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Title: (U) INCORPORATING LOVE- AND RAYLEIGH-WAVE MAGNITUDES, UNEQUAL EARTHQUAKE AND EXPLOSION VARIANCE ASSUMPTIONS, AND INTERSTATION COMPLEXITY FOR IMPROVED EVENT SCREENING

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INCORPORATING LOVE- AND RAYLEIGH-WAVE MAGNITUDES, UNEQUAL EARTHQUAKE AND EXPLOSION VARIANCE ASSUMPTIONS, AND INTRASTATION COMPLEXITY FOR IMPROVED EVENT SCREENING

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ABSTRACT

Our objective is to improve seismic event screening using the properties of surface waves. We are accomplishing this through (1) the development of a Love-wave magnitude formula that is complementary to the Russell (2006) formula for Rayleigh waves and (2) quantifying differences in complexities and magnitude variances for earthquake and explosion-generated surface waves.

We have applied the M_s (VMAX) analysis (Bonner *et al.*, 2006) using both Love and Rayleigh waves to events in the Middle East and Korean Peninsula. For the Middle East dataset consisting of approximately 100 events, the Love M_s (VMAX) is greater than the Rayleigh M_s (VMAX) estimated for individual stations for the majority of the events and azimuths, with the exception of the measurements for the smaller events from European stations to the northeast. It is unclear whether these smaller events suffer from magnitude bias for the Love waves or whether the paths, which include the Caspian and Mediterranean, have variable attenuation for Love and Rayleigh waves.

For the Korean Peninsula, we have estimated Rayleigh- and Love-wave magnitudes for 31 earthquakes and two nuclear explosions, including the 25 May 2009 event. For 25 of the earthquakes, the network-averaged Love-wave magnitude is larger than the Rayleigh-wave estimate. For the 2009 nuclear explosion, the Love-wave M_s (VMAX) was 3.1 while the Rayleigh-wave magnitude was 3.6.

We are also utilizing the potential of observed variances in M_s estimates that differ significantly in earthquake and explosion populations. We have considered two possible methods for incorporating unequal variances into the discrimination problem and compared the performance of various approaches on a population of 73 western United States earthquakes and 131 Nevada Test Site explosions. The approach proposes replacing the M_s component by $M_s + a^*\sigma$, where σ denotes the interstation standard deviation obtained from the stations in the sample that produced the M_s value. We replace the usual linear discriminant $a^* M_s + b^* m_b$ with $a^* M_s + b^* m_b + c^*\sigma$. In the second approach, we estimate the optimum hybrid linear-quadratic discriminant function resulting from the unequal variance assumption. We observed slight improvement for the discriminant functions resulting from the theoretical interpretations of the unequal variance function.

We have also studied the complexity of the "magnitude spectra" at each station. Our hypothesis is that explosion spectra should have fewer focal mechanism-produced complexities in the magnitude spectra than earthquakes. We have developed an intrastation "complexity" metric Δ_{Ms} where Δ_{Ms} = Ms(i)-Ms(i+1) at periods, i, are between 9 and 25 seconds. The complexity by itself has discriminating power but does not add substantially to the conditional hybrid discriminant that incorporates the differing spreads of the earthquake and explosion standard deviations.

OBJECTIVES

The Russell (2006) M_s formula has opened up new avenues of scientific research, such as the development of improved regional surface wave Q models (Stevens *et al.*, 2006; Levshin *et al.*, 2006; Cong and Mitchell, 2006) that may further reduce interstation variance of the magnitudes. We believe that application of the M_s(VMAX) technique to Love waves is the next logical step in the scientific process that could lead to improved discrimination. Our objective is to improve seismic event screening using the properties of Rayleigh and Love waves. We are accomplishing this through (1) the development of a Love-wave magnitude formula that is complementary to the Russell (2006) formula for Rayleigh waves and (2) quantifying differences in complexities and magnitude variances for earthquake and explosion-generated surface waves.

