ABSTRACT

The Nuclear Explosion Monitoring Research and Engineering (NEM R&E) Program has a long-standing magnitude research project in support of regional yield estimation and seismic discrimination. This project has developed magnitude-yield scaling relationships based on regional P, S phases and coda waves to improve the capabilities to monitor nuclear explosions over broad areas and at low yields. Due to the great variability of regional seismograms, the methods developed for broad-area monitoring must be adaptable to different phases and frequency bands. These requirements, along with an understanding of the transportability of scaling relationships, pose significant challenges, both in practice and theoretically, since any broad-area method needs a sound physical basis to be ultimately successful.

We continue to study multi-frequency scaling observations of Pn and Lg-coda waves for explosions detonated at the Nevada (NTS) and Semipalatinsk (STS) test sites. Observations for both test sites show that Pn amplitudes scale with yield ~10-40% higher than coda amplitudes for frequencies between 2-8 Hz. For NTS explosions, the contrast in scaling is even greater (as much as 50-60%) for frequencies < 2 Hz, except for the lowest frequency band analyzed, 0.3-0.5 Hz, where scaling differences are not significant. On the other hand, Pn and coda amplitudes for STS explosions do not scale differently for any band < 2 Hz. These observations have implications for yield estimation and seismic discrimination, among them being that high-frequency phase ratios should display yield dependence.

An analytical source model for explosions generating S waves is under development in order to study the physical basis for scaling differences between P and S waves. The model has three essential elements: (1) a monopole source characterized by emplacement depth, source function, and yield, (2) a shallow conical source of tensile failure described by a compensated linear vector dipole (CLVD) and spallation-like source function, and (3) seismic scattering off topography and structural heterogeneities in the source region. We test the importance of near-source Rg-to-S scattering with this model. The model predicts that the excitation of high-frequency Rg waves is much greater for the CLVD compared to the monopole due mainly to differences in centroid depths. This prediction raises the interesting possibility that high-frequency P and S waves scale differently because under the Rg→S scattering scenario, S wave generation is mediated by the excitation of Rg waves from the CLVD, while P waves are excited directly by the monopole source. Our preliminary model calculations of this scenario do indeed show scaling differences consistent with the observations at high frequencies.

We are also exploring observational evidence of coupling differences between P and Lg-coda waves related to depth of burial (DOB), since such evidence provides clues about the physical basis of coda (S) generation and has implications for yield estimation. The well-known effect of overburden on cavity radius reduces seismic amplitudes for overburied explosions. As DOB decreases from overburied to more normal scaled depths of burial (sDOB), ~150 m/kt^{1/3}, amplitudes increase to a broad plateau. If sDOB continues to decrease below ~100 m/kt^{1/3} the competing effects of confinement begin to dominate over the overburden effects with the opposite result, reducing seismic amplitudes as more and more energy is lost to severe spallation, cratering, and to the atmosphere. We are attempting to identify differences in the coupling of P and Lg-coda waves for small sDOB. Our methods must account for the effects of material properties on amplitudes of P and Lg-coda waves since such effects depend on depth too.
OBJECTIVE

We seek to improve yield estimation and seismic discrimination capabilities for broad areas and small events through the development of regional magnitude methodologies and data sets of direct phases and coda waves. Our research advances the state of the art in nuclear monitoring through (1) characterization of the scaling behavior and transportability of regional magnitudes based on path-corrected amplitudes using advanced calibration techniques and (2) development of physical models to interpret the observations and to lay a physical basis supporting operational techniques.

RESEARCH ACCOMPLISHED

In recent years we have witnessed exciting technical advances with great promise for increasing the precision of seismic yield estimates and extending $M_r - m_b$ discrimination to small magnitudes through the use of amplitudes measured off regional seismograms. With these advances has come an extraordinary change in the measurements seismologists rely upon to do monitoring. They are now often based on the amplitudes of shear phases ($Lg, Sn$) and codas following these phases, and to a lesser degree on the compressional phases that explosions excite with great efficiency. This is because shear phases are usually the largest on regional seismograms and hence are the best recorded as source sizes decrease and noise levels increase, an important consideration for the ability to do low-yield monitoring. The reliance upon regional shear phases represents a major paradigm change from the way seismologists monitor nuclear explosions at teleseismic distances, and this change is a driver for much new, innovative research in our community today.

