EXPLOSION SOURCE MODEL DEVELOPMENT IN SUPPORT OF SEISMIC MONITORING TECHNOLOGIES: APPARENT EXPLOSION MOMENT AND PROSPECTS FOR MOMENT-BASED YIELD ESTIMATION

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ABSTRACT

This paper reports on research activities for the third and final year of a project to develop new explosion source models that include the effects of source medium damage, a form of which is deep-seated, shock-induced tensile failure identified in our previous studies. In general, damage will contribute volumetric, compensated linear vector dipole (CLVD), and double-couple (DC) sources of seismic radiation. Our past work has studied the effects of a CLVD source on Rayleigh wave radiation and its impact on the performance of m_b-M_s discrimination. Part I of this paper shifts attention to the volumetric contribution that source medium damage makes. In the model, there are two possible volumetric sources: (1) the traditional source associated with direct effects of explosions creating a cavity with volume *V* and (2) the damage source due to non-linear free-surface interactions and shock-wave rebound causing abrupt changes of elastic moduli and dilating the source medium with volume *U* due to bulking and shear dilatancy. The CLVD represents a non-volumetric, deviatoric source component of damage. *K* is a source parameter measuring the steady-state strength M_{CLVD} of the CLVD with respect to M_I, the isotropic moment. Moment tensor inversion results for NTS explosions show that *K* steadily decreases with yield, approaching values near 1.0 for highest yield shots. A *K* value of 1.0 implies $M_{CLVD} = 0$ and, by inference, small *U*. Our hypothesis is that the force of spall slapdown is great enough at high yields to crush the tuff matrix, reducing *U* while *V* remains intact. Slapdown at low yields is not great enough to do so, leaving both *V* and *U* unaffected. We tested the hypothesis by comparing measurements of M_I with estimates of "classical" moment based on scaling relationships of *V* and velocity models for Pahute Mesa, including the effects of coupling above the water table. The results support the hypothesis and the conclusion that in general, measurements of M_I are composed of two volumetric components: *V* due to cavity formation and *U* related to material damage of the source medium. Thus M_I is an "apparent explosion moment," quite different from the moment predicted by classical theory for a spherical source model.

Part II of this paper revisits the outstanding problem related to estimating yield from seismic moment, highlighted in the 1990s by tectonic release models to explain surface wave observations for Soviet explosions conducted at the Semipalatinsk Test Site. These models failed to provide estimates of M_I that correlated with explosion yield as well as m_b. Something fundamental was missing in explosion source models where the only contributor to source asymmetry was tectonic release represented by a DC force system. Based on the work in Part I, my co-workers (see Acknowledgements) and I think that the missing ingredient is source medium damage and the contributions it makes to the radiated seismic wavefield. It is straight forward to show that by ignoring the effects of source medium damage, past investigations very likely obtained biased estimates of M_I and deduced source models that over-estimate the importance of tectonic release. The 2006 and 2009 North Korean tests provide an opportunity to show the excellent agreement between tradeoff curves for yield versus depth-of-burial based on estimates of M_I and m_b when source medium damage is suppressed (as it is for these tests) or accounted for by new moment-correction methods. This result is motivation for calibrating new M_I-yield relationships corrected for the volumetric contributions due to source medium damage.

OBJECTIVE

The objective is to develop new analytical explosion source models based on seismic moment tensor theory for further improvement and advancement of regional seismic discrimination and yield estimation technologies. Such technologies rely heavily upon the source information contained in high-frequency shear (*S*) waves. The use of coda waves following regional *S* phases to estimate explosion yield is one example of an emerging technology offering great promise for improved nuclear monitoring. Unfortunately, an understanding of how explosions excite *S* waves is quite limited, and a widening gulf between theory and practice undermines our confidence to monitor broad areas at small yields. The new models will provide a physical basis for explosion-generated *S* waves and theoretical insights for advancing yield estimation and discrimination capabilities, thereby closing the gulf between theory and practice.

RESEARCH ACCOMPLISHED

This project builds upon spherical (monopole) explosion source models developed in the 1970's. An important aspect of those models is the theory relating seismic amplitudes of *P* waves directly to yield, depth of burial, and material properties of the source medium. Analytical relationships predicted by the theory draw upon empirical yield scaling behaviors of key model constructs, such as the elastic radius. Furthermore, the analytical nature of these models facilitated their use since they were easy to implement by researchers, and as such, they were widely applied to study the explosion source. Their application continues to this day, but with the recognition that a spherical point source is inadequate to explain *S*-wave generation.

