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Influence of the Hysteretic Phase Change in Granite on Seismic and Hydrodynamic Coupling of Nuclear Explosives

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INFLUENCE OF THE HYSTERETIC PHASE CHANGE IN GRANITE ON SEISMIC AND HYDRODYNAMIC COUPLING OF NUCLEAR EXPLOSIONS

by

R. J. Bos, T. N. Dey, and J. C. Boettger

ABSTRACT

Using Boettger's new two-phase treatment of hysteretic phase changes, calculations were done to observe the effect of the silicate phase change in the hydrodynamic region and seismic region of an underground nuclear explosion. The results indicate a small effect on shock time of arrival, a moderate effect on peak particle velocities, peak pressures in the hydrodynamic region, and negligible effect on seismic signals in the seismic region.

I. INTRODUCTION

Quartz and a number of other silicate minerals display a hysteretic phase change when shocked to Hugoniot pressures greater than 5 to 10 GPa. A series of one-dimensional calculations of tamped nuclear explosions were performed to examine the significance of this portion of the equation of state (EOS) on parameters of the stress wave generated by an explosion. These parameters are useful for verifying yields of nuclear explosions under the terms of the Threshold Test Ban Treaty. They are also useful in detecting clandestine nuclear explosions and discriminating them from conventional explosions or natural seismic events. These calculations used a recently developed dynamic-phase mixing model developed by J. Boettger, 1993, for granite and implemented in the Lagrangian code SMC2D by T. Dey. The calculations were done to observe the influence of this phase transition on close-in effects (0 to 50 m), such as shock wave velocity as a function of time, peak particle velocity and peak stress, and the far-field seismic coupling effects. The sensitivity of these effects to the behavior of the rock in the hysteretic phase transition region was bounded by using two other simple models of the phase transition. One of these models assumes that the phase changes reverse during unloading along the same path as the model had during loading in the Gibbs free-energy-versus-phase-weight fraction space. This model, called the reversible model here and in Boettger et al., 1993, produces no energy absorption because of phase change hysteresis. The other model assumes that the reverse phase transition does not occur until the material reaches the quasi static equilibrium phase boundary. This model, called the equilibrium model here and in Boettger et al., 1993, produces the greatest hysteretic energy absorption caused by the phase change.

It is postulated that the differences in energy absorption due to the differences in phase change response might produce observable effects in the hydrodynamic and seismic regimes. If so, it would then be possible to see if rock behavior on the large scale is similar to that in the laboratory scale using careful examination of data from nuclear events about how this phase change occurs. If the differences in observable effects were to be significant, it would also indicate that including these complicated hysteretic effects is necessary for accurate modeling of the effects of underground nuclear explosions.

II. HYSTERETIC MODEL DESCRIPTION

In the pressure range from about 10 GPa to 50 GPa, silicates are known to go through a hysteretic phase transition that complicates the modeling of shock behavior in this regime. In order to get a more accurate representation of the behavior of silicates in that pressure range, Boettger assumed a mixture of two distinct phases. These were a low-pressure phase and a high-pressure phase, each with a specific EOS. The percentage of each phase is calculated by relating the mass fraction of the high-pressure phase to the Gibbs free energy difference between the two phases. For a complete description see the paper by Boettger et al., 1993. Also described in the paper are two simple models, equilibrium and reversible, that should bound any hysteretic effects. These can be realized from the hysteretic model by appropriate choice of parameter values.

This hysteretic model was incorporated into the Lagrangian code SMC2D invented by T. Dey. This version of the code was used to run the simulation reported in this document. Tables I, II, and III list the parameters used to run the code for the granite equilibrium, hysteretic, and reversible models.

III. SIMULATION DESCRIPTION

A one-dimensional simulation of a nuclear explosion in a granite formation was performed using the code where Boettger's hysteretic model had been incorporated. The simulation was set up with a 2-m steel sphere into which 1 kt of energy was deposited.

Between 2 m and 11 m the material was granite specifically described by the Sesame tables listed in Tables I to III and using the hysteretic phase-change model. This region contains all the material subjected to sufficient pressures to cause the phase change. Because the hysteretic model does not contain all the parameters required for a

TABLE I

HYSTERETIC PARAMETERS

	Loading	**Low Pressure Release**	**High Pressure Release**
SESAME EOS	9391	9392	9392
Activation Energy (MJ/kg)	0.00	0.00	0.80
Epsilon (MJ/kg)	1.70	0.70	0.90
Eta	0.50	1.80	3.50

(See Boettger et al. for an explanation of the parameters.)

