inch size.

The specimens were obtained by boring holes through the long dimension of the block by means of an annular drill consisting of a diamond set masonry bit mounted on a thin-walled extension tube without core barrel, which was hand fed at 900 rpm. The resulting rods were approximately 24 inches long with a diameter of 0.76-inch, round to within 0.001-inch as drilled. The vibration from drilling may have caused some internal damage to the grain structure during the drilling process. Thermal damage to the specimen during this operation was mitigated by the combination of a large flow of cooling water and a slow feed rate of the drill press.

Specimen breakage occurred as a result of the drill encountering small fractures that had not been detected during the selection of the sample block. A few rods also broke during handling after termination of drilling due to the completion of fractures already present in the rock. The finished bars were trimmed square on the ends with a carborondum cut-off saw, which induces less vibration than a diamond wheel, and were then ground flat by hand with a 400 grit. All subsequent transport was accomplished with the greatest care to eliminate the possibility of damage to individual test rods by rough handling.

COMPOSITION AND GENERAL PHYSICAL PROPERTIES OF DIORITE SPECIMENS

Diorite is defined as an intrusive rock composed of 5–50% dark minerals containing a plagioclase with a composition of oligoclase to andesine, exhibiting a total feldspar content containing less than 5% potash feldspar, and with a total quartz and feldspar content of less than 5% quartz. The samples of diorite used to form the test specimens contain 20% dark minerals, andesine plagioclase, a total quartz and feldspar content comprised of 3–5% quartz and a total feldspar content containing less than 3% potash feldspar. The grain size is typical for intrusive rocks. Scattered mineral grains will occasionally reach 5–6 mm in length, but the average length throughout the rock is closer to 1½–2 mm. Diorite differs somewhat in its constituent composition from the related intrusive materials gabbro, quartz diorite, and granodiorite, but is identical in mineralogy to the extrusive rock andesite which, however, is much more fine-grained as a result of its much more rapid cooling history.

Structurally, the fabric of diorite consists of an interlocking mass of dark minerals and plagioclase feldspar as shown in Fig. 1, which represents a virgin specimen. The dark minerals are predominantly subhedral to nearly anhedral hornblende, a double chain silicate, and anhedral magnetite, an oxide with a spinel structure. The plagioclase feldspar, andesine, is a three-dimensional network structure, showing prominent polysynthetic twinning plus growth zoning and is present in subhedral grains. The quartz present appears as anhedral interstitial fillings. The grain boundaries of all constitutent minerals are sharp and free of deformational textures (Ref. 56).

Table 1 presents physical properties determined for the test specimens of diorite and also indicates typical values obtained for similar rocks by other investigators.

FIG. 1. Normal Grain Structure in Fresh Diorite Specimens Employed for Wave Propagation Tests. (Crossed nicols illumination.)

TABLE 1. Physical Properties of Some Common Hypidiomorphic Granular Rocks

Specimen material	Specific gravity	Strength, lb/in^2		Porosity, %	Velocity, ft/sec		Static Young's modulus, $lb/in^2 \times 10^6$	Poisson's ratio	Ref. no.
		Compressive	Tensile		Longitudinal	Transverse			
Diorite of present investigation	2.83	32,000	800	....	12,000[a] 23,500[b]	......	5.06	....	..
Diorite (Utah)	2.74	48,300	...	0.25	18,200[c]	......	12.2	0.25	45
Diorite (Michigan)	3.01	39,800	...	....	19,700[c]	......	15.47	0.29	46
Granite (Colorado)	2.67	25,500	590	0.5	10,400[c]	......	3.94	-0.19	46
Granite--range of values	2.56–2.74	10,000–60,000	410–560	0.23–1.75	13,000–18,700	6,900–10,800	5.03–9.57	0.20–0.26	56

[a] Surface measurement of propagation of longitudinal pulse propagation due to impact.
[b] Average velocity of explosively induced shock propagation.
[c] Calculated from observed fundamental mode of longitudinal vibration of specimen.

EQUIPMENT, INSTRUMENTATION, AND PROCEDURE

The apparatus employed for the Hopkinson bar experiments has previously been described in detail (Ref. 57 and 58). Briefly, a ballistically suspended rod of diorite or 2024-T4 aluminum alloy of 3/4-inch diameter with a length ranging from 21 to 24 inches was subjected to the longitudinal impact of a $\frac{1}{2}$-inch-diameter projectile fired by means of an air gun at a nearly constant velocity of 3,300 in/sec. The hard-steel bullets were either spheres or flat-nosed cylinders of $\frac{1}{2}$-inch length, counterbored at the free end to maintain a constant projectile weight of 8.[illegible] grams. Strain pulses in the bars were detected by means of strain gages of the FAP-12-12 foil or SR-4 wire resistance type, mounted in pairs at opposite ends of a diameter at various stations of the bar, and so connected as to eliminate any antisymmetric component of the transient. The signals generated were transmitted to and photographed on the screen of commercial oscilloscopes having a band pass ranging from direct current to more than 1 megacycle. Each record was individually calibrated.

The satisfactory employment of strain gages for nonmetallic materials had been previously determined (Ref. 59). Since these gages were of sufficient size to cover several grain boundaries, their application in the present sequence of tests seemed to be warranted.

In view of a common triggering circuit for the oscilloscopes, the velocity of propagation of the pulses could be determined accurately from the arrival time of the first disturbance on each record. The interruption by the projectile of two light beams focussed on miniature photocells located near the slotted muzzle end of the gun barrel permitted a recording of the time of passage of the bullet on a counter with a microsecond scale, providing an accurate monitor of the magnitude of the impact velocity. The second photocell initiated the triggering signal through an adjustable delaying circuit.