The model under development is a linear superposition of spherical (or monopole), double-couple for relaxation of tectonic pre-stress, and compensated linear vector dipole (CLVD) sources. The CLVD body force system is used to represent the deviatoric source due to material damage which occurs as sudden changes in the source medium's elastic moduli. The source process time for this model is longer than the characteristic time of energy release by the explosion itself because it includes stress wave interactions with the free surface and motions in the source region following spall slapdown. A seismic moment tensor representation is used allowing for the possibility of different centroid depths of moment release and different source-time histories for each source component.

To date, our research has focused on long-period applications where all source components are safely assumed to be coincident in time and space, and share the same source-time histories. Future research will tackle high-frequency applications where those assumptions are no longer valid. The new long-period model moves beyond source models developed in the 1960s, 70s and 80s describing an explosion triggering tectonic strain release with an earthquake double-couple mechanism. In the 80s anomalous surface wave observations for many Soviet tests conducted at the Semipalatinsk Test Site (STS) were reported in the literature, where Rayleigh waves showed polarity reversals and time delays compared to their counterparts excited by normal explosions. For some explosions, all Rayleigh waves, no matter what the azimuth or path recorded on, were found to be reversed, and large Love waves usually accompanied the Rayleigh wave

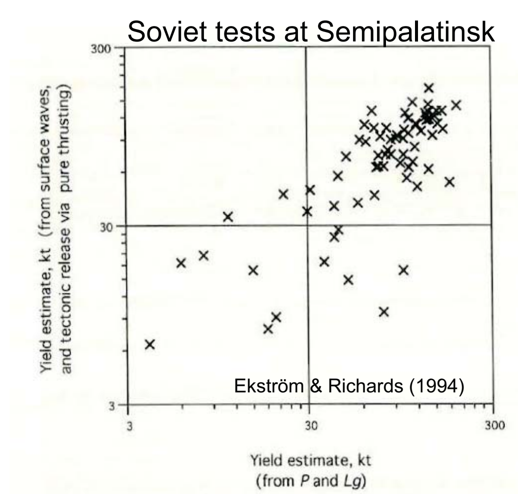

Figure 1. Inferred yields of Balapan tests from estimates of isotropic moment corrected for tectonic release versus empirical m_b-yield relationships for *P* and *Lg* waves (abscissa).

anomalies. These observations were generally accepted to be a consequence of large releases of tectonic strain energy accompanying the detonation of Soviet tests. Sometimes explosions conducted at the Nevada Test Site (NTS) also produced anomalous surface wave observations, but never to the extent found on STS explosions. As such, tectonic release models were put to a test in the 80s and 90s. The failure of these models to explain the surface wave observations and provide estimates of M_I that correlated with explosion yield as well as m_b (see Figure 1) was a disappointment to the monitoring community. At the same time, there was recognition that something fundamental was missing in explosion source models where the only contributor to source asymmetry was tectonic release represented by a double-couple force system (DC).

In the earthquake community, Ben-Zion and Ampuero (2009) renewed interest in the early work of Knopoff and Randall (1970) and others, and demonstrated that the contribution of source medium damage may be comparable to or larger than the contribution from moment release due to slip on earthquake faults and can manifest as a CLVD. Indeed, medium damage can radiate waves as volumetric, CLVD, and DC sources. The implications of damage contributing to seismic radiation from explosion sources are profound for seismic discrimination, as Patton and Taylor (2008; PT08) showed for m_b-M_s, and for yield estimation using isotropic moment, as will be discussed in this paper.

Monopole and CLVD force systems generate Rayleigh waves with opposite polarity below the null frequency f_{null} of the CLVD excitation spectrum, and the waves interfere destructively. Above f_{null}, the interference is constructive. Typically f_{null} is between 0.5 - 2 Hz for a damage centroid located over the explosion at a depth roughly one half the depth of burial. Thus, a CLVD source with a vertical axis in extension superimposed on a monopole reduces long-period Rayleigh-wave amplitudes, reducing the M_s, and making explosions look more explosion-like on a plot of m_b versus M_s. PT08 used this fact to explain why m_b-M_s observations consistently plot below theoretical m_b-M_s relationships for pure explosion sources and why the 2006 North Korean test gave unusually large M_s for its m_b, failing to discriminate. The reason is that this shot was the first to occur in a new test site of a proliferant nation, and the source medium was intact, pristine granite which might have the highest material strength of all geologic materials. That, combined with an emplacement depth quite deep for the yield, would have suppressed material damage mechanisms related to shock-induced deep-seated tensile failure. With damage suppressed and a small amount of tectonic release (Walter *et al*., 2007), this test is very close to being a pure explosion. Its m_b-M_s value should be consistent with a theoretical relationship for a spherical source, which is in fact what was found by PT08.