RESEARCH ACCOMPLISHED

Love and Rayleigh Wave M_s(VMAX) in the Middle East

We have applied the M_s (VMAX) analysis (Bonner *et al.*, 2006) using both Love and Rayleigh waves to ~100 events located in the Middle East. M_s(VMAX) is for estimated both Rayleigh and Love waves using the Russell (2006) formula:

$$M_s = \log(a_b) + \frac{1}{2}\log(\sin\Delta) + 0.0031\left(\frac{T_0}{T}\right)^{1.8}\Delta - \log(f_c) - 0.43 - 0.66\log\left(\frac{20}{T}\right) \quad (1)$$

Our initial hope is to be able to use the same formula for both phases. The details of the processing used to estimate M_s(VMAX) are described in Bonner *et al.* (2006).

The study area (Figure 1) is located in the zone of continental collision between Eurasian, African and Arabian plates. The region of study is very complex and spans a variety of different tectonic regimes. The seismicity in South and Central Iran and Turkey is in the upper crust, shallower than ~20 km (*e.g.* Engdahl *et al.*, 2006). It deepens toward the north in the Alborz region in Northern Iran, where it becomes distributed through the crust. Further to the North in the Central Caspian Sea, the seismicity follows the Apsheron-Balkhan Sill and reaches depths of 30-100 km, deepening toward the north. Turkey seismicity is dominated by strike-slip focal mechanisms and concentrated between depths of 10 and 20 km. Zagros fold-and-thrust region – most of the earthquakes are shallower than 30 km, with median depth 15±7 km.

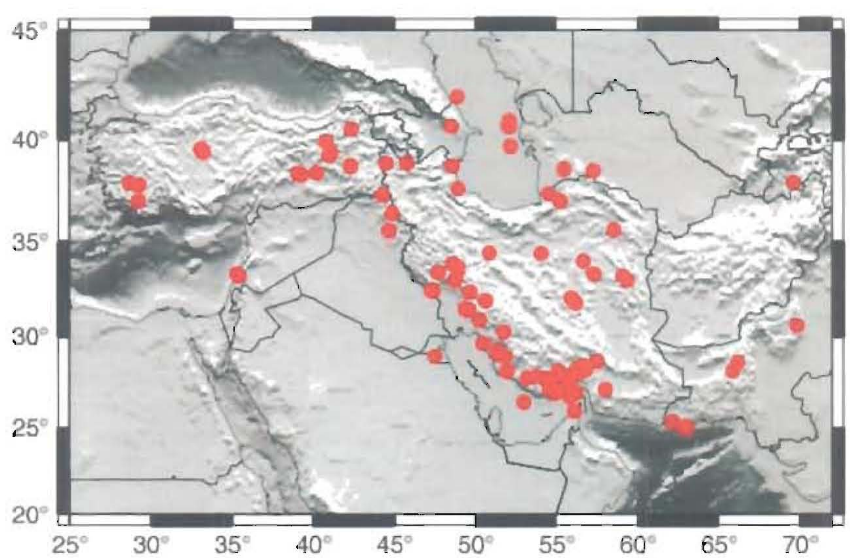

Figure 1. Map of the Middle Eastern events for which M_s(VMAX) for Love and Rayleigh was estimated.

We computed M_s(VMAX) for over 100 seismic events located in this region with reported body wave magnitudes (m_b) between 3.8 and 5.6. The majority of the location and magnitude information (with a few exceptions) was obtained from the NEIC bulletin. The comparison between M_s(VMAX) for Love and Rayleigh waves is shown in Figure 2. The M_s(VMAX) computed using Love waves is greater than the magnitude for Rayleigh waves for the majority of the events of larger magnitudes (above m_b~4). For smaller events, however, we observe a large number of events with the Rayleigh M_s(VMAX) exceeding the Love M_s(VMAX). This peculiarity could be caused by either reduced SNR for smaller magnitude events, or by some unknown source processes, such as a dominant normal fault mechanism. In addition regional differences in the wave attenuation and/or anisotropy could cause changes in the amplitudes for the rays traveling in different directions. Since the station coverage is not homogeneous, these propagation effects could potentially result in biases in M_s(VMAX) estimate for smaller events with limited sampling.