Specimens subjected to the collision of spherical projectiles were suspended with their impact surface located some distance from the muzzle end in order to record the rebound velocity of the bullet by means of a stroboscopic camera. Although this procedure proved to be successful in the case of aluminum bars, the rebound trajectory of the projectile could not be observed for the diorite specimens by this technique, attributable either to obscuration of the field of view by the fragments invariably emitted from the sample upon impact or to the negligible rebound velocity of the bullet, or both. Since these data were to be employed solely as a check of the magnitude of the impulse produced in the bar, it was not considered worthwhile to complicate the experimental procedure by employing a high-speed framing camera for the determination of this parameter. Measurement of the rebound velocity was not even considered in the tests involving the flat-nosed bullets where the specimens were placed as close as possible to the muzzle of the gun in an attempt to achieve a reasonably plane impact condition. This sequence of experiments was conducted with the object of achieving a faster rise time of the pulse, and hence a different harmonic spectrum, than could be obtained with spherical projectiles.

The aluminum alloy bars, whose properties had been previously investigated (Ref. 58), were used repeatedly in the experiments, a small portion of the rod near the impact end being cut off and the new terminal face being reground after each shot. No variations were observed either in macroscopic behavior or microstructural pattern of the material as a result of repetitive shocking provided the immediate region around the small permanent crater formed by the collision was so eliminated. The impact of spherical projectiles on diorite at the standard velocity of 3,300 in/sec resulted in complete disintegration of the collision end of the rod up to a length of 3/4 inches from the point of contact, leaving a highly irregular fracture surface on the remnant of the bar; however, the distal end of the rod remained intact. In the case of flat-ended projectiles, the same demolition pattern occurred at the impact end, but the bar also fractured at an additional position as the result of the action of the reflected tensile wave, indicating a more severe loading condition under these circumstances.

Most of the tests involved the use of two strain gage observation stations spaced 10.68 inches apart, the gages being located from the ends of the virgin bar at nearly equidistant positions ranging from 5 to 6 inches. The data from a typical run are presented in Fig. 2. When a once-shocked sample of the rock was to be used for a second experiment, the bar was simply inverted in position; but for additional tests on that particular specimen, the same cut-off and grinding procedure as employed in the original sample preparation was followed. In two successive impacts of the spherical projectile on the same specimen, five observation stations were employed; here, the bar for the second test was refaced at the impact end and placed in the same position as the fresh specimen.

The suspected damage produced in the grain structure by the passage of the pulses was subjected to examination by a comparison of both static compressive stress-strain data and microscopic inspection of virgin and shocked specimens. Extreme care was again exercised to minimize additional grain damage during preparation. Compression samples were cut with a carborandum saw to the desired length and then wax-mounted on an aluminum V-block for the additional removal of a 1/16-inch length from each end by grinding, finishing with a 0.7-micron grit, to ensure the absence of saw-damaged material. The specimens were then removed with trichloroethylene heated to 80°C, a temperature too low to produce significant grain-bond weakening according to thermal shock studies performed on this diorite, and subsequently air cooled.

All samples were ground parallel to 0.0001-inch across a 0.76-inch diameter. Two lengths of test section were employed, 1.241 and