"Apparent" Explosion Moment and Detection of Volumetric Moment due to Source Medium Damage. The relative strength of the CLVD compared to the monopole is given by an index K defined below.

$$K \equiv \frac{2M_{zz}}{M_{xx} + M_{yy}} \quad , \tag{1}$$

where M_{xx}, M_{yy}, M_{zz} are diagonal elements of the moment tensor. The CLVD is expected to have a vertical axis of symmetry in extension provided that near-by topography is not very great. The reason is that the T axis is aligned along the direction of minimum compressive stress, and for explosion source dynamics, this direction is vertical due to tensile stresses set up by rarefactions off the free surface. Explosions "sense" the closest approach to the free surface owing to the interactions of strong shock waves establishing a tensile regime. If relaxation of tectonic stresses occurs only in the horizontal plane, as Toksöz and Kehrer (1972) proposed for NTS, then the ratio between CLVD and isotropic moments equals

$$\frac{M_{CLVD}}{M_I} = \frac{2(K-1)}{K+2} \quad . \tag{2}$$

A K value of 1 means M_{CLVD} is zero, $K > 1$ means permanent extension along the vertical axis and $K < 1$ means permanent contraction along the vertical axis. PT08 inferred that K decreases steadily as yield or m_b increases. This inference was confirmed with moment inversion results for NTS explosions (see Figure 2 of Patton, 2008). Meanwhile, the impulse of materials falling back onto the Earth's surface during spall slapdown increases steadily with yield (Patton, 1990), showing a jump across the water table due to increased coupling at about the same m_b where the rate of fall off of K seems to increase. This suggests a connection between the CLVD source and the dynamics of shock waves impinging on the free surface, resulting in more spalled mass, higher detachment velocities, and larger spall impulse for well-coupled shots below the water table compared to shots above.

During gravitational unloading due to spallation, stock wave rebound induces material bulking and slippage on reverse faults. Slapdown then compacts materials at shallow depths, but may not affect dilation of the source medium due to bulking and block rotations at depth. However, the impulse of slapdown, if sufficiently large as might be the case for the biggest shots on Pahute Mesa, will induce compaction to greater depths, reverse slip on faults, and crush bulked materials that are intrinsically weak, such as volcanic tuffs, or materials weakened by prior damage. Thus, a hypothesis is that for smaller Pahute Mesa explosions with $K > 1$, the impulse of slapdown does not exceed a material strength threshold. On the other hand, spall impulse for large explosions exceeds the threshold. This hypothesis predicts contributions to the volumetric source due to material damage for $K > 1$. For the largest yield tests, the statics are such that the cavity volume, protected by hoop stresses of the containment cage, remains intact, but due to the effects of compaction, the source medium in weakened materials over the shot point has returned to nearly its original volume or has contracted to a somewhat reduced volume.

This prediction or hypothesis was tested; for details, the reader should see Patton and Taylor (2010; PT10). Isotropic moments M_I from moment tensor inversions were compared against estimates of classical moment predicted for a spherical source, $M_t = \rho \cdot \alpha^2 \cdot V_c$, where ρ and α are source medium density and P wave speed, and V_c is cavity volume (Müller, 1973; Richards and Kim, 2005). Density and velocity models for Pahute Mesa are available (Ferguson *et al.*, 1994; Leonard and Johnson, 1987). Cavity radius r_c scaling has been investigated since the 1960s, and there is excellent agreement for normal-buried explosions in tuff using Heard's relationship in Mueller and Murphy (1971), a relationship due to Denny and Johnson (1991; DJ91), and one developed by PT10 specifically for Pahute Mesa. Using depth of burial h_x as a surrogate for yield (*e.g.*, $W = (h_x/120)^3$) and accounting for reduced coupling above the water table, PT10 found that the ratio M_I / M_t is significantly greater than 1 for smaller tests and decreases to values of ~1 or a little less for the largest shots on Pahute Mesa (Figure 2). The scaling relationship for M_I / M_t in DJ91 (eq. 41), after adjustments for