TABLE II

EQUILIBRIUM PARAMETER

	Loading	Low Pressure Release	High Pressure Release
SESAME EOS	9391	9392	9392
Activation Energy (MJ/kg)	0.00	0.00	0.80
Epsilon (MJ/kg)	1.70	0.70	0.90
Eta	0.50	1.80	3.50

(See Boettger et al. for an explanation of the parameters.)

TABLE III

REVERSIBLE PARAMETERS

	Loading	Low Pressure Release	High Pressure Release
SESAME EOS	9391	9392	9392
Activation Energy (MJ/kg)	0.00	0.00	0.00
Epsilon (MJ/kg)	1.70	1.70	0.00
Eta	0.50	0.50	0.00

(See Boettger et al. for an explanation of the parameters.)

good description of the mechanical behavior of the rock at low stress, the remaining material out to 2 km was granite described by Sesame EOS 7385 together with strength parameters appropriate for a strong intact granite. The EOS and constitutive behaviors of these two models used for the granite merge smoothly into each other for the conditions that occur at the material boundary in the simulations. Therefore, the result resembles a single, more complicated model describing both the low-pressure response and the hysteretic behavior that had been used. Identical runs were also performed with the equilibrium and reversible models of the phase change substituted for the hysteretic model.

IV. COMPARISON WITH SWEGLEÕS GRANITIC RESULTS

Figure 1 shows a comparison between Boettger's model and Swegle's model for granite. Swegle's results (dashed lines) show a wider variation then Boettger's (solid lines). The overall effect appears quite similar. Differences appear to result primarily in the underlying EOS used to describe this granite.

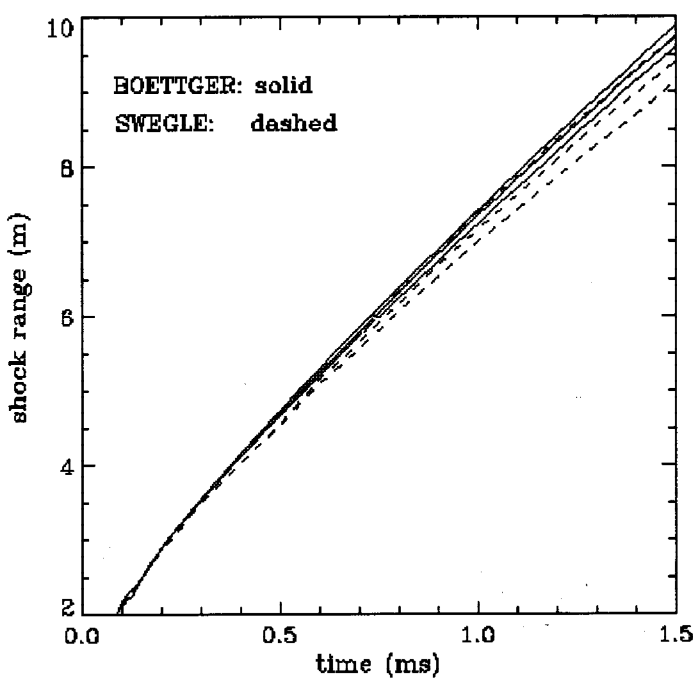

Figure 1. Model comparison for granite by Boettger and Swegle.

V. HYSTERETIC MODEL AND CLOSE-IN EFFECTS

The first area of interest that can be explored using the above-mentioned models is the close-in region. Here we will take that to be the region around the source where the shock wave can crush sensing cables (such as CORRTEX cables). This region typically extends from 0 to about 10 to 20 m/kt**1/3.

Figure 2 shows the radius-versus-time (R/T) curves for the three models. Differences among them are less than 20%. A more informative plot is found in Figure 3. Here differences of the equilibrium and reversible models from the hysteretic model are plotted. When the typical accuracy of cable-crush sensors, which is between 2 and 5 cm, is taken into account, it is clear that at later times (>1 ms) the effect of phase transition should be detectable in field experiments.