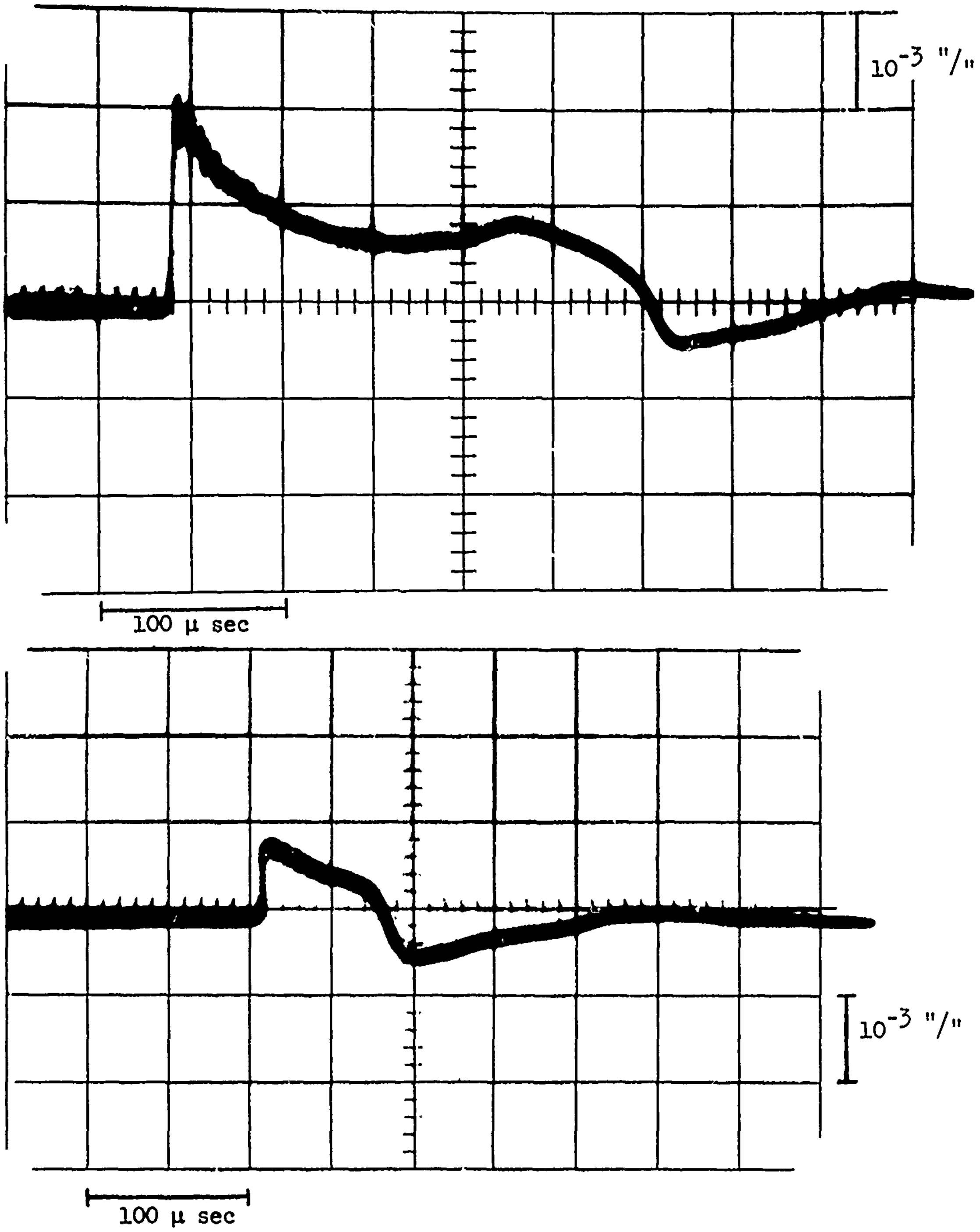

FIG. 2. Strain-Gage Data Obtained During the Impact of a $\frac{1}{2}$-Inch Diameter Steel Sphere at a Velocity of 3,294 in/sec on a 0.76-Inch Diameter Bar of Diorite. Strain Gages (1) and (2) were located 5.19 and 15.87 inches from the impact point, respectively.

1.005 inches, yielding length to diameter ratios of 1.63 and 1.32, respectively. These values are intermediate to those recommended in the literature (Ref. 44 and 60). Since variations in the compressive strength of granite with moisture content had been shown to be small (Ref. 44), no special effort was exercised to control this factor other than to assure identical moisture content of the specimens at the time of testing. The samples were loaded without a cap in a standard commercial testing machine at the rate of 100 lb/sec, representing a value midway in the range of 100 to 400 lb/in^2/sec, where published information has indicated no change in results with loading rate for the same rock type (Ref. 44). The swivel head of the testing machine was not locked in position as suggested (Ref. 60), but was adjusted to be parallel to the samples.

The examination of the internal structure of the diorite consisted of the grinding of standard petrographic thin sections, 0.03 mm thick, followed by microscopic inspection for shattered grain boundaries and fractures. Care must be exercised in this interpretation to ensure that breakage caused by grinding and mounting processes is not attributed to stress-wave induced damage.

The contact explosion experiments were conducted by means of the donor-receptor arrangement sketched in Fig. 3, the thickness d of the specimen being varied from 0.5 to 3.5 inches. The explosive consisted of composition B whose threshhold detonation pressure of 300,000 lb/in^2 served as the basis for the computation of the attenuation of the pulse at the center of the specimen with variations in thickness. Shock velocity measurements were carried out by means of a high-speed camera.

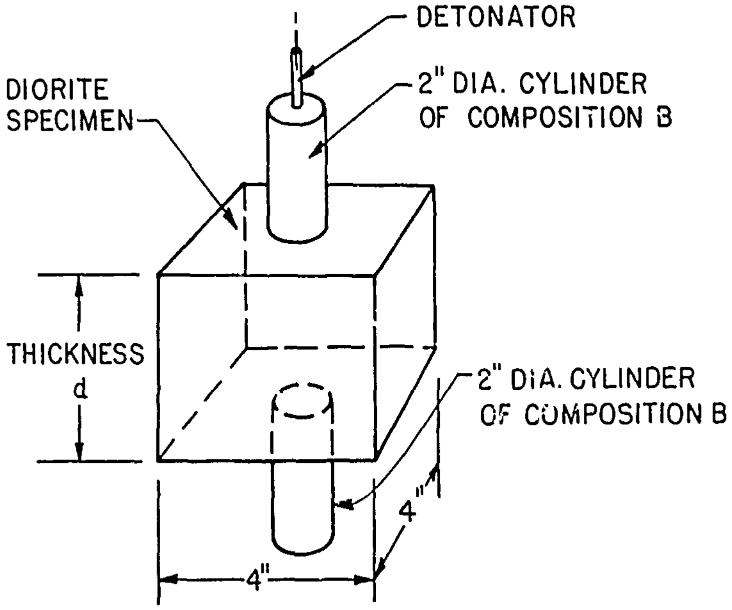

FIG. 3. Sketch of a Donor-Receptor Arrangement

RESULTS AND DISCUSSION

The results of the dynamic investigations are summarized in Table 2 for both the diorite and aluminum specimens. The pulse data for diorite are reported in terms of the measured peak strain, while comparable information for aluminum has been converted to force, using a dynamic Young's modulus equal to the static value of 10^7 lb/in^2. Figures 4 and 5 show the respective effects of a spherical and a flat-faced projectile striking virgin bars of the rock at comparable velocities; though the amplitudes in the second case are considerably higher, the general pulse shapes produced by the two types of bullets are similar. The strain-time curves shown here are typical; their appearance consists of a rapid rise followed by a decay until the effect of the pulse reflected from the free end manifests its influence. The reflected transient generally tends to produce a strain of opposite phase, but is sometimes preceded by a small reflected compressive precursor. In some instances, the gages closest to the impact point appeared to have been subjected to a permanent strain before the arrival of the reflected wave.