In order to address the challenges confronted by monitoring small events in broad areas, a significant component of this project’s research is directed at characterizing the scaling behavior of regional magnitudes over a broad yield range and in different frequency bands. In the process, we are forming an observational basis from which to draw new insights for improving yield estimation and extending $M_r - m_b$ to smaller magnitudes. Equally important is the need to develop a physical model for shear-wave generation by underground explosions and to lay a theoretical foundation supporting the empirical methods in operational use. We believe that both components, empirical characterization of scaling behavior and development of a physical basis, are essential for the success of new, improved methods for broad-area monitoring at small yields.

The ability to estimate yields and discriminate seismic events especially at small magnitudes depends in large part on understanding the energy partitioning between $P$ and $S$ phases and the manner in which the phases scale with yield or source size. Another important consideration is the portability of seismic measurements across broad areas. Scatter between areas could be a sign that path effects are not being adequately corrected for in our measurements and/or it could be a sign of intrinsic source effects. This is one reason that so much research has been invested in the calibration of regional path effects and the development of tomographic models for 1- and 2-D path corrections. In many areas of monitoring concern, these models are mature to the point that we are confident the path effects are effectively removed. We believed this is true for the corrected amplitudes used to measure magnitudes in this study.

Much effort has been spent developing methodologies to estimate regional magnitudes and building magnitude databases of historic explosions in Asia, as well as at NTS where so much ground truth information is available. Over the years, our efforts, joint with Livermore’s, have investigated coda amplitudes of $Lg$ and $Sn$ waves, tied to seismic moment through an innovative calibration method (Mayeda and Walter, 1996); the results of this method have shown great promise. The corrected coda measurements are referred to as “apparent coda source amplitudes” (ACSA) with units of Newton-meters (Nm), and they are measured through a bank of narrowband filters with set bandwidths. The most extensively-studied bands to date are 0.3-0.5, 0.5-0.7, 0.7-1.0, 1.0-1.5, 1.5-2.0, 2.0-3.0, 3.0-4.0, 4.0-6.0, and 6.0-8.0 Hz.

A remarkable finding discovered early in our studies is the fact that $Lg$ and $Sn$ 1.0-1.5 ACSA yield scale differently compared to teleseismic $m_b(P)$. Apparently, teleseismic 1-Hz $P$ wave amplitudes yield scale ~15% faster than shear-based coda-wave amplitudes. Similar differences were noticed in $m_b(Lg)$ and $m_b(Pn)$ observations of NTS explosions for the traditional 1-Hz short-period passband of the World-Wide Standard Seismographic Network response (Patton, 2000). At the 2005 Seismic Research Review (SRR) meeting, Patton and Phillips (2005) documented the differences in scaling between $Pn$- and $Lg$-coda amplitudes for a range of frequencies and for NTS and STS. Further work this
year has served to validate the method we used to detect these scaling differences. Below we present the scaling results, and discuss the initial work developing a new explosion source model that may provide a physical basis for differences in the scaling and new insights into $S$ wave generation by underground explosions.

**Observations of $Pn$, $Lg$-Coda scaling differences.** The interested reader is referred to our extended abstract from last year’s SRR meeting for background on the relative-scaling analysis that we use to detect differences in the scaling of $Pn$- and $Lg$-coda waves. Briefly, relative scaling slopes were estimated using two methodologies summarized in the following equation:

$$slope = \frac{\Delta \log A_{Pn}}{\Delta \log A_{LgC}} \approx \left( \frac{\Delta \log A_{Pn}}{\Delta \log W} \right) \left( \frac{\Delta \log A_{LgC}}{\Delta \log W} \right),$$

where $A_{Pn}$ and $A_{LgC}$ are amplitudes of $Pn$- and $Lg$-coda waves passed through identical narrowband filters, $W$ is yield, and base-10 logarithms are used. The first method determines the scaling slope on log-log plots of $A_{LgC}$ versus $A_{Pn}$ for a common station and for many explosions spanning several orders of magnitude in yield. If the explosions are located in small test areas, the path effects on $A_{Pn}$ and $A_{LgC}$ to a given station should be the same. This method was applied to both NTS and STS explosions. If ground-truth information on yields and emplacement conditions are available, amplitude-yield regressions can be performed, estimates of the yield coefficient for $Pn$- and $Lg$-coda waves determined, and the relative yield scaling calculated by taking the ratio. This second method was applied to NTS explosions to validate the results from the first method. The results from method 1 do not necessarily have to equal the ratio of yield coefficients if other excitation factors come into play such as the effects of depth burial alluded to in the abstract and discussed in our 2005 SRR paper. In carrying out the yield regressions, the effect of gas porosity was accounted for, and for both methods, overburied explosions were avoided.

