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STRESS WAVE PROPAGATION IN ROCK*

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ABSTRACT

Earth penetration, design and hardening of structures to explosive or earthquake-induced ground shock effects, rapid excavation, and *in situ* preparation of coal, shale, or geothermal deposits are representative problems in which accurate constitutive descriptions of the geological medium are required to provide meaningful predictions. The rock or rock masses involved undergo complex, finite amplitude deformation during the process of transient dynamic loading, and quasi-static experimental compression techniques are normally used to provide much of the necessary data base. Strain rates typically range between 10^1/s and 10^5/s in the problems of interest, however, and further studies are required to determine the importance of rate dependence in the mechanical constitutive behavior of rock. Material response at the higher strain rates can be investigated with impact generated stress waves where controlled strain rates between about 10^4/s to 10^7/s can be achieved. Experimental methods have been developed to conduct and analyze impact-induced shock wave, ramp wave, and tensile fracture studies. Experimental results on some select crustal silicate and carbonate rocks show that strain rate dependence and the processes of phase transformation, compressive yielding, and fracture are important features in the dynamic constitutive response.

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INTRODUCTION

There are a number of pressing engineering and geophysical problems involving transient finite deformation of rock and rock masses. An interesting and representative example is a borehole drilled into a geological formation which is packed with explosives and detonated in an attempt to rubblize the adjacent medium for the purpose of *in situ* resource recovery. The explosive energy is coupled into the rock near the borehole perimeter and the initial compressive stresses can be on the order of 5 GPa. The disturbance is propagated away from the borehole as a large amplitude deformation wave which attenuates with radial distance, eventually reaching a level for which material response is purely elastic. Wave propagation and attenuation to this level is complex and depends on the dynamic material response of the zone affected. Such response can involve compressive shear yielding, phase transitions, and tensile fracture. Strain rates typically range between about 10^5/s during early time response to about 10^1/s during late time response.

The calculation of an event such as the borehole detonation problem requires constitutive models which accurately describe the dynamic deformation of the rock medium involved. Much of the data base currently used to develop these models is generated with quasi-static compression facilities. However, it is becoming recognized that such data are not sufficient because of possible strain rate sensitivity of rock deformation and dynamic testing methods must be employed to supplement quasi-static testing.

Planar impact techniques have achieved some success in this regard. With planar impact methods controlled stress waves with loading strain rates between about 10^4/s to 10^7/s can be generated and used to investigate the response of rock medium. States of both compressive and tensile stress can be achieved.

In this paper, experimental methods currently used to conduct and analyze planar impact experiments will be described. Some recent results on select rocks will be presented to illustrate the various methods. Lastly, some results relating to strain rate dependence and processes of dynamic yielding, fracture, and phase transition during rock deformation will be considered.

EXPERIMENTAL METHODS AND TYPICAL RESULTS

The general method for producing stress waves by impact loading is illustrated by the particular experimental assembly shown schematically in Figure 1. A projectile, impelled by a light gas gun, is allowed to impact the target assembly containing the rock sample. An impactor material, with known mechanical properties, is mounted on the face of the projectile and provides the initial input stress pulse. This pulse propagates through the rock sample and evolves according to the material characteristics of the test specimen. Sample dimensions are selected so that a condition of uniaxial strain persists during the time of interest. Material response (usually stress or particle velocity) is subsequently measured at some Lagrangian (material) point downstream from the impact interface. Velocity interferometry[1] is the experimental technique illustrated in Figure 1. Alternatively, such methods as manganin stress gages,[2] magnetic particle velocity gages[3] or quartz gages[4] may be used. The instrumentation selected depends on experimental requirements and properties of the material under test.

Planar impact experiments are not limited to compressive, step loading configurations. Methods have been developed to achieve states of tensile stress and to control the rate of strain during dynamic compressive or tensile loading. These methods will be discussed subsequently.

The wave profiles measured in planar impact experiments contain considerable information about the dynamic constitutive properties of the rock under test. Frequently the dynamic stress-strain response must be determined from the wave profile data to acquire the constitutive property information required. The methods available for achieving this end have been recently reviewed.[5]

Compressive shock waves: The term shock wave here refers to the input stress pulse only. The conditions required to sustain a shock wave are seldom achieved in stress wave studies at the amplitudes of interest here ($\sim$ 0-5 GPa). The necessary experimental arrangement provides for nearly instantaneous loading at the impact interface to some predetermined stress amplitude. Usually a thin impactor plate is used so that the sample is subject to subsequent stress unloading within the time that conditions of one-dimensional strain are maintained. By this method, the sample is subject to a single dynamic stress loading and unloading cycle. Results obtained from experiments conducted in this manner on Oakhall limestone[6] are shown in Figure 2. The input profile was a square wave. Subsequent wave profiles were measured in separate experiments at increasing distances from the impact interface. Features which evolve in the wave structure during both loading and unloading vividly illustrate complexity in the constitutive response of this rock type.

Compressive ramp waves: When direct impact such as that illustrated in Figure 1 is used and near instantaneous loading is achieved, it is difficult to assign a loading rate or strain rate to the dynamic experiment. Frequently, such knowledge is desired to model the material or to correlate with lower strain rate experiments. Methods for controlling the rate of strain in planar impact experiments are available. One technique is to precede the rock sample (in Figure 1) with a predetermined thickness of fused silica. The nonlinear elastic properties of fused silica are such that an initial input step wave spreads into a ramp wave during propagation through the fused silica. The rise time of the ramp wave depends on the distance propagated. When such a ramp wave is used as the input to the rock specimen, the rate of straining can be controlled quite accurately. Particle velocity profiles obtained from experiments on Blair dolomite[7] by this method are shown in Figure 3. The strain rate achieved in these tests was about 3×10^4/s, nearly two orders of magnitude below that usually occurring in direct impact experiments.