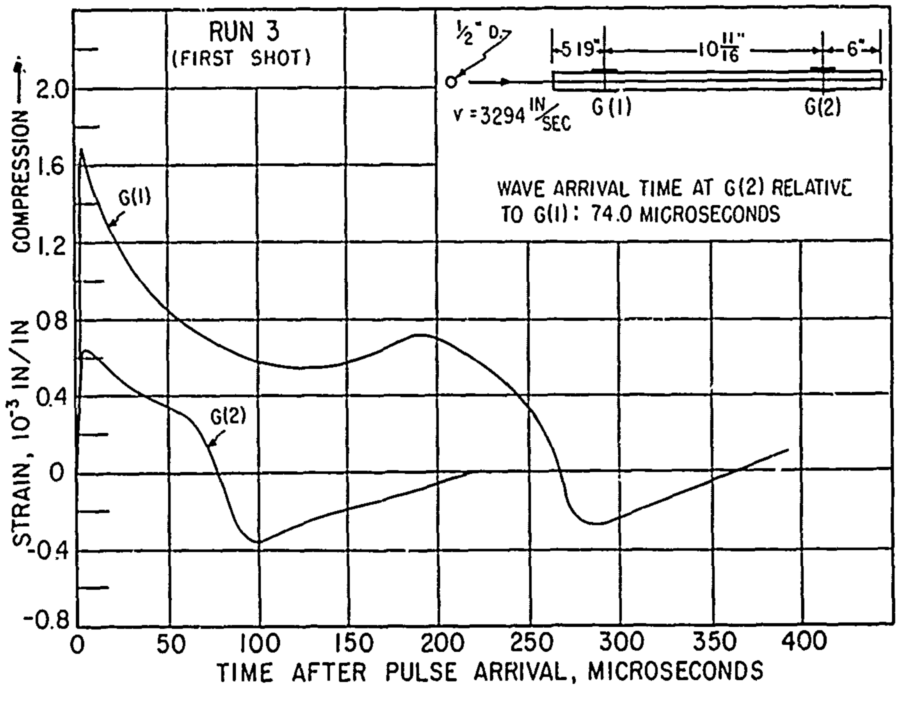

FIG. 4. Strain-Time Curves at Two Stations of a Diorite Bar of 0.76 Inches Diameter Resulting From the Impact of a ½-Inch Diameter Spherical Projectile Composed of Hard Steel at a Velocity of 3,294 in/sec.

TABLE 2. Summary of Dynamic Tests on 3/4-Inch Diameter Rods of Diorite and Aluminum

Run no.	Type of bullet[a]	Previous shocks, no.	Distance of first gage G(1) to impact point, in.	Initial projectile velocity, in/sec	Strain amplitude of initial pulse at station, 10^{-3} in/in					Propagation velocity between stations, 10^3 in/sec[b]			
					G(1)	G(2)	G(3)	G(4)	G(5)	G(1)—G(2)	G(2)—G(3)	G(3)—G(4)	G(4)—G(5)
A. Diorite													
1	S	0	5.5	3,327	1.82	....	0.56	0.56	0.18	144.5		144.8	144.4[c]
2	S	1	4.34	3,253	2.26	1.06	0.68	0.59	0.20	103.0	123.5	136.0	175.0[d]
3	S	0	5.19	3,294	1.69	0.65	....	....	....	144.2	.....	.....	.....
4	S	0	5.13	3,291	1.54	0.39	....	....	....	142.4	.....	.....	.....
5	S	0	5.54	3,294	1.59	0.99	....	....	....	144.8	.....	.....	.....
6	S	1	6	3,289	1.55	1.25	....	....	....	142.5	.....	.....	.....
7	S	2	4.05	3,275	2.01	0.68	....	....	....	143.0	.....	.....	.....
8	S	3	3.88	3,181	1.85	0.76	....	....	....	104.0	.....	.....	.....
9	S	4	2.5	3,291	1.77	1.02	....	....	....	106.8	.....	.....	.....
10	S	5	3.56	3,302	2.26	0.60	....	....	....	127.0	.....	.....	.....
11	F	0	5.5	3,211	2.44	1.16	....	....	....	144.8	.....	.....	.....
12	F	1	5.61	3,201	1.52	0.82	....	....	....	129.6	.....	.....	.....
13	F	1	5.62	3,215	2.70	1.00	....	....	....	131.3	.....	.....	.....
14	F	4	2.53	3,164	3.24	1.28	....	....	....	142.5	.....	.....	.....
15	F	5	3.12	3,167	3.72	1.52	....	....	....	104.0	.....	.....	.....
B. 2024-T4 Aluminum Alloy													
16	S	..	6.05	3,278	2.27	2.21	....	....	....	205.4	.....	.....	.....
17	F	..	5.5	3,213	3.51	3.26	....	....	....	205.4	.....	.....	.....

[a] S = $\frac{1}{2}$-in.-diameter steel sphere, weight is 8.35 grams; F = $\frac{1}{2}$-in.-diameter flat-nosed cylinder, $\frac{1}{2}$-in.-long, hollowed out to weigh 8.35 grams.

[b] Gage stations for Run No. 1 and 2 are 3.5 inches apart. Five observation stations were employed for these runs, but the record from station 2, G(2), was lost in Run No. 1. Gage stations for Run No. 3–17 are 10.68 inches apart. Two observation stations were employed for these runs.

[c] Over-all velocity c = 144,500 in/sec.

[d] Over-all velocity c = 131,500 in/sec.

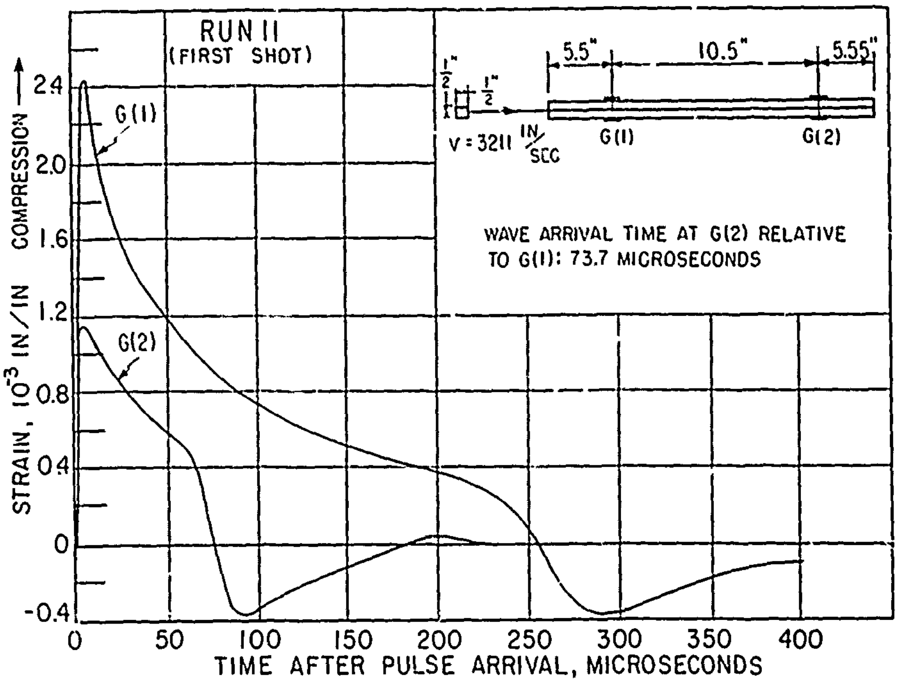

FIG. 5 Strain-Time Curves at Two Stations of a Diorite Bar of 0.76 Inches Diameter Resulting From the Impact of a ½-Inch Diameter Flat-Nosed Projectile of Hard Steel at a Velocity of 3,211 in/sec.