As should be expected, the reversible phase-transition model maintains the greatest shock velocity of the three models at any given time, and the equilibrium model maintains the least shock velocity. The equilibrium model gives the greatest energy absorption through the phase transition leading to a more rapid attenuation of the shock wave and a more rapid slowing down of the shock. The reversible transition model gives the least energy absorption because of the phase transition leading to a less rapid attenuation and a less rapid slowing of the shock.

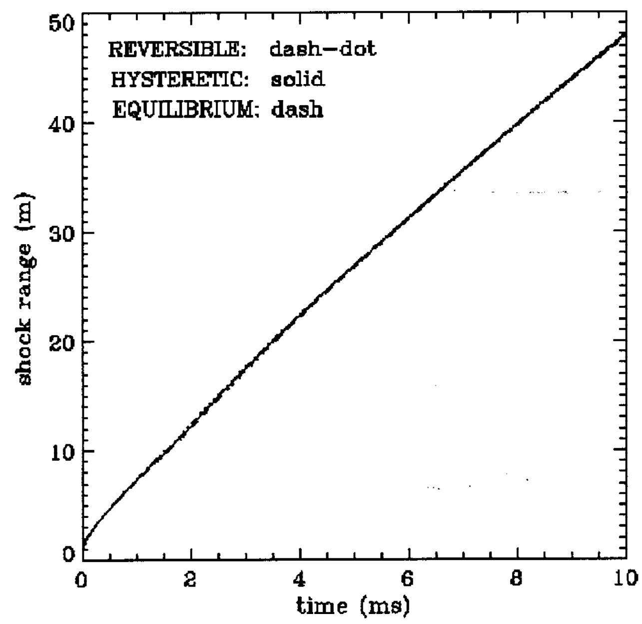

Figure 2. Model comparisons for granite shock range curves.

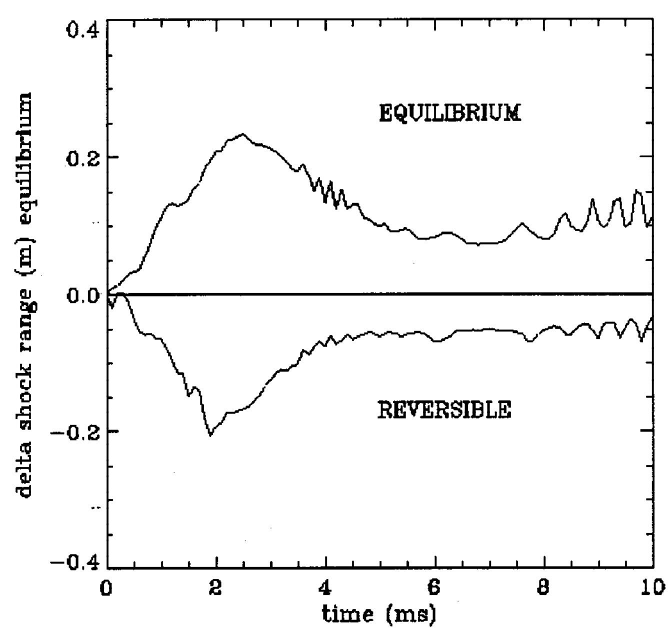

Figure 3. Model comparisons for granite delta shock range curves.

Figure 4 shows peak pressure as a function of range. In the range from about 4 to 10 m, the difference among the models is on the order of a few GPa, which amounts to roughly 25% to 30% of the value. This is a substantially larger variation among the models than is observable in the shock-range time measurements. Currently, the best pressure gauges have a accuracy of .1 to 1 GPa. The accuracy of the current generation of pressure gauges is marginal to be able to give information to help refine the hysteretic model. Note

