SCALING LAWS FOR SECONDARY SEISMIC RADIATION GENERATED BY FRACTURE DAMAGE

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ABSTRACT

The non-linear source region of an underground explosion can be divided into a series of nested spherical shells, each characterized by a different deformation rheology. Between the detonation point and the cavity radius, r_c, rock is vaporized. Between r_c and the "failure radius", r_f, rock is fragmented. Between r_f and the "damage radius" r_d, new cracks are nucleated and grow, but rock is not fragmented. Between r_d and the "elastic radius" r_e, existing cracks slide, deformation is anelastic, but no new damage is generated. The micromechanical damage mechanics formulated by Ashby and Sammis (1990) allows us to quantify this model by calculating the bounding radii once the size and density of initial fractures in the rock is specified. Recently Johnson and Sammis (2001) and Sammis (2002) have shown that the integrated effect of the nucleation and growth of fracture damage in the non-linear source region between r_c and r_e can generate secondary seismic waves comparable to those generated by the source. We show here that the spectrum of this secondary radiation scales with the failure radius r_f, in the same way that the primary radiation has long been known to scale with the elastic radius r_e. This scaling is established using results from the Non-Proliferation Experiment (NPE) chemical explosion from Johnson and Sammis (2001) and near-field records from the PILEDRIVER nuclear explosion in granite.

OBJECTIVE

The objective of this research has been to identify and understand the nonlinear processes that contribute to the seismic signal radiated by underground explosions. Our specific focus is on crystalline rock where sliding on preexisting cracks and the nucleation and growth of new cracks contribute to the signal. In the past, in collaboration with Rimer and Stevens (Rimer *et al*., 1999; Stevens *et al*., 2002), we have shown that such processes provide a physical explanation for the “pulse broadening” observed in the near-field seismic records from the PILEDRIVER event. Our recent focus has been on the secondary radiation generated by these fracture processes, which we describe using micromechanical damage mechanics (Ashby and Sammis, 1990). Because this damage mechanics models the cracks, we are able to calculate the dilatational and shear moment tensors of each and sum their net effect over the entire source region. While the contribution of each crack is small and high-frequency, Johnson and Sammis (2001) have shown that the integrated signal is of comparable magnitude to the main pulse and in the seismic band. Because this higher frequency secondary radiation may contribute to regional phases currently being used to identify and characterize explosive sources, it is important that its scaling properties be understood. This report is a step in that direction.

RESEARCH ACCOMPLISHED

The source region of an underground explosion can be described by a nested set of concentric spheres, each characterized by a distinct rheology (Figure 1). Closest to the source, rock vaporizes and flows plastically to produce a cavity of radius r_c. At greater distances, the rock is driven to brittle failure, granulates, and may be further weakened by acoustic fluidization. Brittle failure extends to a radius r_f, which, for a given source model, may be calculated as the onset of failure in the Ashby and Sammis damage mechanics. At distances greater than r_f, radial cracks grow from preexisting flaws, but the rock does not fail and is not granulated. This process extends out to a distance r_d where stresses have fallen to the point where new cracks no longer nucleate from the preexisting ones. For a given source model, r_d is calculated using the nucleation condition in Ashby and Sammis (1990). At distances larger than r_d, sliding is still possible on the preexisting cracks, but new crack damage is not nucleated. The hysteresis associated with crack sliding results in an anelastic rheology, which extends out to the elastic radius r_e. The elastic radius may be estimated using the Couloumb friction criterion for sliding on a preexisting surface.