All amplitudes were subjected to signal-to-noise checks. It should be noted that the signal-to-noise ratios for $Lg$-coda waves decrease rapidly above $\sim 6$ Hz for recordings off the Livermore NTS Network. Nevertheless, it is clear that the codas are those of $Lg$ waves for all bands, as $Sn$ is not as well recorded on this network compared to $Lg$. On the other hand, $Lg$ amplitudes recorded at Borovoye for STS explosions can drop below the level of $Sn$-coda waves for frequency bands above the 2-3 Hz passband. Thus, even though many recordings of the Borovoye archive (Kim et al., 2001) are well above the noise levels at high frequencies, our measurement windows contain a superposition of $Sn$ and $Lg$ codas, where $Lg$ codas appear more important for frequencies below the 2-3 Hz passband, while $Sn$ codas may dominate the higher frequency bands.

Figure 1 is a summary of scaling results for NTS explosions. The results from method 1 are shown with open symbols, and those involving yield regressions (method 2) with solid symbols. The various frequency passbands are denoted with horizontal lines on the abscissa. The results for both methods are in reasonably good agreement for stations Elko and Kanab. Both stations have similar frequency dependence, showing rapid change at low frequencies, going from no scaling differences in the lowest band to 50-60% faster scaling for $Pn$ relative to $Lg$ coda in the next band, 0.5-0.7 Hz. The differences lessen for the traditional bands between 1 and 2 Hz. Above 2 Hz, there is a suggestion that the differences increase again, but discrepancies between stations (3-4 Hz band) and between methods (6-8 Hz band) make such a determination difficult. With the exception of the lowest band, the results of all bands indicate that $Pn$ amplitudes scale at a higher rate than $Lg$ coda amplitudes, and the close agreement between results of both methods strengthen the reliability of these findings.
NTS results were based on just explosions detonated on Yucca Flats. Our analysis of STS explosions drew on explosions from Balapan and Degelen Mountain test areas, as data from both test areas were necessary in order to provide adequate sampling over a broad enough yield range to ensure that slopes were well determined using method 1. Paths to Borovoye are similar enough between the two test areas that we believe the common path assumption still holds. However, these test areas are geophysically distinct and that raises the possibility that energy partitioning differences could bias the slopes since explosions conducted in the Degelen tunnels tend to be smaller than explosions fired in shafts at Balapan. Thus, to address these concerns and the possibility that there could be some path differences, the data from each test area were made zero-mean before the data sets were combined for regression analysis. Zero-mean data sets decouple the slope determination from a systematic offset that may pre-exist between the test sites.

Relative scaling slopes from zero-mean regressions on combined data sets are plotted in Fig. 2, along with the NTS results (blue shaded region). The frequency dependence of STS results show marked contrast to NTS, particularly at low frequencies below 1.5 Hz where scaling differences are negligible. The most stable results are found for the 2-3 Hz band. A perusal of Fig.1 reveals that the shaded region greatly exaggerates the spread in the observations for this band, and the stability/agreement of 2-3 Hz results is excellent for both test sites. Interestingly, the trend in STS results changes abruptly above the 2-3 Hz band. This might be related to the fact noted above that \( Lg \) drops below the amplitude level of \( Sn \) coda in the higher frequency bands, so \( Sn \) might control the scaling, while the lower bands are controlled by \( Lg \). In any case, both \( Sn \) and \( Lg \) codas are shear-dominated and both show lower scaling relative to \( Pn \) waves at high frequencies for NTS and STS explosions.

The observations in Fig. 2 are of fundamental importance, not just for the implications related to yield estimation and seismic discrimination, but also for the potential information about the mechanisms of S wave generation. For this reason, we are continuing work to improve these scaling observations by adding new measurements. Analysis of new STS measurements will be done with hopes of placing better control on the high-frequency scaling observations. Another team of researchers led by J. Murphy has failed to detect significant differences in the scaling at high frequencies for STS explosions using an approach similar to method 2 but employing amplitude ratios instead of straight amplitudes. Since similar data sets were used by both teams, this suggests the cause of differences in our results and Murphy’s might be methodological.