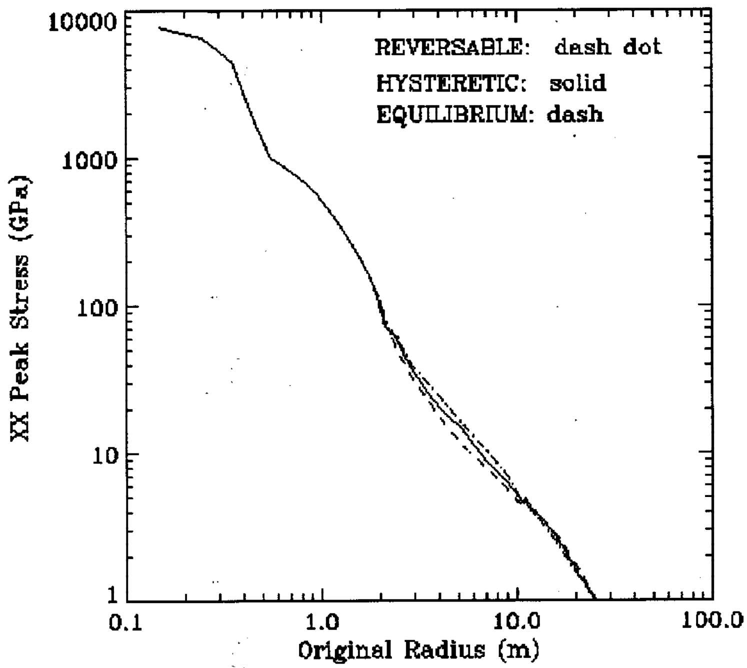

Figure 4. Model comparisons for granite peak stress.

that the region where there is a significant difference among the models is just the region where the phase change occurs. At greater ranges the peak pressures show smaller differences. Figure 5 shows the peak velocity from each of the models. Again, in the range of 3 to 10 m from the source, the difference in models is on the order of a 100 m/s, less than about 10% of the magnitude. However, this is well within the accuracy of current particle gauges to register. Again, the only significant particle velocity differences occur in the region where the phase change is active, not at greater ranges.

VI. HYSTERETIC MODEL AND SEISMIC COUPLING

In the seismic region, we can look at the apparent yield and the spectrum of the reduced velocity potential (RVP) to see the potential effect of the hysteretic model.

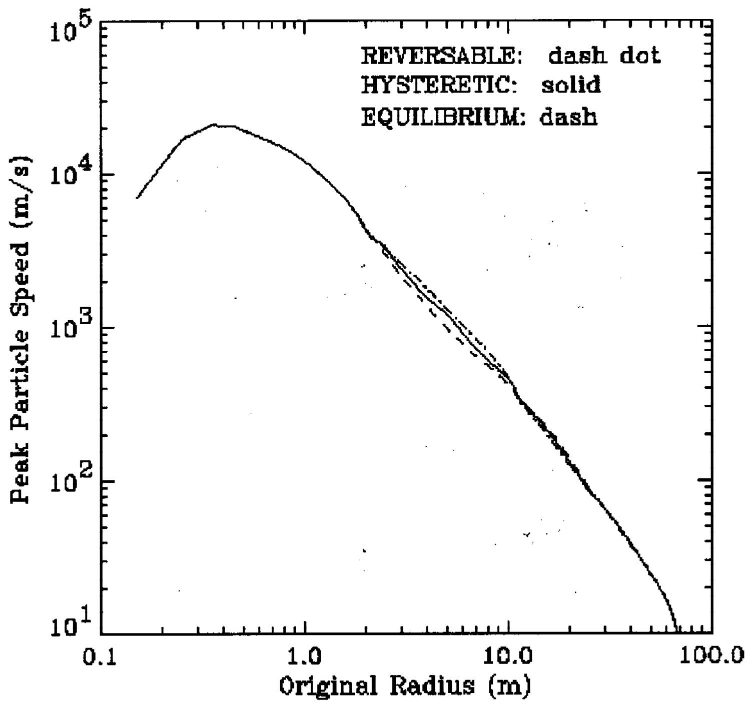

Figure 5. Model comparisons for granite peak particle speed.

Figure 6 shows a plot of the cumulative distribution of energy as a function of range at the end of each calculation. One result immediately apparent is that 95% of the total device energy is retained within the first 100 m of the explosion by the dissipative processes, such as shock heating, shear failure, and the hysteretic phase transition. Less than 5% of device energy is able to escape to the seismic regime in these simulations. Figure 7 shows the spectrum of the RVP at 200 m from the source, a distance sufficient to be in the linear elastic regime in these calculations. Both figures indicate that in the seismic region the effect of the hysteretic model is negligible. Minor differences of a few percent do occur among the spectra, particularly at the lowest frequencies, but these are far too small to be significant to seismic observations.