Figures 6 and 7 present similar results for four and five gage stations, respectively, in a virgin and shocked diorite bar subjected to collision by a spherical projectile. A remarkable feature of these diagrams is the fact that the amplitude of the reflected component increases with distance during its traversal towards the impact end. It is hypothesized that this phenomenon may be due to the presence of stored energy in the grains that is released upon arrival of the reflected wave. The initial shape of the pulse can not be predetermined, being controlled by the material properties and the fragmentation process near the impact point as well as by the geometry and initial velocity of the bullet. A logarithmic plot of the portion of the curves representing the incident wave indicated the existence of exponential decay with a virtually constant attenuation factor of 0.93×10^4 $\text{sec}^{-1} \pm 7\%$. An examination of the remaining data indicated a similar trend, independent of the bullet geometry, though a somewhat larger scatter in the magnitude of the attenuation coefficient was obtained. In any event, no dispersion of the initial pulse was observed within the limits of experimental error.

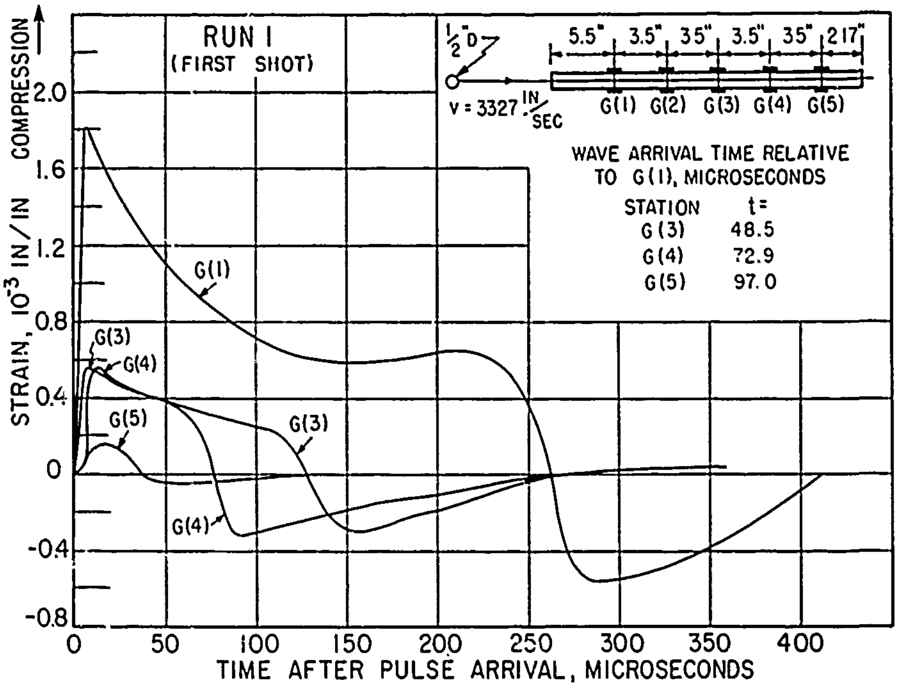

FIG. 6. Strain-Time Curves at Four Stations of a Virgin Diorite Bar of 0.76 Inches Diameter Resulting From the Impact of a Spherical Hard-Steel Projectile of ½-Inch Diameter at a Velocity of 3,327 in/sec.

On the other hand, this transient was subjected to drastic attenuation in the traversal of the bar. An examination of the peak amplitudes recorded at stations 1–4 in Fig. 6 and 7 indicated that this decay was not linearly exponential, but varied more nearly as $x^{-0.55}$, where x is the distance traversed in inches. The results from the station nearest the free end were discarded for this purpose, since the pulse did not fully develop at this position before the arrival of a reflected wave. Any frequency dependence of the attenuation factor should be canceled out by the conditions of pulse propagation. Since the strain-time curves at all stations exhibit the same exponential decay, their Fourier spectra and ratio of energy levels of their respective components will be identical, and the attenuation parameter should consequently be identical at all positions. The absence of exponential attenuation was also indirectly supported by the auxiliary data listed in Table 2 that, under the hypothesis of linear exponential decay, exhibited attenuation factors ranging from -0.02 to -0.13. According to Eq. 10, an average value of α, for instance -0.1, would require a single equivalent frequency of the pulse spectrum of 3,600,000 rad/sec to correlate with the value of $\Delta E/E$ cited by Ref. 22 for diorite. This frequency is not only well above the recording capability of the equipment, but does not seem to correspond to the dominant frequency of the pulse that, in view of the magnitude of the decay constant, would appear to be more of the order of 10 kc. The exponent of -0.55 does not provide the best fit for the remainder of the data and is thus subject to adjustment pending further investigation, but the power law is a better representation of the complete set of results than the exponential decay.