Tensile Waves: Planar impact methods can also be used to generate states of tensile stress. Dynamic tensile loading is achieved through the interaction of two opposing relief waves within the test specimen. The production and timing of such relief waves is accomplished through choice of dimensions and mechanical impedance of the materials selected for the impactor plate and window plate backing the rock sample.

Interaction of the relief waves results in both forward and backward facing tension waves and, if the tensile strength of the rock is exceeded, dynamic tensile failure occurs. The initial tensile wave and subsequent response during failure propagates toward, and is transmitted through, the interface at the back of the sample. The particle velocity history at this interface can be measured and carries information on the processes of dynamic tensile failure in the rock sample.

Profiles obtained from tensile fracture experiments in Arkansas novaculite[8] are shown in Figure 4. The first particle velocity level in either profile corresponds to the initial compressive wave transmitted through the sample prior to tensile loading. The reduction in particle velocity and wave structure between about 0.7 and 1.2 μs carries the information on maximum tensile stress and time until total failure during the dynamic fracture process. Subsequent structure in the particle velocity profiles corresponds to reverberations of stress waves trapped in the sample piece separated by the fracture process.

DYNAMIC RESPONSE OF ROCK

Wave profiles measured in planar impact studies such as those shown in Figures 2 through 4 suggest a remarkable complexity in the dynamic behavior of rock. It is clear that models developed to describe such behavior must accurately describe the processes of yielding, fracture, and phase transitions occurring in the dynamic compression process.

Dynamic yielding: Yielding and subsequent flow during uniaxial compressive loading of rock represents a deviation from elastic response and provides a mechanism for dispersion of the wave profile and dissipation of energy during the propagation process. It is, therefore, a material behavior which must be treated with care in the constitutive modeling.

Blair dolomite is a representative competent crustal rock which has received considerable attention regarding its compressive response. Both quasi-static uniaxial strain compression studies[9] and planar impact studies[7,10] at several rates of strain have been conducted on this rock. Comparison of the shock compression ($\dot{\epsilon} \sim 10^6$/s) and quasi-static compression ($\dot{\epsilon} \sim 10^{-4}$/s) results indicate significant differences both in the yield stress level and flow stress subsequent to yielding. A yield stress of approximately 0.25 GPa is measured in the quasi-static experiments. Under shock loading, a stress of about 2.5 GPa is achieved before yielding proceeds; nearly a factor of ten greater than the quasi-static value and an appreciable fraction of the theoretical strength of crystalline dolomite.[10] Ramp wave studies have also been conducted on Blair dolomite[7] (Figure 3) and loading strain rates of about 10^4/s, nearly two decades below the shock wave experiments, were achieved. The ramp wave results were found to be in essential agreement with the earlier shock wave results and still differed significantly from the quasi-static results. The compressive stress-strain paths determined from the three strain rates experiments are shown in Figure 5. Recent torsion split Hopkinson bar experiments on several rocks[11] suggest that the characteristic strain rate at which dynamic response relaxes to quasi-static response is between about 10^2/s and 10^3/s.

Dynamic tensile fracture: The process of dynamic fracture is not instantaneous but has been observed to depend in a complicated way on the peak tensile stress achieved and the rate at which the material is carried into tension.[8] In Figure 4, particle velocity histories were shown which were obtained from tensile fracture experiments conducted on Arkansas novaculite subject to planar impact with a thin disc of PMMA (polymethylmethacrylate). The profiles were measured at the back interface between the novaculite and a PMMA laser window material. Through an impedance match solution, the primary fracture signal (pullback wave) can be used to determine the stress-time history in the novaculite adjacent to the PMMA window material. Such stress time histories corresponding to the particle velocity profiles in Figure 4 are shown in Figure 6. The stress histories shown initiate at a compressive stress level, continue through the maximum tensile stress achieved and conclude upon arrival of the first reflected wave from the damage interface interior to the sample. Also indicated in Figure 6 is the maximum tensile stress achieved in the damage zone calculated from the interacting relief waves and the calculated time of arrival of the first reflected wave assuming zero thickness of the damage zone. The stress profiles illustrate several features pertaining to the dynamic fracture process: (1) tensile stress attenuation occurs during propagation of the wave out of the damage zone, (2) the maximum tensile stress depends on the rate of tensile loading, (3) the time to total failure (indicated by the tensile stress pulse width in Figure 6) depends on the rate of tensile loading or the maximum tensile stress achieved during initial tensile loading, and (4) premature arrival of the first reflected wave indicates a finite thickness of the damage zone.

It appears that the dynamic fracture in brittle material is a gradual, rate-sensitive process and there are indications that the Griffith criterion for fracture may not be strictly applicable at the high loading rates achieved.[8] Calculations have shown that a simple rate independent tensile fracture criterion is inadequate in modeling the dynamic fracture process.[12] Models based on a continuum description of fracture nucleation and subsequent accumulation of void volume or damage,[13,14] however, have had some success in predicting the observed response.