In the case of NTS explosions, both methods gave similar results, and both show significant differences in the scaling of \( P \) and \( S \) waves, \( P \) waves scaling ~30% higher on average. In light of the good agreement for the 2-3 Hz band and the apparent differences at low frequencies between the test sites (here Murphy’s STS results and ours agree), an effort to interpret the higher frequency observations in terms of a new source model has been initiated. Simple extensions of existing source models are not adequate for this purpose. For example, the Fisk conjecture (Fisk, 2006) that \( S \) wave spectra may be modelled with the same functional form as \( P \) wave spectra predicted by the Mueller-Murphy (MM) model is not consistent with the high-frequency observations in Figs. 1 and 2. This year we started development of a next generation analytical model in the mold of MM but incorporating more phenomenology. In particular, secondary sources exist to some degree on virtually every explosion owing to strong interactions of the stress waves with the free surface. Even the most overburied NTS explosions spall, and a chemical explosion at STS with \( sDOB \) of ~1400 m/kt\(^{1/3}\) was documented to have spalled (Patton et al., 2005). Thus the new model builds on the MM model incorporating free surface phenomenology and new insights into the near-source scattering of \( Rg \) waves. The following subsection summarizes the progress made to date on a new analytical explosion source model to support further development of regional seismic discrimination and yield estimation technologies.
Explosion source model. Three essential elements of the source model are: (1) the explosion, modelled as a monopole source and characterized by emplacement depth $h_e$, moment source spectrum $M_e(\omega, W)$, and $W$, (2) non-linear free surface interactions resulting in a shallow conical source of tensile failure which spallation is a part of and is kinematically described by a CLVD with centroid depth $h_{clvd}$ and source spectrum $M_{clvd}(\omega, W)$, and (3) near-source scattering of $P$, $R_g \rightarrow S, P$ waves off topography and material heterogeneities (faults, basins, etc). The combined source is assumed to be a linear superposition of monopole and CLVD point sources and is axisymmetric. $M_e$ is related to the reduced displacement potential $\Psi(\omega, W)$; we have used the RDP development of Denny and Johnson (1991) throughout this study. $M_{clvd}$ is related to particle displacements on/within the conical source volume. We have adopted a variant of the spall time histories developed by Stump (1985) to provide an analytical expression for this source spectrum. The moment rate spectrum falls off as $\omega^{-3}$ (as opposed to $\omega^{-2}$ for the explosion) and has no net moment (i.e., $\omega$ slope at low frequencies). Thus no residual particle displacement is associated with the CLVD. This is an assumption, although we have evidence to believe that it is indeed the case for NTS explosions, while studies of chemical explosions at STS come to the opposite conclusion (Patton et al., 2005). The fact that explosions in hard rock media are characterized by residual displacements while explosions in weak rock are not suggests that shear-dilatancy may play a role in the free-surface interactions in hard-rock media.

Nearfield scattering is assumed to be dominated by $R_g \rightarrow S$, and at this stage the model ignores contributions from $R_g \rightarrow P$ and $P \rightarrow S$ scattering. Furthermore, $P$ and $S$ waves excited directly by the CLVD are ignored, which might be justified for $P$ by cancellation with a depth phase ($pP$) and relatively large $P$ waves from the explosion, and for $S$ by radiation pattern effects. The details of these assumptions have yet to be verified, but for purposes of initial model development, $R_g$ waves are the sole mediator of $S$ wave generation, while the only source of $P$ waves is the explosion.

If all explosions occur in a localized test area where the scattering transfer function is in common, then the relative scaling slope can be related to spectral quantities of the model,

$$\frac{(\Delta \log A_{Pn})}{(\Delta \log A_{Sclvd})} \equiv \frac{(\Delta \log A_{Pn})_{\Psi}}{(\Delta \log A_{Sclvd})_{\Psi}} \equiv \frac{\Delta \log \Psi(\omega, W)}{(\Delta \log \Psi(\omega, W))_{\Psi}} \equiv \frac{(\Delta \log \Psi(\omega, W))_{\Psi}}{(\Delta \log \Psi(\omega, W))_{\Psi}} ,$$

where $A_{R_g}(\omega, W)$ is the $R_g$ amplitude spectrum of the composite source. Thus linear scattering is invoked and the shape and indeed the scaling of the $R_g$ spectrum are imprinted onto the scattered $S$ waves. This is a fundamental tenet of the model, and is motivated by the results of Patton and Taylor (1995). Based on the model outlined in the paragraphs above, an expression for $A_{R_g}$ is