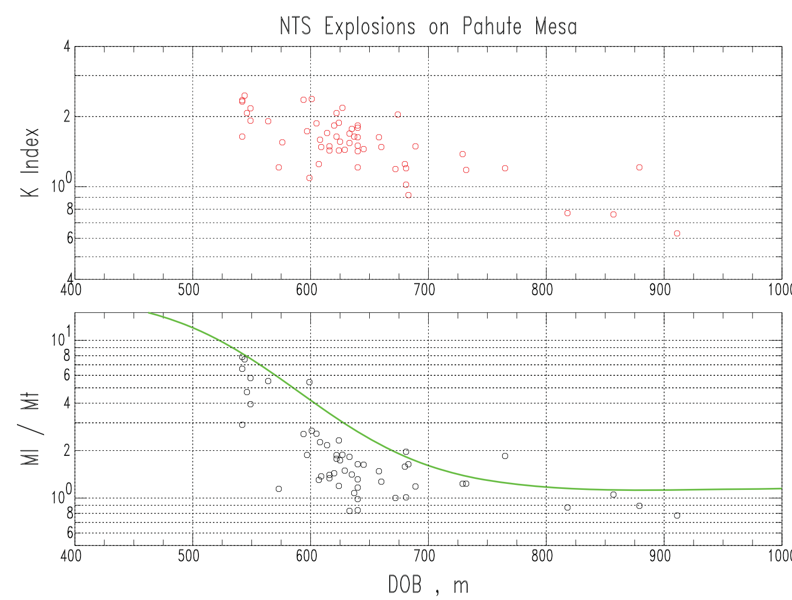

Figure 2. Plots of K and moment ratio M_I / M_t versus depth of burial for explosions on Pahute Mesa. Not shown are 10 very large shots with DOB greater than 1000 m; their K values range from 0.5 to 0.9 and moment ratios between 0.71 and 2.0. The green curve uses equation (41) of DJ91 and corrections for Rayleigh wave coupling as a function of depth from Jones and Taylor (1996) and Taylor (1982).

coupling, is in good agreement with these results. Note the correlation between changes in M_I / M_t and K, and to first order, $M_I / M_t \sim K^{1.5}$. For a K value of two, this relation gives an "apparent" explosion moment three times larger than the moment predicted by cavity creation, implying a volumetric moment due to damage that is significantly greater than the direct effects of the explosion source. The results in Figure 2 are consistent with the slapdown-dynamics hypothesis posited above.

Moment-Yield Scaling: An Outstanding Problem Revisited.

By ignoring the effects of source medium damage, past investigations very likely obtained biased estimates of M_I and deduced source models that over-estimated the importance of tectonic release. To show this, we first write a formula for the Rayleigh wave source term U_1 (Ekström and Richards, 1994) assuming shallow source depths h_x and long periods (note U_1 is proportional to the gain factor A' in PT08; see Patton, 2008, for details).

$$U_1 = \frac{2\beta^2}{\alpha^2} \cdot M_{zz} + \frac{1}{2}(M_{xx} + M_{yy} - 2M_{zz}) - \frac{3\alpha^2 - 4\beta^2}{\alpha^2} \cdot DS \quad , \tag{3}$$

where the source is a sum of axisymmetric and deviatoric moment tensors, the latter representing shear dislocation of arbitrary orientation. M_{xx}, M_{yy}, and M_{zz} are diagonal elements of the axisymmetric tensor, expressed in terms of isotropic and CLVD moments:

$$M_{xx} = M_{yy} = M_I - \frac{1}{2}M_{CLVD} \tag{4}$$

and

$$M_{zz} = M_I + M_{CLVD} \quad . \tag{5}$$

DS and SS are defined by Ekström and Richards,

$$DS = \frac{1}{2}M_0 \sin 2\delta \sin\lambda \tag{6}$$

and

$$SS = M_0 \sin\delta \cos\lambda \quad , \tag{7}$$

for tectonic release with moment M_0, slip angle δ, and dip angle λ. Substituting for M_{ij} and DS into equation (3) yields

$$U_1 = \frac{2\beta^2}{\alpha^2} \cdot M_I - \frac{3\alpha^2 - 4\beta^2}{2\alpha^2} \cdot (M_{CLVD} + M_0 \sin 2\delta \sin\lambda) \quad . \tag{8}$$

This model (explosion + damage + tectonic release) will be referred to as the "new" model.