Phase transitions: The influence of phase transitions in calcite rock has been found to markedly increase the complexity of the constitutive response in this material as illustrated by the complexity of the wave profile structure measured in Oakhall limestone and shown in Figure 1. Both the calcite I-II and II-III transitions are active in producing the total response observed. The first break in the loading profile and the rarefaction shock wave in the release profile are produced by onset and reversion of the calcite I-II transition. A study of the Oakhall limestone results has shown that the stress-strain response through the I-II transition is nonlinear and reversible to approximately 2.0 GPa; consistent with a reversible displacive polymorphic phase change.[6]

The calcite II-III transition initiates under dynamic loading at a stress of approximately 2.4 GPa and is responsible for the more subtly loading and release structure in the upper portion of the wave profiles in Figure 2. The dynamic II-III transition is more characteristic of a slower, reconstructive behavior in that the Hugoniot properties and wave structure are similar to behavior observed in the shock-induced silicate transitions.

The dynamic transitions have been found to be sensitive to the microstructure of the rock specimen. Factors such as porosity, grain size, and geological history are apparently important. This sensitivity is illustrated by comparable profiles, shown in Figure 7, which were measured in three calcite rocks; Solenhofen limestone, Oakhall limestone, and Vermont marble.[6] The first transition initiates between 0.6 and 1.2 GPa depending on rock type. In Vermont marble, yielding apparently precedes initiation of the transition.

Modeling of the phase transition has required attention to the microstructural state and there are indications that sensitivity to shear stress is important.[6] Results suggest, however, that the strain rate effects relating to the transition are not critical below 2.0 GPa.

SUMMARY

Plate impact techniques can provide a useful tool for studying the dynamic mechanical behavior of rock. Experimental methods and instrumentation originally developed to investigate engineering materials such as metals and ceramics have been fruitfully employed in the study of rock media. Results, such as those presented here, show that rock can be consistent in its mechanical behavior and displays a richness in constitutive response that few other materials can equal. It is becoming clear that strain rate effects cannot be ignored in rock deformation and preclude the use of quasi-static models in many dynamic applications. Material processes such as phase transitions, compressive yield, and dynamic fracture must also be incorporated to obtain a complete constitutive description of rock behavior.

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FIGURE CAPTIONS

Fig. 1 Planar impact target configuration including impacting projectile, rock sample and holder assembly, and near target velocity interferometer optics. Target configuration and interferometry techniques are representative of those used to obtain the results presented in this report.

Fig. 2 Wave profiles in Oakhall limestone.[6] The square wave is the input profile. Subsequent profiles correspond to sample thicknesses of 5.0, 8.5, and 11.9 mm, respectively. Peak stress attained is aoproximately 3.4 GPa.

Fig. 3 Wave profiles in Blair dolomite[7] which evolved, over the indicated propagation distance, from an initial ramp wave input. Loading strain rate was approximately 3×10^4/s.

Fig. 4 Wave profiles obtained in Arkansas novaculite[8] subject to planar impact tensile fracture experiments. The profile in (a) corresponds to an impact velocity of 0.0598 km/s, in (b) to 0.0914 km/s.

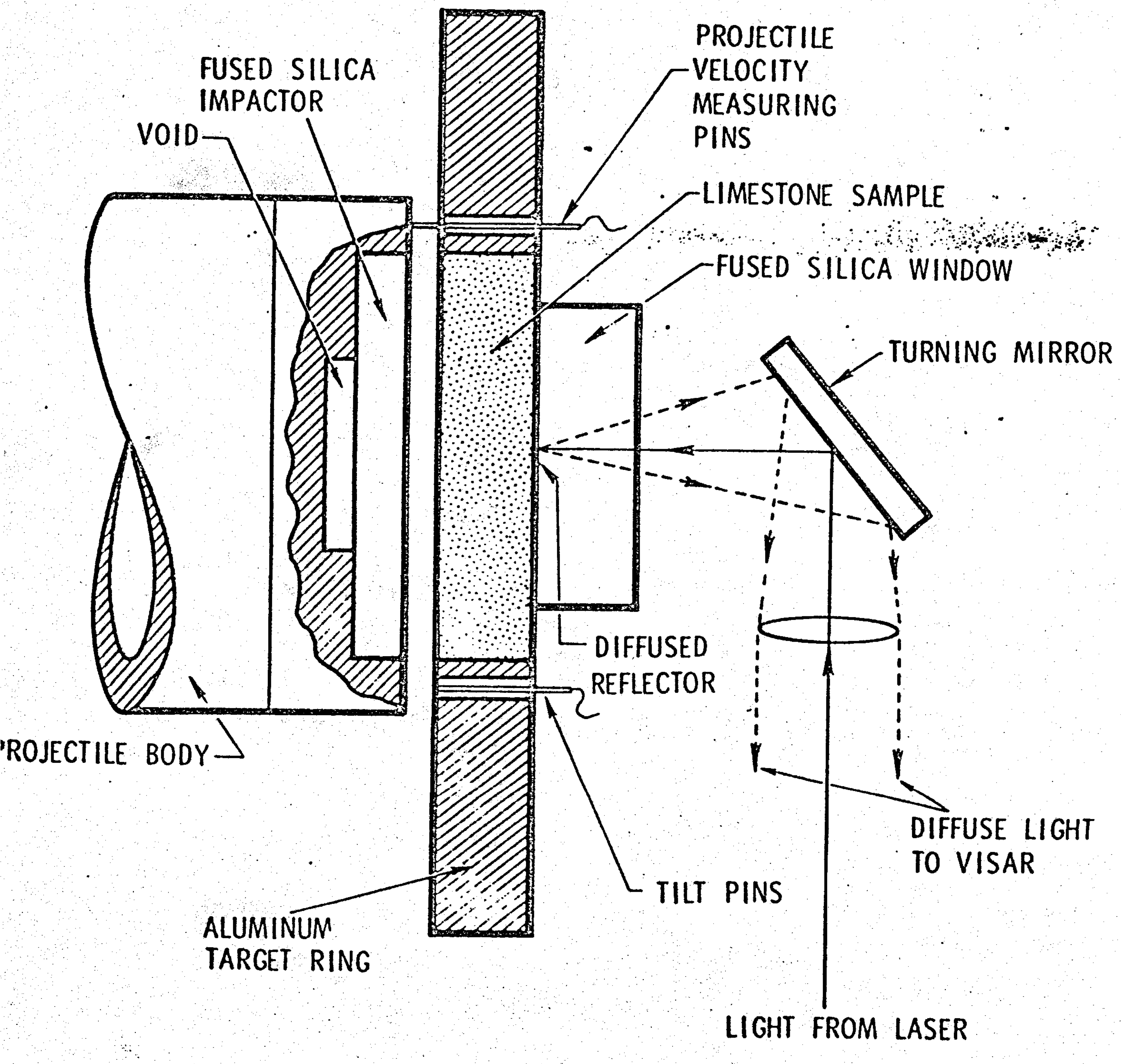
Fig. 5 Stress-uniaxial strain response for Blair dolomite at different strain rates. Experiments include shock wave,[10] ramp wave,[7] and quasi-static[9] results.