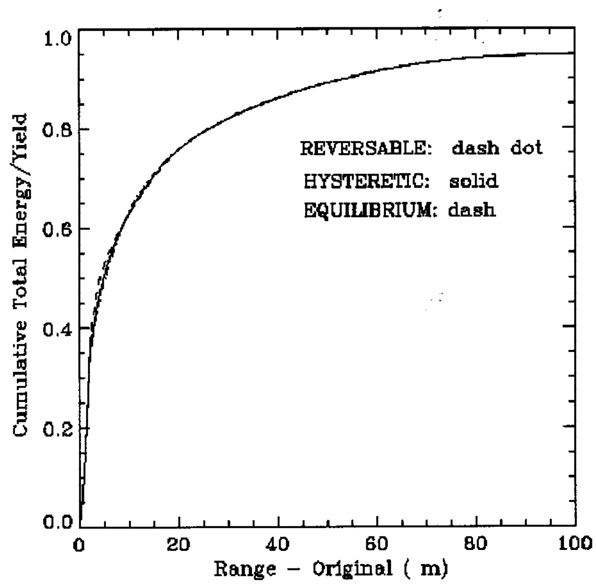

Figure 6. Model comparisons for granite cumulative total energy.

From the previous discussion of close in effects, we would expect the maximum effect to be seen on a spectra obtained from a range in between 5 meters and 11 meters. In Figure 8, RVP spectra are again plotted for all three models. The figure shows that the effect of hysteresis is contained only in the higher frequency component of the spectrum above 100 Hz. We would expect that this information would be lost rapidly as the range increases from the source.

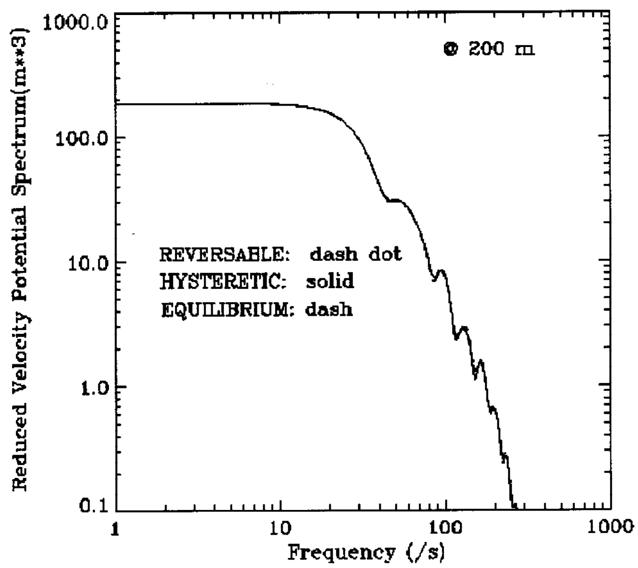

Figure 7. Model comparisons for granite Fourier spectrums.