The Ekström-Richards model consists of just explosion + tectonic release source components. The isotropic moment for this model is called $\tilde{M}_I$. Noting that tectonic release is the same whether damage is included or not, then

$$U_1 = \frac{2\beta^2}{\alpha^2} \cdot \tilde{M}_I - \frac{3\alpha^2 - 4\beta^2}{2\alpha^2} \cdot M_0 \sin 2\delta \sin\lambda \quad . \tag{9}$$

Since equations (8) and (9) are equal, the relationship between M_I and $\tilde{M}_I$ is

$$M_I = \tilde{M}_I + \frac{5}{4}M_{CLVD} \quad , \tag{10}$$

for a Poisson medium $\alpha^2 = 3\beta^2$. M_I is greater than $\tilde{M}_I$ for a CLVD in extension ($M_{CLVD} > 0$).

The moment ratio $M_I / \tilde{M}_I$ is plotted in Figure 3 as a function of the relative CLVD source strength M_{CLVD}/M_I and K. For M_{CLVD}/M_I of 0.8, $M_I/\tilde{M}_I = \infty$. A moment ratio of infinity is not physical, and results from the fact that equation (3) is an asymptotic approximation for $h_x \to 0$ and $\omega \to 0$; in reality these limits are never attained. The results in Figure 3 illustrate a systematic bias in isotropic moments estimated for models omitting source medium damage.

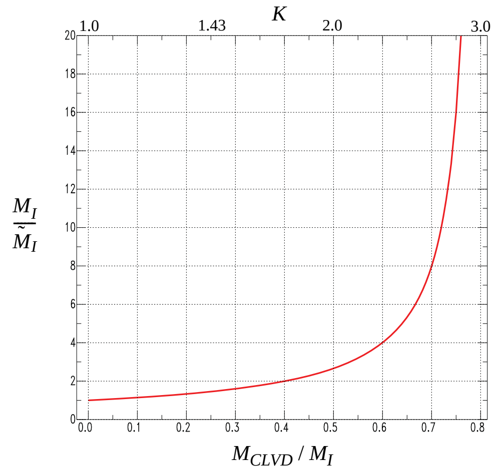

Figure 3. Inferred moment ratio of isotropic moments for models with and without source medium damage. Models without damage will systematically under-estimate the isotropic moment.

Equation 2 above does not strictly apply here because it was defined for a pure strike-slip tectonic release mechanism, while the new model is for tectonic release of arbitrary orientation. Nevertheless, this equation is still applicable to dislocation mechanisms of any orientation, even for the highest levels of tectonic release observed at STS, as will be shown below.

The index F (= M_0/M_I) introduced by Toksöz and Kehrer as a relative measure of tectonic release source strength, decreases for models including damage as the inverse moment ratio

$$F = (\tilde{M}_I / M_I) \cdot \tilde{F} \quad . \tag{11}$$

Assuming a nominal K value of 2 for STS explosions, $\tilde{F}$ values are over-estimated by more than a factor of 2. Thus, a vast majority of STS explosions analyzed by Ekström and Richards have smaller F values, averaging only ~0.1, if a nominal amount of source medium damage occurs.

The relationship between K and M_{CLVD}/M_I in equation (2) is based on a strike-slip tectonic mechanism. Let K' be a measure of relative source strength for a general tectonic model. Then, it can be shown that

$$K' \equiv \frac{2M'_{zz}}{(M'_{xx} + M'_{yy})} = \frac{2(M_{zz} + 2DS)}{(M_{xx} + M_{yy} - 2DS)} \quad , \tag{12}$$

where M_{xx}, M_{yy}, and M_{zz} are defined in equations (4) and (5). Assuming $M_{CLVD}/M_I \approx 0.5$ and denoting $max\{DS\}$ as the maximum absolute value of DS, the following inequalities hold true

$$M_{zz} \approx 1.5M_I \gg 2max\{DS\} = M_0 = FM_I \approx 0.1M_I \tag{13}$$

and

$$M_{xx} + M_{yy} \approx 1.5M_I \gg 2max\{DS\} = M_0 = FM_I \approx 0.1M_I \quad . \tag{14}$$

For most STS explosions, $M_{zz} \gg 2DS$ and $M_{xx} + M_{yy} \gg 2DS$ since F values are small. K' will not differ much from K even if tectonic release occurs as a dip-slip thrust mechanism. So equation (2) still applies.

There is little evidence for tectonic release affecting m_b (Bache, 1976). Khalturin *et al*. (2001) found good support for an m_b-log$W$ scaling relationship of the form $m_b = 0.75 \cdot \log W + c_1$ for shots at STS with announced yields. Ringdal *et al*. (1992) discovered that the constant c_1 is different for northeast, southwest, and transition test areas at Balapan. Adopting a M_I-W scaling relationship of the form $\log M_I \sim 0.85 \cdot \log W + c_2$ from DJ91 and substituting $(m_b - c_1)/0.75$ for log$W$, it is of interest to plot the quantity $0.9\log\tilde{M}_I - m_b + c_1$, which is called Δ, against $\tilde{F}$. This is done in Figure 4 using estimates of $\tilde{M}_I$ and $\tilde{F}$ from Ekström and Richards and m_b from Ringdal *et al.*, adjusted for test areas.