Fig. 6 Tensile stress histories in Arkansas novaculite[8] determined from the particle velocity profiles in Figure 4. Also shown is the maximum possible tensile stress calculated from the relief wave amplitudes for both experiments, and the calculated first reflected wave arrival assuming zero thickness to the damage zone.

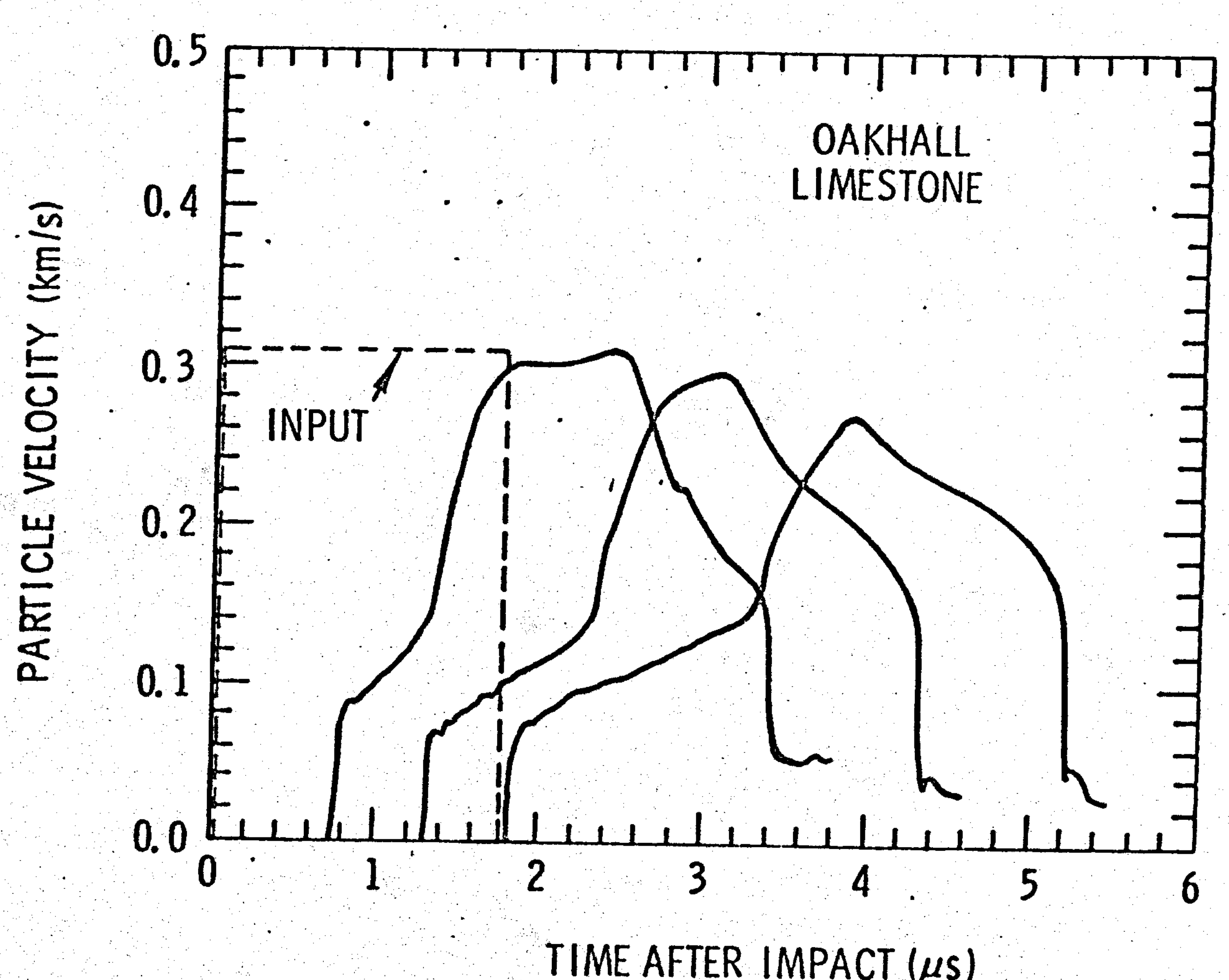
Fig. 7 Loading wave profiles measured in three calcite rocks[6] which illustrate differences in wave structure with rock microstructure.