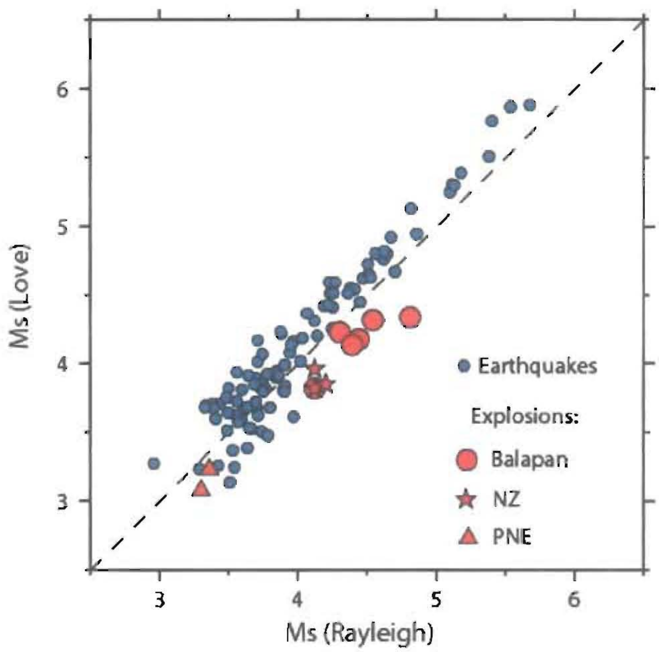

Figure 2. Comparison of M_s(VMAX) computed using Rayleigh and Love waves. Small blue circles show earthquakes, the red symbols show M_s estimate using on station (BRVK) for some Soviet nuclear explosions.

Azimuthal dependency of the estimated M_s(VMAX) for several larger events of known magnitudes (m_b) is shown in Figure 3. The azimuthal differences are most likely caused by source effects (*e.g.* non-isotropic source radiation), however the propagation effects (*e.g.* anomalies in regional attenuation, anisotropy) can play a certain role. The stations located between the azimuths 0° and 60° often have higher magnitude measurements, than the stations located in other directions. Notice that for larger events the Love M_s(VMAX) is greater than the Rayleigh M_s(VMAX) for most azimuths. This difference is more pronounces for strike-slip type events, and becomes smaller for the thrust events, common for the Zagros region.

To test whether the azimuthal differences in the magnitudes are caused solely by the focal mechanisms, or if there are propagation effects, we plotted M_s(VMAX) for the individual stations grouped by the direction of propagation. Figure 4a shows the cross-plot between Rayleigh and Love M_s(VMAX) for the stations located to the NE from the corresponding events (back azimuth range between 20° and 70°). There is a significant number of measurements with Rayleigh M_s(VMAX) exceeding Love M_s(VMAX) for smaller events. The measurements for the stations located to the NW of the events (azimuth range between 270° and 360°) show smeared distribution for broader range of magnitudes (Figure 4b). No significant anomaly for smaller events is observed. Therefore it is likely that the reverse in Love and Rayleigh M_s(VMAX) for smaller magnitudes is cause by the regional propagation effects, rather than by the source characteristics.