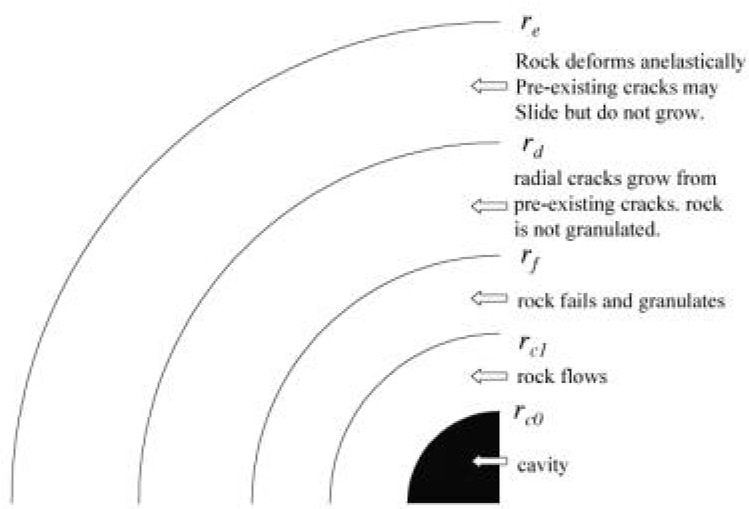

Figure 1. Rheological radii for the non-linear region of an explosion source

Johnson and Sammis (2001) used the Ashby and Sammis (1990) damage mechanics in a simple "equivalent source model" to calculated source radii r_c, r_f, and r_d, as well as the secondary radiation generated by the 1kt NPE explosion in tuff for a range of the two damage mechanics model parameters: a, the radius of the initial cracks in the source medium, and D_o, the initial damage in the source medium. D_o is defined as

$$D_o = \frac{4}{3} p \left(a \cos c \right)^3 N_v \qquad (1)$$

where N_v is the number of initial cracks per unit volume and c is a geometrical factor near one. These results were reported last year (Sammis, 2002), and are summarized here in Tables 1 and 2. Note that the initial crack size controls the nucleation radius r_d, while the initial damage controls the failure radius r_f.

Table 1. Effect of initial damage on source dimensions. (crack radius *a* =0.1 cm in all cases)

Initial damage D_o	Failure damage D_f	Failure radius r_f (m)	Damage radius r_d (m)	Maximum velocity at 450 m (cm/sec)
0.01	0.09	25	25	0.9
0.05	0.26	35	45	8.4
0.10	0.40	35	45	16.1
0.20	0.53	35	45	28.2
0.40	0.73	35	45	44.8
0.80	1.13	35	45	88.9

Table 2. Effect of initial crack radius on source dimensions. (initial damage $D_o = 0.1$ in all cases)

Crack radius a (cm)	Failure damage D_f	Failure radius r_f (m)	Damage radius r_d (m)	Maximum velocity at 450 m (cm/sec)
0.01	0.22	18	18	2.6
0.10	0.40	35	45	16.1
1.00	0.39	75	90	21.1
10.0	0.40	90	150	13.1

The question now is, what controls the peak frequency of the secondary radiation? In order to answer this question, we used Fast-Fourier analysis to find the peak frequency of the secondary radiation for the cases calculated by Johnson and Sammis (2002). Results are summarized in Table 3 where the various rheological radii and peak spectral frequencies are computed for $D_o = 0.1$ and a range of initial flaw sizes, a.

Table 3. Spectral analysis of NPE source.

	D_o	a (cm)	r_c (m)	r_f (m)	r_d (m)	f_{max} (Hz)
Explosion (observed)						9
Explosion (modeled)	0.1	0.1	15	35	45	6
Secondary P	0.1	0.01	15	18	18	31
	0.1	0.1	45	28.2		17
	0.1	1.0	45	44.8		12
	0.1	10.0	45	88.9		9
Secondary SH (Prestress)	0.1	0.1	15	35	45	7
Secondary SH (Preferred orientation)	0.1	0.1	15	35	45	7

When the peak frequency f_{max} was plotted as a function of the various radii, the following dependencies were found:

$$f_{max} \propto r_f^{-1}, \qquad f_{max} \propto r_d^{-1/2}, \qquad f_{max} \propto \left(r_f - r_c\right)^{-1/2}, \qquad f_{max} \propto \left(r_d - r_c\right)^{-1/3} \tag{2}$$

Only the first relation in equations (2) makes physical sense, and is the same scaling observed for the main pulse where the corner frequency in the spectrum f_c, scales with the elastic radius as (Denny and Johnson, 1991)

$$f_c = v / r_e \tag{3}$$

The scaling relation between the secondary radiation and the failure radius is shown in Figure 2. Note that f_{max} for the secondary SH waves are lower than for secondary P (at the same value of r_f) as expected from (3) above, but that the ratio $f_{max}(P)/f_{max}(SH) = 2.4$ while the ratio $v_P / v_S = 1.36$ in tuff. It may be that the frequency of the SH waves, being more sensitive to the sliding, scales with r_d. In that case, $(v_P / v_S)(r_d / r_f) = 1.75$, which is still less than 2.4. It may be that that the SH waves see the crack sliding all the way out to the elastic radius, while the P waves only see the major dilatation within the failure radius.