FIGURE CAPTIONS

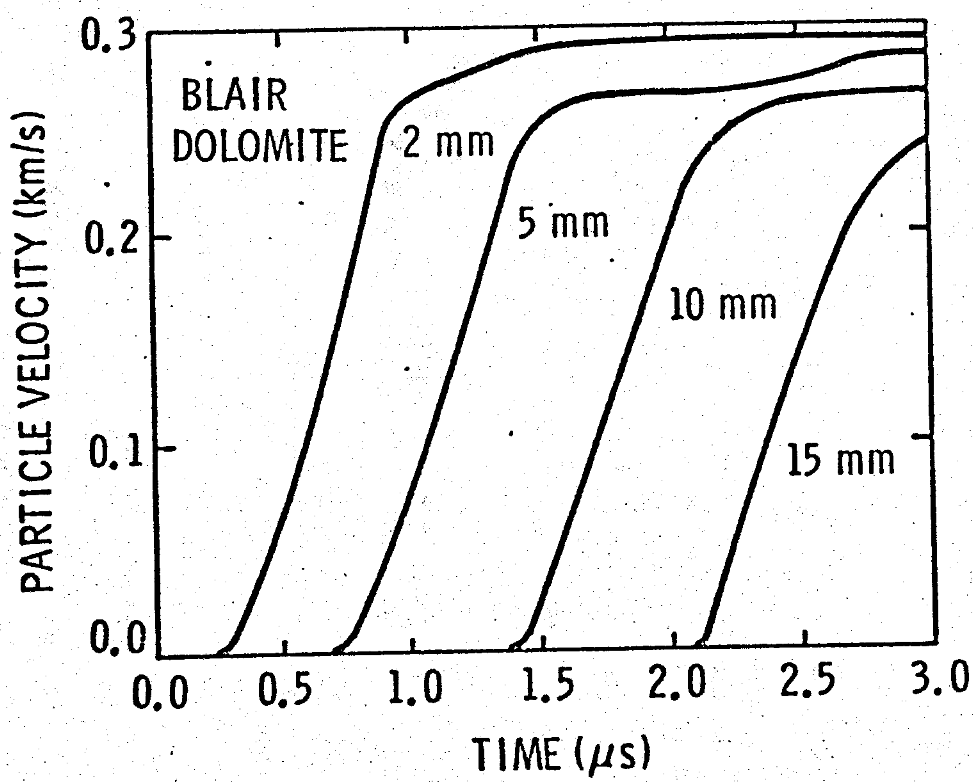
Fig. 7 (cont.) The particle velocity scale is accurate. The stress scale is necessarily approximate.



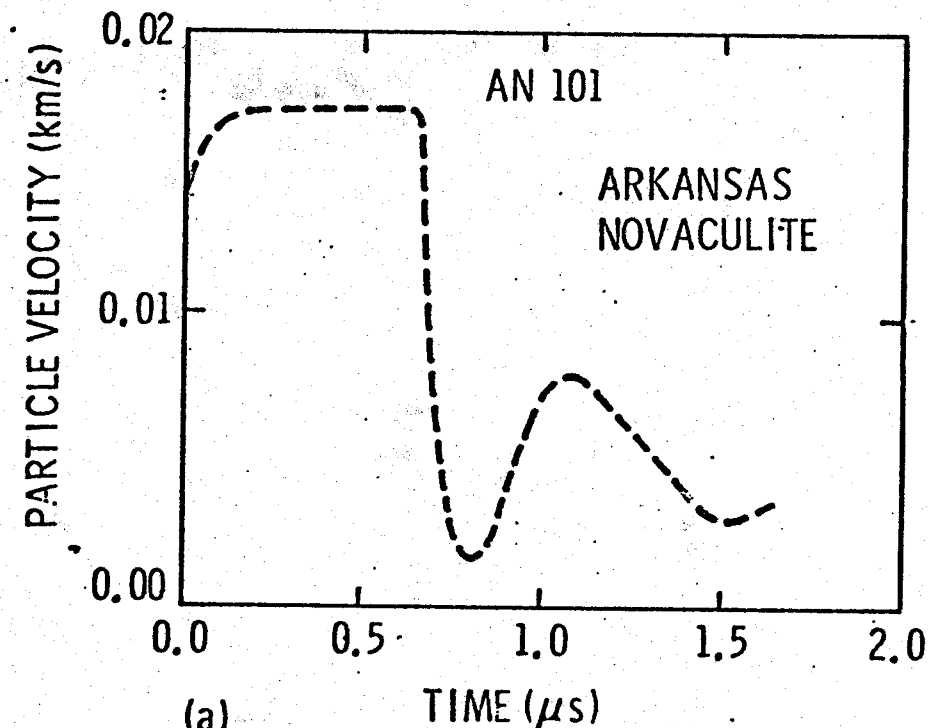
PROJECTILE VELOCITY MEASURING PINS
FUSED SILICA IMPACTOR
VOID
LIMESTONE SAMPLE
FUSED SILICA WINDOW
TURNING MIRROR
DIFFUSED REFLECTOR
PROJECTILE BODY
DIFFUSE LIGHT TO VISAR
TILT PINS
ALUMINUM TARGET RING
LIGHT FROM LASER