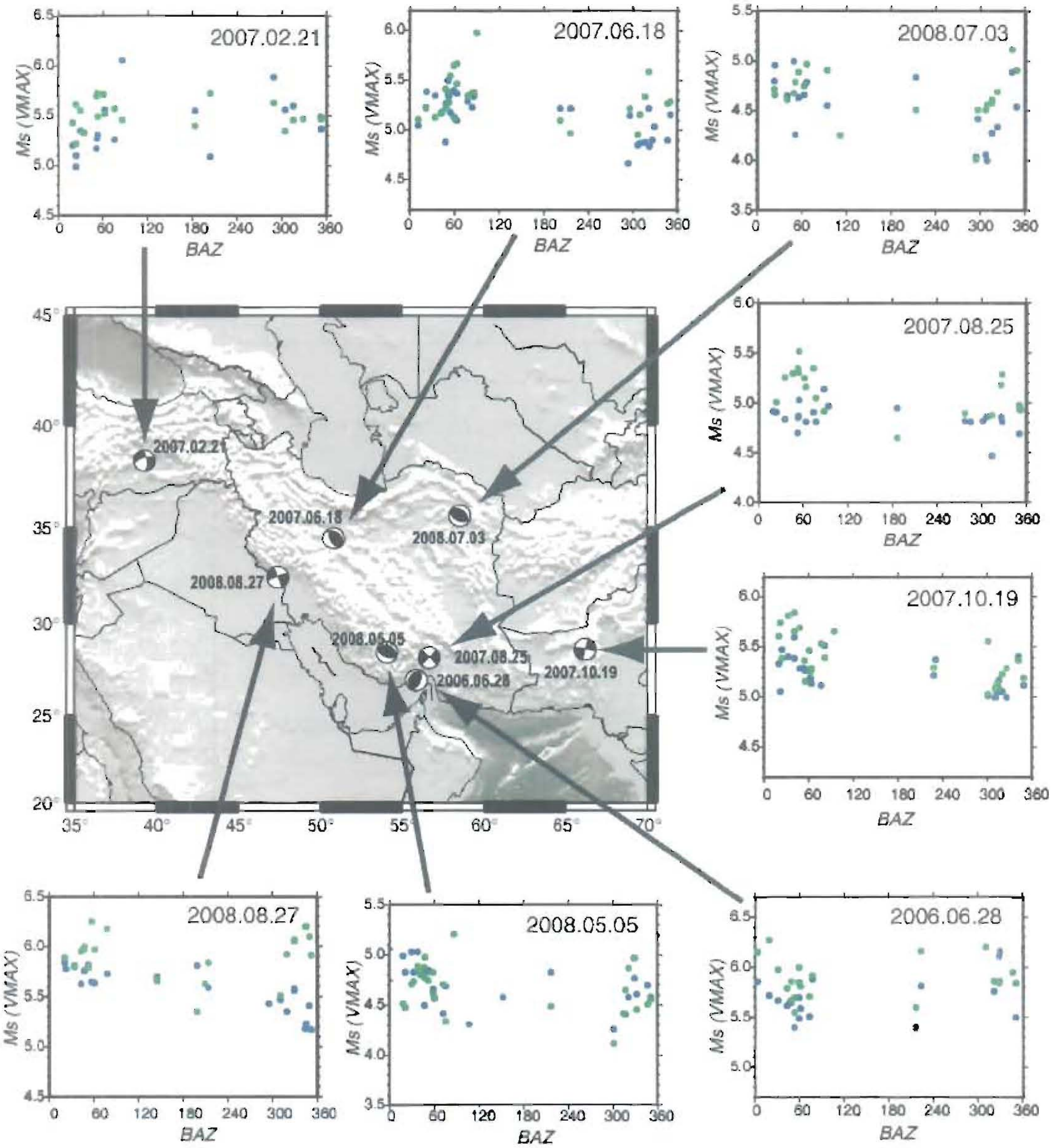

Figure 3. Azimuthal dependence of M_s(VMAX) for some events with known focal mechanisms. Blue and green circles show Rayleigh and Love M_s(VMAX) estimates, respectively.

Love and Rayleigh Wave M_s(VMAX) in the Korean Peninsula

We applied the M_s(VMAX) technique to 31 earthquakes (Figure 5) occurring between 1996-2008 located in the Korean Peninsula and surrounding regions. The events ranged in size between $3.2 < M_w < 5.1$. The distances to the three-component stations (red circles in Figure 5) recording the events ranged from 55 km to 1900 km. For the estimation of Love-wave magnitudes data were converted to transverse motion, while the Rayleigh-wave magnitudes were estimated using vertical component data. The analysis resulted in 298 single-station estimates of M_s(Love) and 266 estimates of M_s(Rayleigh).