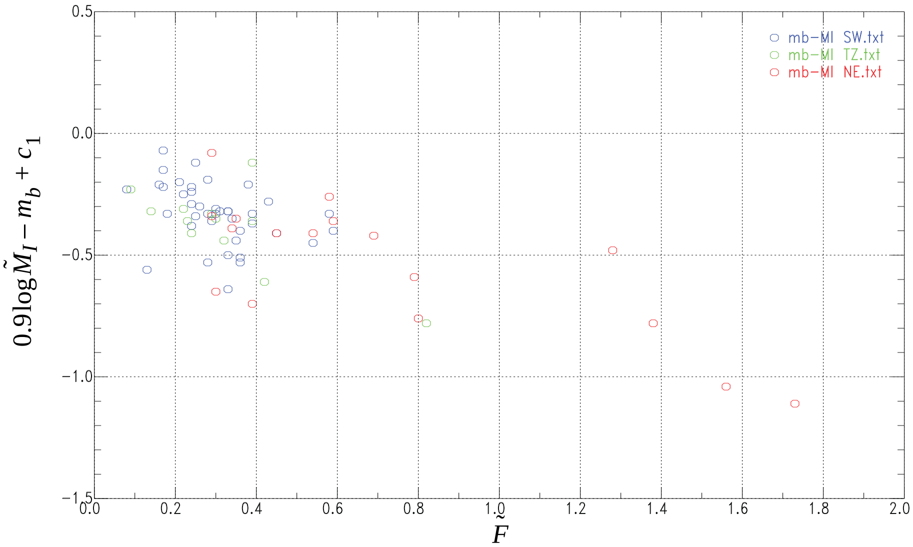

Figure 4. The quantity Δ (= $0.9\log\tilde{M}_I - m_b + c_1$) plotted against $\tilde{F}$ for Balapan explosions analyzed in Ekström and Richards. The constant c_1 was adjusted for test area (NE: 4.35; TZ: 4.43; SW: 4.50) based on the results of Ringdal *et al*. Δ was set equal to 0.0 for $\tilde{F}$ of 0.

An apparent dependence of Δ on $\tilde{F}$ is observed, suggesting an "isotropic moment deficit" increasing with $\tilde{F}$. The deficit is large enough to preclude an effect from m_b (> 0.5 magnitude units for $\tilde{F} > 0.6$). Our interpretation is that this deficit is caused by under-estimation of $\tilde{M}_I$ due to model bias. If that's the case, then $\tilde{F}$ is systematically over-estimated as the deficit grows, and the trend of measurements in Figure 4 is not real, but only apparent.

Several interesting implications can be deduced if the moment deficit is assume to equal Δ. For low tectonic release ($\tilde{F} \approx 0.3$), Δ is ~0.3 log units or a factor of 2, while for moderately high to high levels of tectonic release, the deficits are factors of 5 and 10, respectively. The moment ratio $M_I/\tilde{M}_I$ is set equal to these deficit factors in Table 1. Working backwards using equation (10), the relative source strength of damage M_{CLVD}/M_I can be inferred, and F is inferred by taking the product of the inverse moment ratio and $\tilde{F}$.

Table 1: K' as a Function of Strength of Tectonic Release

Ekström-Richards Model		New Model: Source Medium Damage + Tectonic Release					PT08
$\tilde{F}$	$M_I/\tilde{M}_I$	$\frac{M_{CLVD}}{M_I}$	F	$M_{zz} = M_I{+}M_{CLVD}$	$2max\{DS\} = F{\cdot}M_I$	K'	K
0.3	× ~2	0.4	0.15	$1.4M_I$	$0.15M_I$	$\approx K$	1.75
0.8	× ~5	0.64	0.16	$1.64M_I$	$0.16M_I$	$\approx K$	2.4
1.5	× ~10	0.72	0.15	$1.72M_I$	$0.15M_I$	$\approx K$	2.7

It can be seen that the inequality $M_{zz} » 2DS$ holds true for all cases, as does $M_{xx} + M_{yy} » 2DS$. Thus $K' \approx K$ for all three cases in Table 1 and in general for all STS tests studied by Ekström and Richards. Remarkably, F values remain constant and quite small. This result suggests that the appearance of high tectonic release explosions could actually a mirage owing to M_I estimates systematically biased low since the effects of damage were overlooked. Meanwhile, K values increase by about 1 unit showing the tradeoff with $\tilde{F}$ of the Ekström-Richards model.