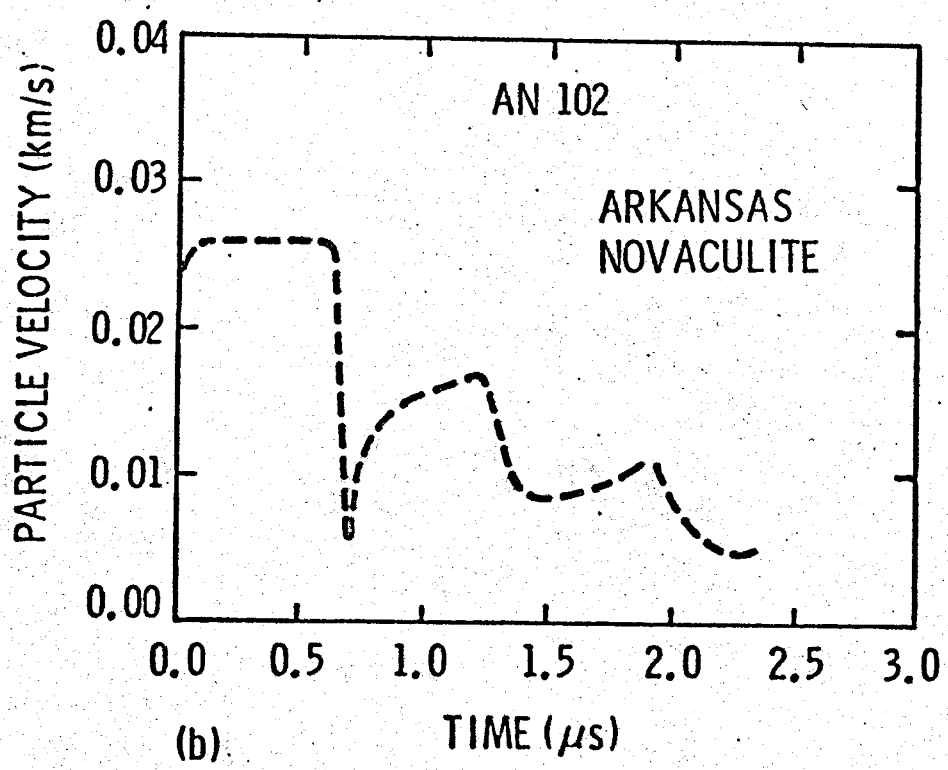
OAKHALL
LIMESTONE
INPUT
PARTICLE VELOCITY (km/s)
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
TIME AFTER IMPACT (μs)



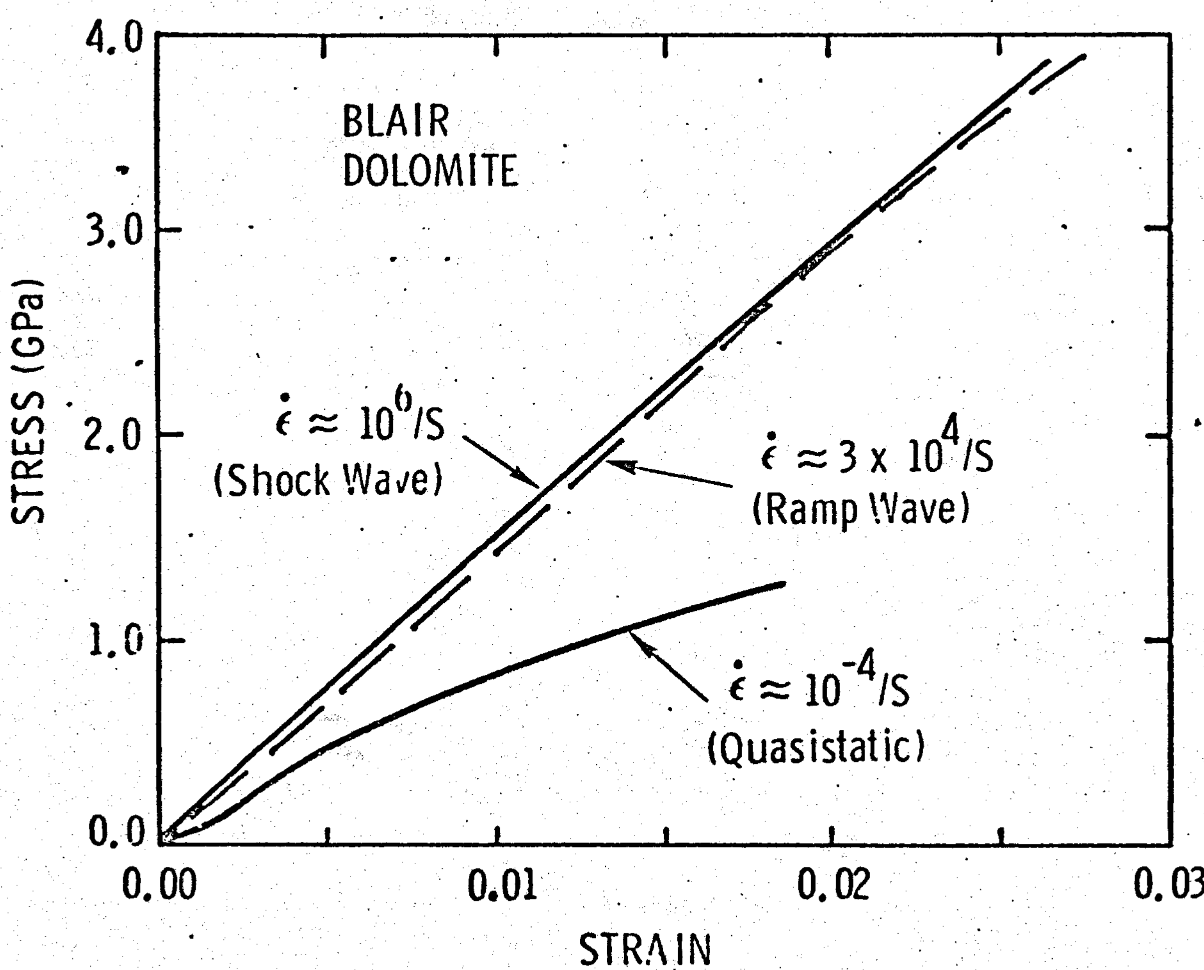
BLAIR
DOLOMITE
2 mm
5 mm
10 mm
15 mm
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
PARTICLE VELOCITY (km/s)
TIME (μs)