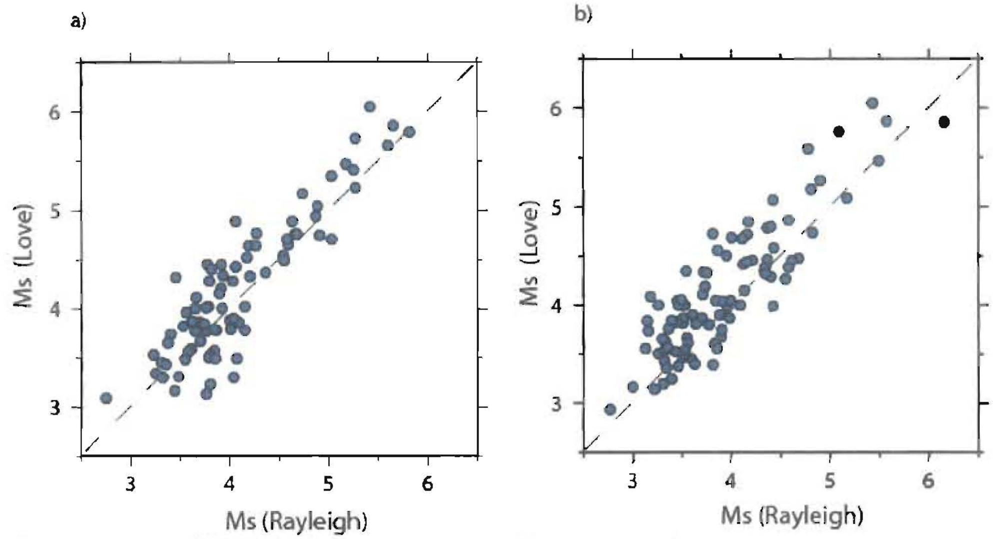

Figure 4. Comparison of M_s(VMAX) computed using Rayleigh and Love waves for individual stations: a) stations located to the NE from the events (back azimuth ranges between 20° and 70°); b) stations located to the NW (back azimuth ranges between 270° and 360°).

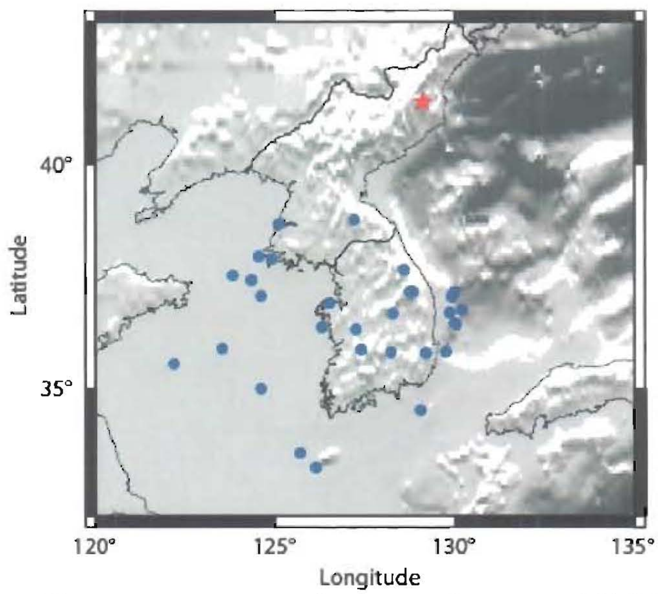

Figure 5. Map of the Korean Peninsula region events (yellow stars) for which M_s(VMAX) for Love and Rayleigh was estimated. The red circles are stations used in the analysis.

Figure 6 provides a comparison of Love vs. Rayleigh wave M_s(VMAX) estimates. Applying Equation 1 calibrated for Rayleigh-waves results in a positive bias for the Love wave magnitudes. This result is consistent with the results for events with Ms(VMAX) > 4 in the Middle East study. Only 6 of the 31 network magnitudes had a larger Rayleigh-wave magnitude than Love wave, although when the standard deviation was considered, these events could fall below the line representing equivalent Love- and Rayleigh-wave magnitudes.