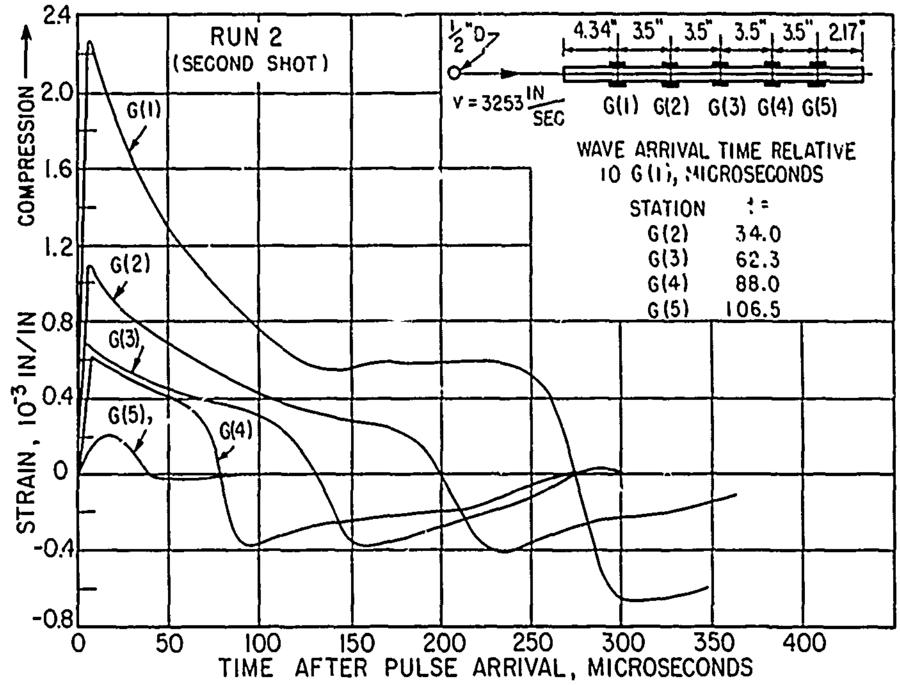

FIG. 7. Strain-Time Curves at Five Stations of a One-Shocked Diorite Bar of 0.76 Inches Diameter Resulting From the Impact of a Spherical Hard-Steel Projectile of $\frac{1}{2}$-Inch Diameter at a Velocity of 3,253 in/sec.

To assess the effects of dispersion resulting from the three-dimensional nature of the bar, some auxiliary experiments were conducted under identical conditions on 3/4-inch-diameter bars of 2024-T4 aluminum alloy, a material that had been previously subjected to extensive investigations involving pulse propagation (Ref. 57 and 58). The results of these "calibration" tests are shown in Fig. 8 and 9; the transient produced by the spherical projectile was transmitted between the measuring stations virtually intact, with a loss of less than 5% of the impulse. A larger dispersive effect was observed in the case of the cylindrical bullet, though the general pulse form was still preserved. The reduction in amplitude even in the second instance can not begin to account for the attenuation observed in the diorite bars, which must consequently be attributed to an internal frictional mechanism such as relative sliding along the grain boundaries.

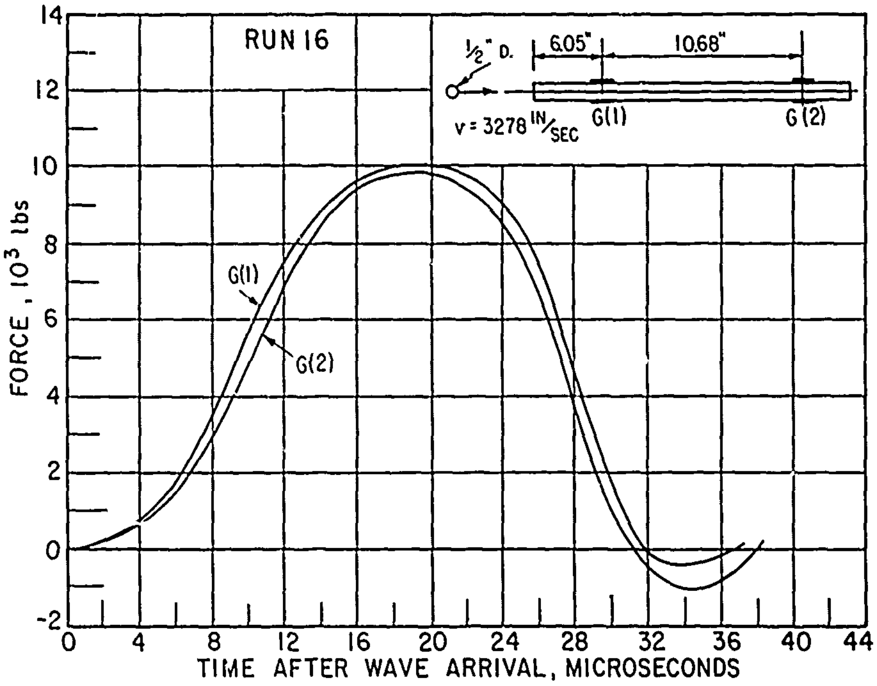

FIG. 8. Force-Time Curves at Two Stations in a 3/4-Inch Diameter 2024-T4 Aluminum Alloy Bar Resulting From the Impact of a ½-Inch Diameter Hard-Steel Spherical Projectile at a Velocity of 3,278 in/sec. Observed change of momentum of the bullet: 0.177 lb-sec. Impulse recorded by gage (1): 0.174 lb-sec. Impulse recorded by gage (2): 0.168 lb-sec.