$$A_{R_g}(\omega, W) = M_e(\omega, W) \cdot G_{R_g}(\omega, h_e(W)) + M_{clvd}(\omega, W) \cdot G_{R_gclvd}(\omega, h_{clvd}(W)) \cdot e^{\frac{\omega}{\alpha \tau}},$$

where the yield dependence of the spectral $R_g$ Green’s functions $G_{R_g}$ and $G_{R_gclvd}$ enters through the source depth scaling, and the origin of CLVD source is delayed $\tau_s$ seconds since the stress wave must propagate to and reflect off the free surface before tensile failure can occur (e.g., $t_s = (h_c + h_{clvd})/\alpha$, where $\alpha$ is the $P$ wave speed). We have chosen to use analytical expressions for $R_g$ Green’s functions in a halfspace to start with to keep the model strictly analytical. This allows for simplified analysis of the high frequency scaling in the next subsection. But first, we discuss key source parameters of the CLVD and revisit spectral ratio modeling of Patton and Taylor (1995).

CLVD source parameter scaling. Three key source parameters are (1) the source process time $T$, (2) the relative source strength $\Phi_s/M_e$, where $\Phi_s$ is the “zero-frequency” strength of the CLVD source and $M_e$ the scalar moment of the explosion, and (3) the centroid depth $h_{clvd}$. In our model $T$ is identified with the duration of a source located just beneath the spall-parting depth where ground motions are in a state of “incipient spall”; this state is modelled by Stump’s time histories when the rise time and dwell time are set equal. Thus $h_{clvd}$ corresponds to the deepest extent of

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**Figure 3. A cartoon depicting the essential elements of a new explosion source model.**

Two sources, the explosion plus a CLVD representing a conical zone of extensional deformations, excites $P, S,$ and $R_g$ waves. High-frequency $R_g$ waves propagate near the Earth’s surface and scatter mainly into $S$ waves off topography and material heterogeneities in the source region.
Yield scaling relationships for these source parameters must be developed, and this is work in progress. To date, we have drawn upon published information related to close-in ground-motion measurements of spall. We have found the best constraints are on the scaling relationships for $T$ and $h_{clvd}$.

The relative source strength $\Phi_o/M_x$ can be estimated from modeling $Lg$ spectral ratios as in Patton and Taylor. It has come to our attention that the Rayleigh wave source phase was violated by models in the 1995 study because the estimates of $\Phi_o/M_x$ are too large and the CLVD source, which looks like an impulse at long periods, perturbs the phase. Long-period observations on typical NTS explosions are consistent with a step function of the monopole source, not an impulse. The new modeling results discussed below do not violate the long-period phase owing to smaller estimates of $\Phi_o/M_x$. Importantly, these revisions have led to a new interpretation of the spectral null in the $Lg$ spectral ratios identified by Patton and Taylor. The revised model suggests that the null is caused by interference between $Rg$ waves emitted by the CLVD and monopole sources, not by an $Rg$ excitation null related to the CLVD source depth.

Network-averaged $Lg$ spectral ratios for BASEBALL/BORREGO modelled in Patton and Taylor are plotted in Fig. 4a along with a prediction based on the source model developed herein. This prediction was computed by taking the amplitude ratio of $Rg$ spectra plotted in Fig. 4b under the assumption that the $Rg$ spectrum is imprinted on the scattered $S$ waves making up $Lg$ at regional distances. I have used “order-of-magnitude” yields 100 and 1 kt for this generic calculation. Located within 1 km of BASEBALL at the same emplacement depth, the overburied explosion BORREGO serves as an empirical Green’s function source. BORREGO’s source effects are dominated by the monopole at low frequencies due to a much-reduced relative source strength $\Phi_o/M_x$. Indeed, based on displacements measured over ground-zero on BASEBALL and BORREGO and on estimates of the CLVD source dimensions, the relative source strength is roughly a factor of 50 less than BASEBALL’s.

Scaling relations for corner frequency $f_c$ and $M_x$ for normal-buried explosions were taken from Denny and Johnson (1991). For a 100 kt explosion, $f_c$ equals 0.91 Hz. The moment scaling has no impact on our estimate of $\Phi_o/M_x$ for
BASEBALL, and was used for the sole purpose of scaling unit-moment spectra \( A_{Rg}/M_x \) upward for a 100 kt explosion in order to calculate the model spectral ratios. Thus the first term in the expression for \( A_{Rg}/M_x \) (see equation for \( A_{Rg} \)) is completely specified for BASEBALL and utilizing scaling relationships for \( T \) and \( h_{clvd} \), the second term can be specified to within a constant (\( \Phi_{\omega}/M_x \)). We are able to model the first spectral null in the \( Lg \) spectral ratio (see Fig. 4a) without violating the long-period phase with \( \Phi_{\omega}/M_x \) set equal to 0.17 s. The second spectral null is also modeled well because the lowest frequency notch in the spectrum of the CLVD time function occurs very close to 1.1 Hz.