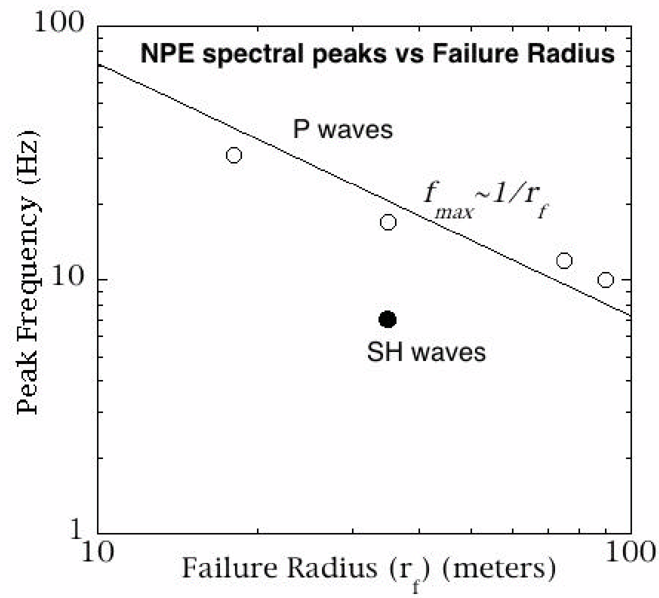

Figure 2. Peak frequency as a function of the failure radius. Note that the P waves frequency scales as $1/r_f$.

Finally, we compare these results with secondary radiation generated by the 61 kt PILEDRIVER event detonated in granodiorite.. Fourier analysis of the near-filed records (one of which is shown in Figure 3) reveals a high-frequency component with $f_{\max} \approx 25$ Hz. For granodiorite, $v_P \approx 5.5$ km/sec, so, the scaled frequency in the tuff ($v_P \approx 2.6$) is $f_{\max} = (2.6/5.5)25 = 12$ Hz. For the damage parameters used to construct Figure 2, this corresponds to $r_f \approx 70$ m, not an unreasonable value based on the post-shot core data (Borg, 1970). We are currently modeling the granite explosions PILEDRIVER, HARDHAT, and SHOAL to further quantify this result.

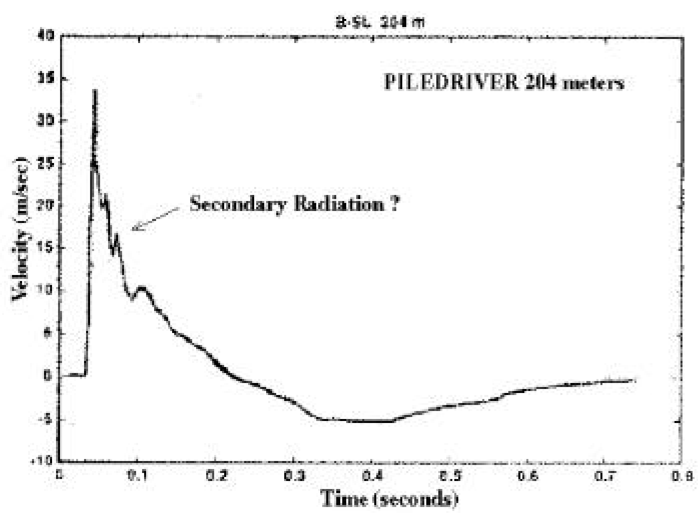

Figure 3. Velocity seismogram for PILEDRIVER at 204 m. (from Stevens et al., 2002).

CONCLUSIONS AND RECOMMENDATIONS

The frequency of secondary P wave radiation generated by fracture damage scales with the failure radius as $f_{\max} \propto v_P / r_f$. The frequency of secondary SH radiation appears to scale with the elastic radius as $f_{\max} \propto v_S / r_e$, possibly reflecting the fact that dilatation is most pronounced near failure while significant sliding on preexisting cracks occurs out to the elastic radius. We are currently exploring these scaling relations by modeling the nuclear explosions PILEDRIVE, HARDHAT, and SHOAL.

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