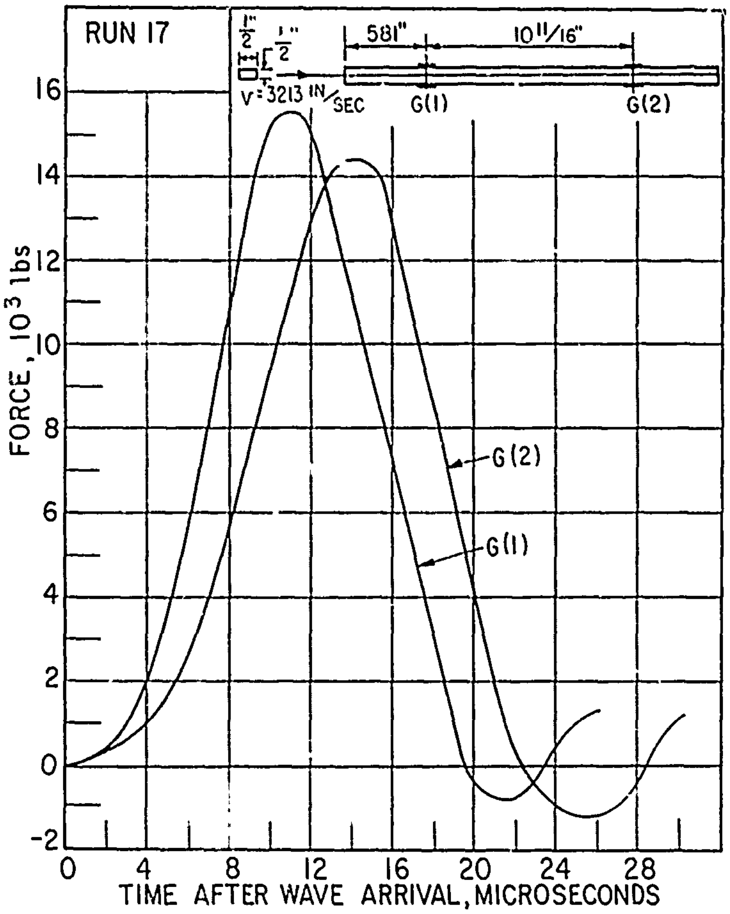

FIG. 9. Force-Time Curves at Two Stations in a 3/4-Inch Diameter 2024-T4 Aluminum Alloy Bar Resulting From the Impact of a ½-Inch Diameter Hard-Steel Cylindrical Projectile With a Flat Nose at a Velocity of 3,213 in/sec. Initial bullet momentum: 0.153 lb-sec. Positive impulse recorded by gage (1): 0.150 lb-sec. Positive impulse recorded by gage (2): 0.146 lb-sec.

In view of the experimental evidence, some conclusions can be drawn concerning the applicability of the various proposed models previously discussed in Summary of Previous Investigations. The Kelvin-Voigt solid or other types of viscoelastic models must be rejected as suitable representations for the diorite, since all of these models will exhibit dispersive characteristics in contrast to the observed results. The same objection applies to the use of the hypothetical substance defined by Eq. 15 and 16. The solid friction mechanism expressed by Eq. 7 is far more acceptable in view of the absence of dispersive features, but, pending additional study, the exponential decay and frequency dependence stipulated by Eq. 10 and the analogous result predicted by Eq. 14 may need to be adjusted. A proper model for the diorite must incorporate the features of absence of dispersion and an attenuation most likely based on some power of the ratio of travel distance to bar diameter.

The velocities of propagation of the pulse presented in Table 2 are uniformly consistent for the virgin bars at a value of 144,000 in/sec ± 1.5%. This magnitude is somewhat less than that reported for other diorites, which were determined by the resonant frequency method--though in the range of some granites--and considerably smaller than values determined from field tests. However, the discrepancy between field and laboratory tests is not unique (Ref. 47), since ratios of better than 2 to 1 have been reported for substances very similar to the diorite employed in the present investigation. This difference is presumably due to the absence of a controlled medium and the effect of confinement in the field. On the basis of the quoted measurement, the computed value of the "dynamic" Young's modulus for the diorite is 5.5×10^6 lb/in^2. A consistent trend can be observed from the data of Table 2 in that successive shocks in the rock result generally in lower velocities of pulse propagation, indicating a reduction in the modulus with number of collisions, as the porosity and hence density of the material remained invariant (except for minor changes resulting from the formation of microfractures). An examination of the data from Run 2, a specimen previously subjected to an impact, reveals that the velocity of propagation increased in sections successively further removed from the original collision end, indicating that the reduction in modulus and thus strength also depends upon location relative to the point of prior contact. This feature is responsible for the observed variations in strain amplitude exhibited by specimens previously subjected to the same number of shocks.

Corroborating evidence of the existence of significant shock damage were obtained from static compression tests and microscopic examination of both virgin and shocked specimens. Table 3 presents a compilation of the compression test results. Three unshocked samples, E-1, E-2, and E-3--two being cut from the same rod, the third being selected at random --yielded essentially identical ultimate strengths of 31,800 lb/in^2 ± 2%. Specimens C-1, D-1, and D-2 were removed from a single rod that had been subjected to an impact at each end by a spherical projectile traveling at 3,300 in/sec. Samples D-1 and D-2 were cut from the strain-gage stations of the rod and exhibited essentially identical strengths of 20,678 lb/in^2 and 21,053 lb/in^2, while the third sample, which displayed a considerably lower value of 17,467 lb/in^2, was cut from a section immediately adjacent to an impact end.

TABLE 3. Summary of Compression Data

Sample no.	Length, in.	Diameter, in.	Area, in^2	Load to failure, lb	Breaking strength, lb/in^2	Previous shocks, no.	Impact velocity, in/sec[a]
A-1	1.0067	0.7659	0.461	12,500	27,115	2	3,285, 3,300
A-2-2	1.0055	0.7660	0.461	13,000	28,200	1	3,285
B-1	1.2400	0.7613	0.455	13,000	28,571	1	3,300
C-1	1.2411	0.7633	0.458	8,000	17,467	2	3,300
D-1	1.2427	0.7626	0.457	9,450	20,678	2	3,300
D-2	1.2396	0.7616	0.456	9,600	21,053	2	3,300
E-1	1.2392	0.7604	0.454	14,700	32,379	0	.....
E-2	1.2410	0.7653	0.460	14,400	31,304	0	.....
E-3	1.2410	0.7662	0.461	14,550	31,562	0	.....

[a] ½-in.-diameter steel sphere.

Additional rods were tested to further verify these results. Two singly shocked rods, samples B-1 and A-2-2, also yielded nearly identical values of 28,571 lb/in^2 and 28,200 lb/in^2, respectively, somewhat lower than that of the virgin material. The second of these specimens was subjected to a second impact after which a test section A-1 yielded a strength of 27,115 lb/in^2. All of these changes in ultimate strength are in the direction of lowered sample strength with increasing number of impacts and also with increasing proximity to the impact point, resulting in a distinct weakening of the material. The validity of the change in strength between samples A-1 and A-2 is considered to be particularly strong since the same rod was employed for both specimens. The individual rods were found to perform quite uniformly in the compression tests.