In addition to the earthquake dataset we analyzed the two North Korean underground nuclear explosions (UNE). Bonner *et al.* (2008) found M_s(VMAX)=2.93 for the Rayleigh waves from the 9 October 2006 North Korean UNE. There were no Love waves registered on any of the analyzed stations. The 25 May 2009 announced UNE in North Korean had a larger magnitude (M_s(VMAX)=3.6) and had Love waves large enough for analysis. The M_s(VMAX) estimated for the Love waves was 3.1, which placed it below the earthquake population in Figure 6. The 25 May

2009 event's standard surface wave magnitude, based on Rayleigh waves, plots above the Murphy *et al.* (1997) screening line for M_s:m_b and is perhaps even more anomalous than its predecessor (Bonner *et al.*, 2006). It appears that the reason the first event did not separate from the earthquake population well was not due to convergence of the populations near m_b ~4.

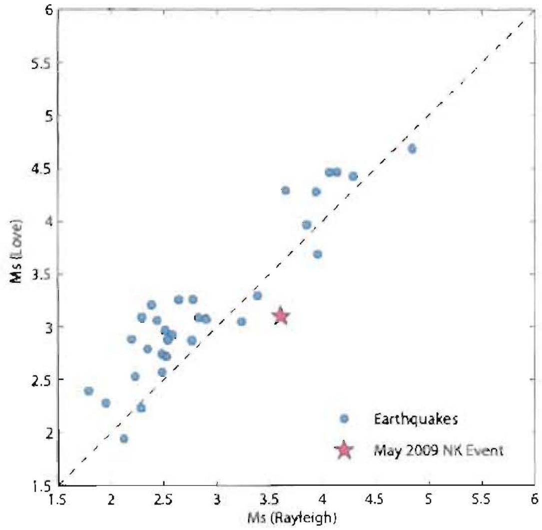

Figure 6. Comparison of M_s(VMAX) computed using Rayleigh and Love waves for the Korean Peninsula region. Small turquoise circle show earthquakes, the purple symbols show M_s estimates for the 25 May 2009 announced nuclear test.

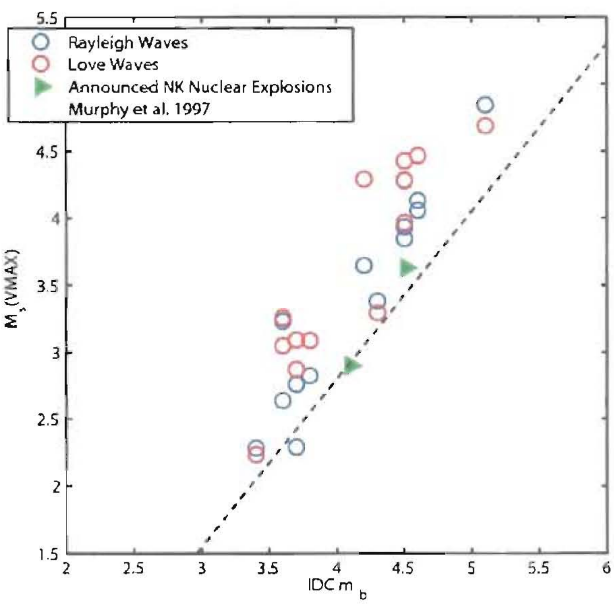

Figure 7. Comparison of network M_s(VMAX) estimates for Rayleigh- and Love-waves versus International Data Center (IDC) body wave magnitude m_b for Korean Peninsula earthquakes and the two announced North Korean nuclear explosions. The dashed line represents the event screening line proposed by Murphy *et al.* (1997).

Unequal Variance Assumptions and Improved Discrimination

We have attempted to use the potential of observed variances that differ significantly in earthquake and explosion M_s(VMAX) populations (Figure 7) for improved event screening. We have considered two possible methods for incorporating unequal variances into the discrimination problem and compare the performance of various approaches on a population of 73 Western U.S. Earthquakes and 131 Western U.S. Explosions.