AN 101
ARKANSAS
NOVACULITE
PARTICLE VELOCITY (km/s)
0.02
0.01
0.00
0.0
0.5
1.0
1.5
2.0
TIME (μs)

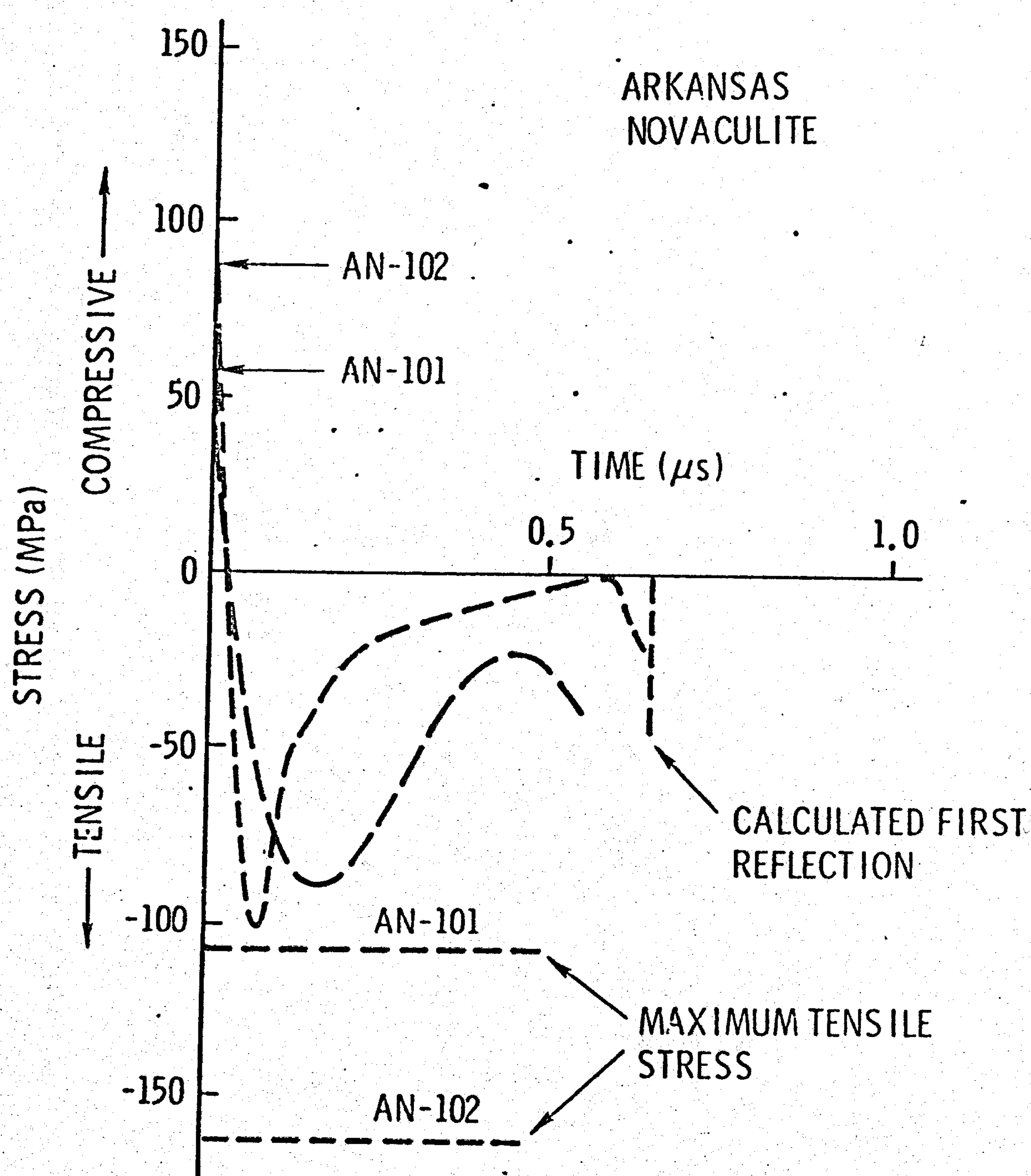
(a)