A remarkable feature of the composite spectrum for the 100-kt explosion is that the high frequencies are controlled well because the lowest frequency notch in the spectrum of the CLVD time function occurs very close to 1.1 Hz.

To explore this possibility, we can write simple expressions for the high frequency scaling slopes of \( P \) and \( S \) waves using our analytical source model. For \( P \) waves, yield slope \( YS(P) \) is

\[
YS(P) = a + m \cdot b, 
\]

where \( a \) is the yield exponent on \( M_x \) scaling, \( m \) is the high frequency roll-off, and \( b \) is the yield exponent on corner frequency scaling. The results of Denny and Johnson (1991) for normal-buried explosions give \( a = 0.85, b = -0.15 \), and \( m = 2 \), or \( YS(P) = 0.55 \). For \( S \) waves mediated by the excitation of \( Rg \) waves, the yield slope \( YS(S) \) involves the CLVD source function and a high-frequency asymptotic expression for \( GR_{clvd} \).

\[
YS(S) = a + \kappa + n \cdot b' - \omega \cdot \hat{\eta}_b \cdot h_{clvd} \cdot c, 
\]

where \( \kappa \) is the yield exponent on \( \Phi_{\omega}/M_x \) scaling, \( n \) is the high frequency roll-off, \( b' \) is the yield exponent on corner frequency, \( \hat{\eta}_b \) is a slowness parameter, and \( c \) is the yield exponent on \( h_{clvd} \) scaling. The first three terms are completely analogous to \( YS(P) \) since the sum of exponents \( a \) and \( \kappa \) is nothing more than the yield exponent on \( \Phi_{\omega} \) scaling. The last term is contributed from \( Rg \) excitation and introduces frequency and yield dependences. Using the scaling relationship for \( h_{clvd} \) and \( 2 \times 10^{-4} \) s/m for \( \hat{\eta}_b \), the last term can be written \( -3 \times 10^{-2} \cdot W^{1/3} \cdot f \), where \( f \) is frequency in Hz and \( W^{1/3} \) comes from the \( h_{clvd} \) scaling relation. \( b' \) equals the exponent on \( 1/T \), or \(-0.1\), and \( n = 4 \) in the case of Rayleigh wave excitation. At this stage is our research, our best estimate of \( \kappa \) is \(-0.2\) based on self-similarity analysis of synthetic \( Rg \) spectra, like the analysis Jones and Taylor (1996) performed on \( Lg \) spectra for NTS explosions. Summarizing, for frequencies \( >3 \) Hz and for yields distributed around 10 kt, \( YS(S) \) is bounded from above,

\[
YS(S) < 0.85 + 0.25 + 4 \cdot (-0.1) - 3 \times 10^{-2} \cdot 10^{1/3} \cdot 3 = 0.5.
\]

The model predicts the yield scaling slope of \( S \) waves \( YS(S) \) is less than 0.5 at high frequencies and thus smaller than the \( P \) scaling slope \( YS(P) \), consistent with the observations we reported on earlier in this paper.

CONCLUSIONS AND RECOMMENDATIONS

The NEM R&E magnitude research project is focused on improving yield estimation and seismic discrimination capabilities for broad areas and small events through the development of regional magnitude methodologies and data sets of direct seismic phases and coda waves. A significant component of the research empirically characterizes the yield scaling behavior of regional magnitudes in different frequency bands under a variety of underground testing environments, both in terms of containment and geology. Equally important is the development of physical models for shear-wave generation by underground explosions to lay a theoretical foundation supporting the empirical methods in operational use. We believe that both components, empirical characterization of scaling behavior and development of a physical basis, are essential for the success of new, improved methods for broad-area monitoring at
small yields. We have summarized some research results from the past year in this paper, and are excited by the prospects of coda-based methodologies in operational use. At the same time, there are many open questions about the operational performance of coda-wave techniques, and full confidence to monitor broad areas effectively will only come with continued research on both empirical and theoretical fronts.

REFERENCES