Yield-depth tradeoff curves for the 2006 North Korean test.
In the absence of significant radiation from damage, the measured isotropic moment should be related to yield through cavity radius scaling using classical theory. While material damage undoubtedly occurred on the 2006 North Korean test, there was no expression of damage in the long-period radiation. As such, this explosion provides an excellent opportunity to test the consistency of yield estimates based on M_I and m_b. Here we follow a procedure similar to one used by Koper *et al*. (2008) to develop tradeoff curves between yield and depth of burial. However, the difference between our approach and the one taken by Koper *et al*. is that we set the measured M_I equal to M_t whereas Koper *et al.* used equation (41) in DJ91 for M_I / M_t, which was calibrated against explosions that suffered source medium damage.

Tradeoff curves are plotted in Figure 5 (see Patton and Taylor, 2010, for details). Their impressive agreement suggests that M_I for the 2006 North Korean test is fully consistent with an explosion source in hard rock medium suffering negligible radiation from either source medium damage or tectonic release. Also plotted in Figure 5 is the tradeoff curve from Koper *et al*. (2008) based on M_I. The difference between this curve and my result is due to the fact that Koper *et al*. employed equation (41) of DJ91 which relates M_I and M_t through additional factors related to overburden and gas porosity. DJ91 used explosions that suffered source medium damage to calibrate this equation, while damage appears not to be a significant source at long periods for the 2006 Korean test. A better physical basis of the source is the reason why I chose the classical formula ($M_t = \rho \cdot \alpha^2 \cdot V_c$) and equated M_I to M_t.

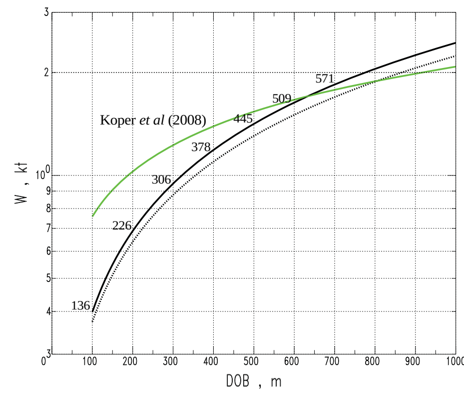

Figure 5. Yield versus depth of burial tradeoff curves for the 2006 North Korean test. Curves plotted with a solid line are based on isotropic moment M_I. The result of Koper *et al*. is the green curve and the result from this study is the black curve. The black dotted curve is based on m_b. Scale depth of burial (h / $W^{1/3}$ in units of m per $kt^{1/3}$) is provided on the M_I curve from this study.

CONCLUSIONS AND RECOMMENDATIONS

Over the course of this three year project, a great deal of progress has been made developing a new explosion source model grounded in a physical basis for seismic wave generation. The source model to date moves beyond simple models describing a spherical explosion releasing stored tectonic strain in the medium. Such tectonic release models were incomplete descriptions of a far more complicated source process. They ignored non-linear failure mechanisms caused by shock wave interactions at the free surface and hydrodynamic flow at depth giving rise to stress-wave rebound and rotational motions on multiple scale lengths. Source medium damage resulting from these non-linear mechanisms is a source of seismic radiation in itself, as pointed out by many researchers in the past. The form of this radiation is consistent with volumetric, CLVD, and DC body-force systems. The model under development has taken into account the radiation from damage, and our investigations have explored the implications for seismic discrimination and yield estimation. As summarized below, the implications are far-reaching and offer the promise for a physical source model for S wave generation, not just for long-periods but for high frequencies too. Also summarized below are recommendations for future research.

• Source medium damage radiating as a CLVD is a source of Rayleigh waves that destructively interfere on all azimuths with Rayleigh waves excited by the spherical explosion source. The resulting interference lowers Rayleigh wave amplitudes and reduces the M_s making explosions look more explosion-like on a plot of m_b-M_s. The m_b-M_s discriminant owes a large measure of its success to the presence of significant Rayleigh wave radiation from source medium damage. This explanation has implications for test site evolution of the m_b-M_s discriminant. The medium is relatively strong and intact at nascent test sites, where depending on emplacement conditions, seismic radiation from damage is minimal and the m_b-M_s performance is degraded, as seen for North Korean tests. Over time, as the medium is weakened by more testing, the m_b-M_s performance should improve. Another way to state this concept is that the potential for seismic radiation due to damage increases as the source medium of a mature test site is conditioned by previous tests. On the other hand, just the opposite is true for tectonic release since the first explosions release the pre-stress, lowering the potential for tectonic release as testing continues. Research might detect such evolution in a record of m_b-M_s measurements if it is complete enough. The CLVD source of long-period radiation has been quantified for explosions in weak rock; such quantifications are still needed for hard rock explosions.