AN 102
ARKANSAS
NOVACULITE
PARTICLE VELOCITY (km/s)
0.04
0.03
0.02
0.01
0.00
0.0
0.5
1.0
1.5
2.0
2.5
3.0
TIME (μs)

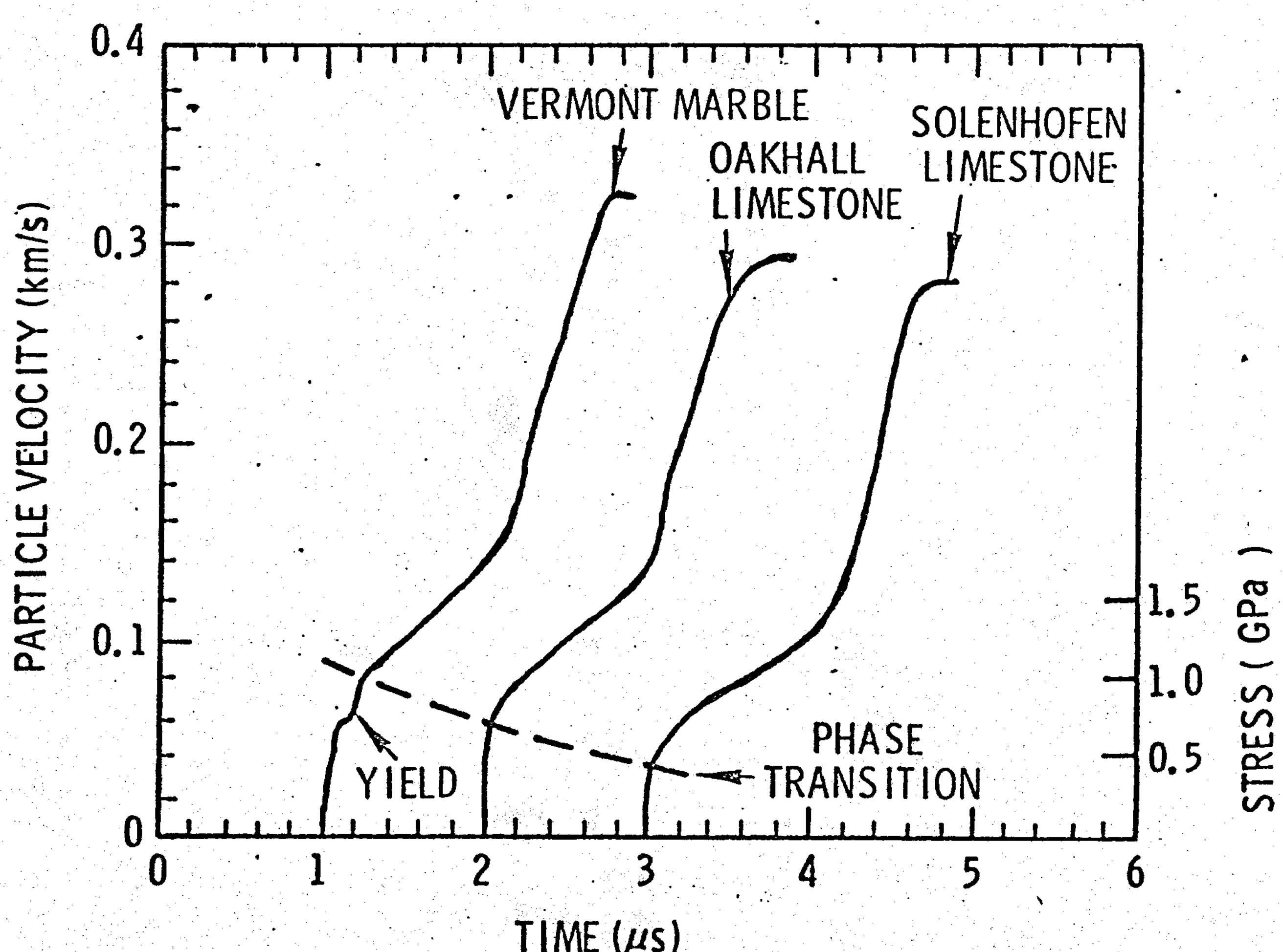
(b)



BLAIR
DOLOMITE
STRESS (GPa)
4.0
3.0
2.0
1.0
0.0
0.00
0.01
0.02
0.03
STRAIN
$\dot{\epsilon} \approx 10^6$/S
(Shock Wave)
$\dot{\epsilon} \approx 3 \times 10^4$/S
(Ramp Wave)
$\dot{\epsilon} \approx 10^{-4}$/S
(Quasistatic)



ARKANSAS
NOVACULITE
STRESS (MPa)
COMPRESSIVE
TENSILE
150
100
50
0
-50
-100
-150
AN-102
AN-101
TIME (μs)
0.5
1.0
CALCULATED FIRST
REFLECTION
AN-101
MAXIMUM TENSILE
STRESS
AN-102



PARTICLE VELOCITY (km/s)
0.4
0.3
0.2
0.1
0
VERMONT MARBLE
OAKHALL
LIMESTONE
SOLENHOFEN
LIMESTONE
YIELD
PHASE
TRANSITION
STRESS (GPa)
1.5
1.0
0.5
0
1
2
3
4
5
6
TIME (μs)