Figure 10 presents load-deformation curves for samples E-1, D-1, C-1, and B-1, showing the variations in response as shocking history is varied. The tangent modulus of the unshocked specimen corresponds to a value of 5.06 x 10^6 lb/in^2, approximately 10% lower than the corresponding dynamic value. Although metals apparently exhibit the same elastic modulus under both static and dynamic conditions at moderate pressures, the increase in modulus observed for the diorite may well correspond to the observed increase in strength of metallic substances in the plastic range under dynamic conditions. Specimens D-1 and C-1 yielded values of the tangent modulus of 3.32 x 10^6 and 3.06 x 10^6 lb/in^2, respectively, representing a reduction of almost 40% of this parameter from that of the virgin specimen. The significant decrease in both ultimate strength and tangent modulus of the shocked material emphasizes the serious nature of the damage produced in the grain structure and bonding elements. This effect also accounts for the lower velocity of pulse propagation in shocked and refaced diorite bars. The concept was further confirmed by microscopic examination. Figure 11 is a typical microphotograph of a thin section located $1\frac{1}{2}$ inches from the point of impact, which clearly exhibits a number of microfractures not present in the virgin material (Fig. 1). Any grain damage beyond this region was too subtle to show in the specimens utilized. This fracturing process is one of the principal mechanisms of energy dissipation resulting in pulse attenuation. All these results clearly indicate the presence of a new material after each shock, and attempted reuse of each sample by refacing the impact ends must be approached in the light of this situation.

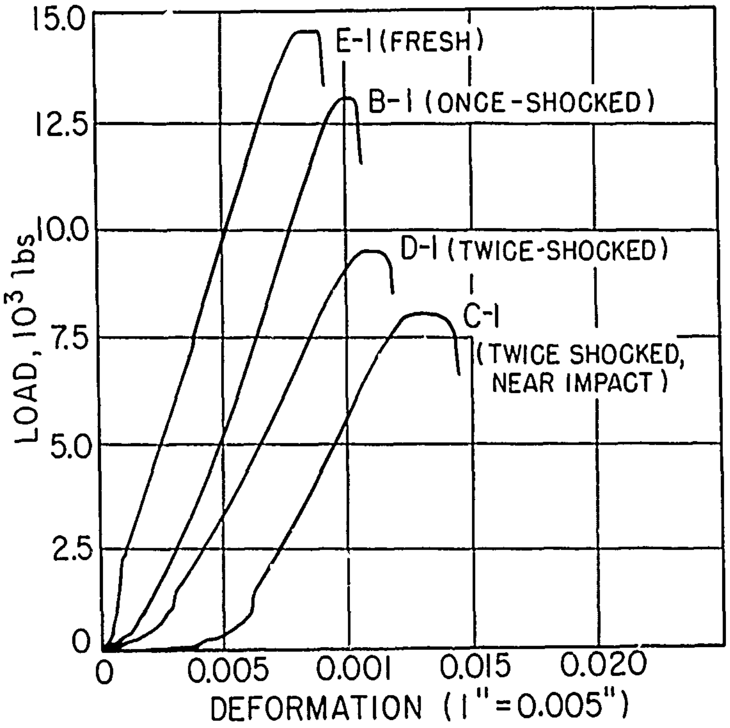

FIG. 10. Comparison of Load-Deformation Curves for Diorite Subjected to Different Conditions of Repeated Impact.

FIG. 11. Photomicrograph of Portion of Once-Shocked Diorite Rod Adjacent to the Point of Impact and Showing Development of Microfractures.

The average velocity of propagation of explosively induced shocks in diorite for specimen thicknesses in the range from 2 to 3 inches was found to be 282,000 in/sec, corresponding to an incident pressure in the sample of about 5×10^6 lb/in^2. The velocity of propagation in 2024-T4 aluminum alloy under the same conditions of incident pressure was found to be 296,000 in/sec (Ref. 61). The ratio of propagation velocities at this high pressure to that at the moderate pressures encountered in the pulse propagation produced by impact loading of a projectile for diorite is hence equal to 1.96, while that for aluminum is only 1.44, indicating a considerably greater compressibility of the diorite. The total attenuation of the shock wave pressure in a diorite specimen 2.78 inches thick between the centers of the two interfaces was found to be 3.98×10^6 lb/in^2, though the greater portion of this attenuation must be attributed to lateral expansion of the wave.

CONCLUSIONS

1. Repeatable and consistent data can be obtained in specimens of rock provided sufficient care is exercised in the selection and preparation of samples. The results obtained concerning pulse form, velocity of propagation, and grain bond damage in diorite rods of 3/4-inch diameter due to the impact of ½-inch-diameter steel projectiles at a velocity of about 3,300 in/sec exhibited little scatter and could be readily interpreted.

2. The pulse form produced in the rock is not directly controllable and its shape is not significantly influenced by projectile geometry. The pulse propagates without dispersion and with an attenuation proportional to some power of the ratio of distance traversed to bar diameter. A solid-friction type of mechanism accounts for the first feature, but may require some modification to properly represent the observed attenuation phenomenon.

3. The ultimate strength of the diorite and its static Young's modulus decrease in direct proportion to the number of impacts previously experienced by the specimen. The damage to the internal structure is a function of this parameter as well as to the proximity to the impact point. The velocity of propagation, and hence the dynamic Young's modulus are also lower in a shocked specimen of the rock.

4. Under identical loading conditions, the rock selected exhibits drastically different characteristics from an aluminum alloy used as a reference with respect to pulse form and manner of propagation, change in mechanical properties, microscopic damage, and compressibility.

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Ballistically suspended Hopkinson bars of diorite of 3/4-inch diameter and approximately 22 inches long were subjected to longitudinal impact by spherical

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