• The new model predicts two sources of volumetric moment, one from direct effects of the explosion (i.e., cavity formation) and the other from indirect effects related to damage. The volumetric moment due to damage has been detected in the seismic radiation from Pahute Mesa explosions (Patton and Taylor, 2010) by comparing the measured "apparent" explosion moment with estimates of the classical moment based on cavity volume. Such comparisons show that the volumetric moment due to damage can be up to four times larger than the traditional explosion moment due to cavity formation. The net volumetric moment is controlled by dynamics of spallation since the impulse of slapdown can induce compaction at depth, reverse slippage on thrust faults that occurred earlier in the source process, and crush bulked materials that are intrinsically weak, such as volcanic tuffs, or weakened by prior damage. The effects of slapdown are expected to be smaller for explosions in hard rock, which should translate into a weaker yield dependence of the source parameter K than what is observed for NTS explosions. This prediction is supported by preliminary results (Patton, 2008), and future quantifications of the CLVD source will test it by measuring K on hard rock explosions (see previous bullet). It is my opinion that the disappointing past performance of isotropic moment as an indicator of yield is due to the fact that previous source models ignored contributions of source medium damage to the long-period radiation. The prospects of improved methods for moment-based yield estimation rests on a deeper physical understanding of explosion moment, which the new model provides, but much more empirical and theoretical work is needed. A challenge is to extract from observables the volumetric moment due to cavity formation since classical source theory relates this moment to yield through scaling relationships of cavity radius. Developing empirical relationships between apparent and classical moment, such as the one for Pahute Mesa M_I / M_t ~ $K^{1.5}$, is one research avenue worth pursuing since excursions from the relationship for individual explosions could provide clues about material properties and emplacement conditions controlling the extent of damage. But more importantly, there is need for theoretical development of damage models to predict analytical volumetric and CLVD moments caused by changes in material properties. Armed with a physical basis theory for relating the two moments, a correction theory could be developed to extract estimates of damage moment from measurements of apparent explosion moment and K, thereby isolating the moment due to cavity formation. It is worth mentioning that in the absence of significant radiation due to damage, as is the case for the North Korean tests, the measured moment should be related to yield by classical theory. Excellent agreement between moment-based and m_b-based tradeoff curves for yield and depth of burial was shown in this paper. This result is expected if damage is not contributing volumetric moment, and m_b is properly calibrated for measurement of explosion yield at the North Korean test site.

• The ultimate goal is an explosion source prediction capability for P and S radiation across the measurable spectrum of seismic frequencies. Extensions of the current model to higher frequencies is the next evolutionary step in our research agenda. An encouraging sign for a successful outcome of such an agenda is when the basic physics applied in the current model carries over to model extensions for the purpose of explaining other key observations. After all, a unifying explanation for a host of observations is a hallmark of a successful physical model and instills confidence in the model's utility for broad applications. The source model under development has such encouraging signs since the monopole-CLVD interference phenomenon for long-period Rayleigh waves applies to *Rg* waves too and can explain certain observed features in *Lg* spectra near 1 Hz. These features include amplitude modulations in *Lg* spectral ratios and in *P*/*Lg* ratios for NTS explosions (Gupta and Patton, 2009; Fisk, 2007) and low-frequency amplitude rolloff in what should be the flat portion of the *Lg* spectrum (and corresponding increase in *P*/*Lg* ratios) for Balapan explosions (Patton, 2009; Fisk, 2006). In this case, *Rg*-to-*S* scattering and seismic wave imprinting must be invoked as a mechanism for generating *S* waves at the source. A challenge at high frequencies is to quantify multiple sources of seismic radiation, e.g., direct radiation due to damage and indirect radiation resulting from near-source scattering of *P* and *Rg* waves emitted by a complex source. Such quantification depends critically on source-time functions and Green's function excitation of damage mechanisms. This will require research using nearfield data recorded on historic explosions and new data collected on field experiments devoted to explosion source physics.

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