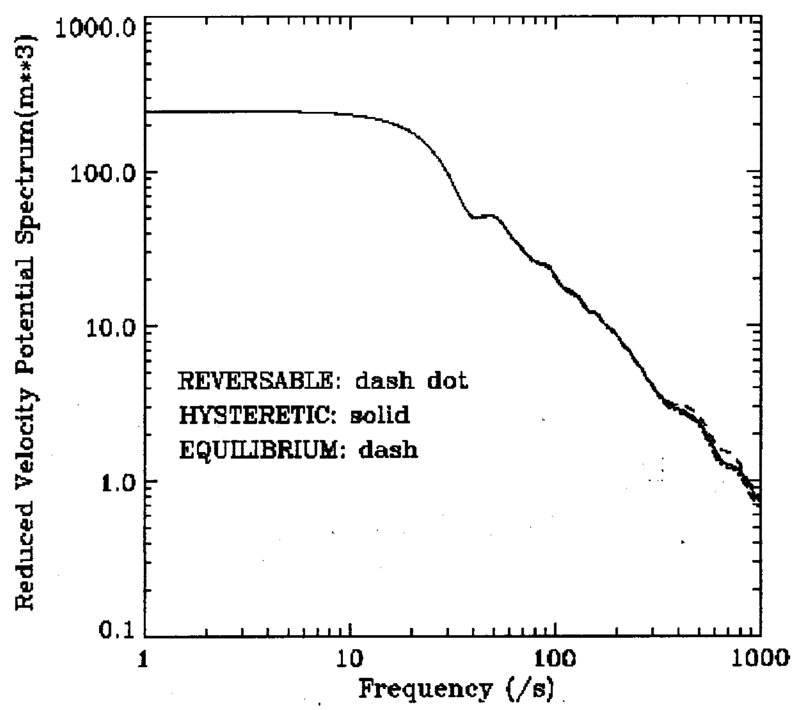

Figure 8. Model comparisons for granite Fourier spectrums at 10 M.

The fact that all information about the hysteretic effect is lost by a range of 100 meters due to the variety of processes proposed above can be seen in more detail in Figure 9. In this figure, RVP spectra at different ranges are plotted. Note that the as the distance from the source increases, the high frequency component of the spectra (above 50 Hz) systematically falls off until somewhere between 50 m and 100m. What this implies is that a considerable amount of the energy contained in the higher frequencies is very rapidly lost leaving only the lower frequencies to propagate out to seismic distances.

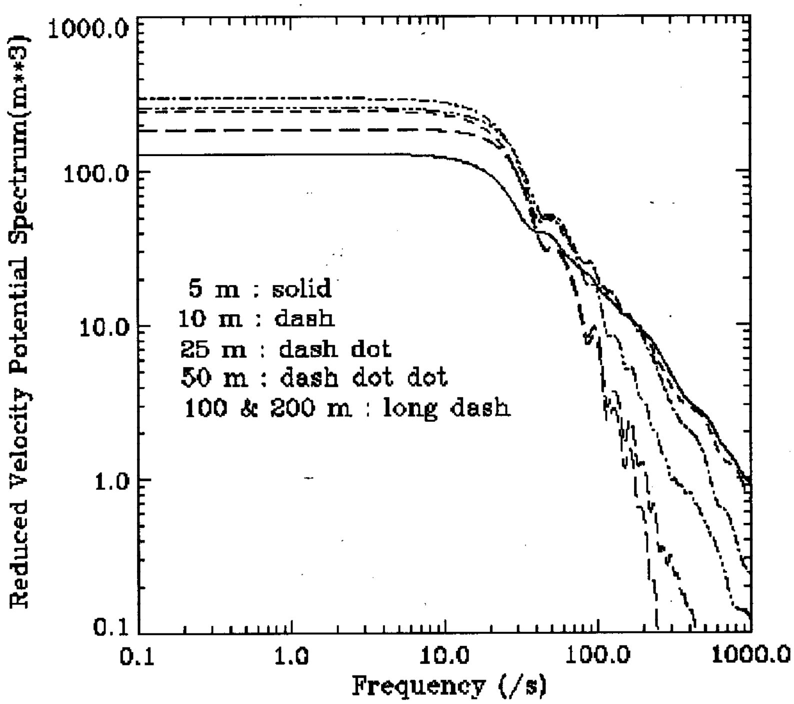

Figure 9. Model comparisons for granite RVP at increasing range.

VII. CONCLUSION

For the close-in region, the effect of phase transitions is large enough and the present generation of sensors (particularly particle velocity sensors) are sensitive enough to be able to calibrate the parameters used in the hysteretic model and to find if other effects are also important and must be included into the model.

A number of these nuclear events had cable crush sensors, such as CORRTEX, on them in a granite formation. We have also not yet looked at the data nor calibrated the granite hysteretic model.

For the far-field region, it appears that the hysteretic phase transitions have negligible effects on the seismic spectrum for sources in granite.

Although it was postulated that the energy absorption of the hysteretic phase change might produce significant changes in the energy coupled into both the hydrodynamic and seismic fields, observable effects seem to be limited only to the hydrodynamic regime. The effects of this phase transition on seismic waves appear to be thoroughly masked by the other dissipative processes occurring in the rock. In the hydrodynamic regime, the influence of the phase change should be observable, but not huge. Depending on the phenomena one is interested in, these effects may or may not be significant.

ACKNOWLEDGMENTS

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