The conventional statistical approach to separating the distributions with unequal variances would be to derive the likelihood ratio criterion for that case which yields a hybrid discriminant composed of a linear term and a quadratic term with weights dependent on the unequal covariance matrices for the two populations. Taking the solution involving the likelihood ratio guarantees that the probability of correctly ruling out an event as an explosion subject to a fixed probability of failing will be maximized under the multivariate normal assumption for the input variables, usually taken to be Ms and mb. Sometimes, additional tuning parameters are added to covariance matrices that may improve performance in particular samples or when the joint Gaussian assumptions are not satisfied (see Friedman, 1989, Anderson et al 2007). The common assumption that the covariance matrices of the two populations are approximately equal reduces the classification function to a linear function of the input variables. For example, the simple difference Ms-mb is often used as a further approximation. This approach, however, is not recommended because of poor performance in sample populations such as the one considered here.

An alternate method proposes replacing the M_s component by $M_s + a*\sigma$, where σ denotes the interstation standard deviation obtained from the stations in the sample that produced the M_s value. In this context, we interpret this as replacing the usual linear discriminant $a* M_s + b* m_b$ by $a* M_s + b* m_b + c* \sigma$ (Figure 9). We also estimate the optimum hybrid linear-quadratic discriminant function resulting from the unequal variance assumption. While, the input standard deviations will not be normally distributed (they follow the chi distribution), the linear approximation may be reasonable for the same reasons that the linear discriminant function works in the usual case. While the two discriminant functions resulting from the two theoretical interpretations of the unequal variance function did slightly better in the test samples used here, all methods except M_s - m_b did extremely well using the western United States dataset. We plan on evaluating this method further using our entire dataset of earthquakes and explosions.

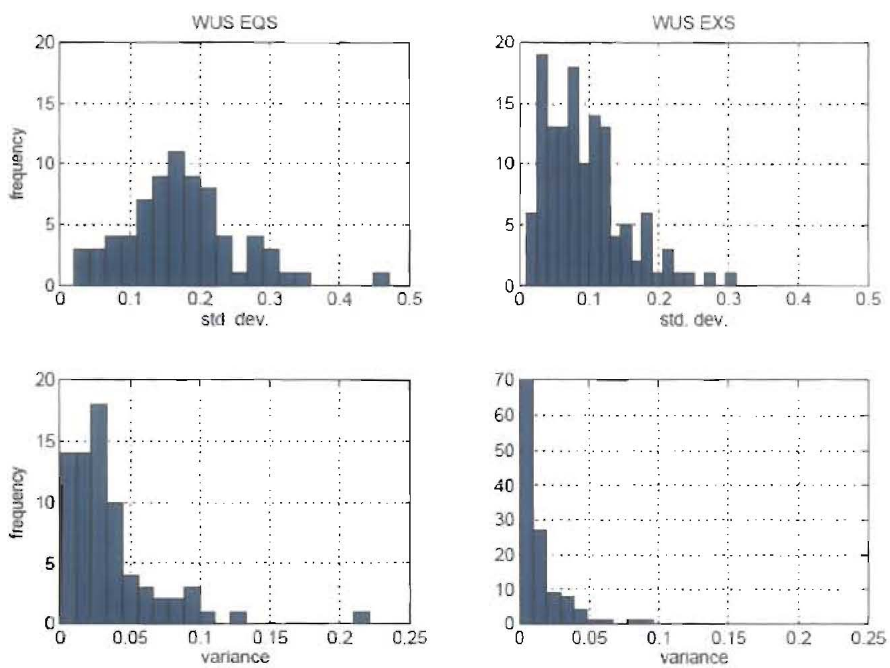

Figure 8. Frequency histograms for the station standard deviations (top) and variances (bottom) for 73 Western U.S. Earthquakes and 131 Explosions.

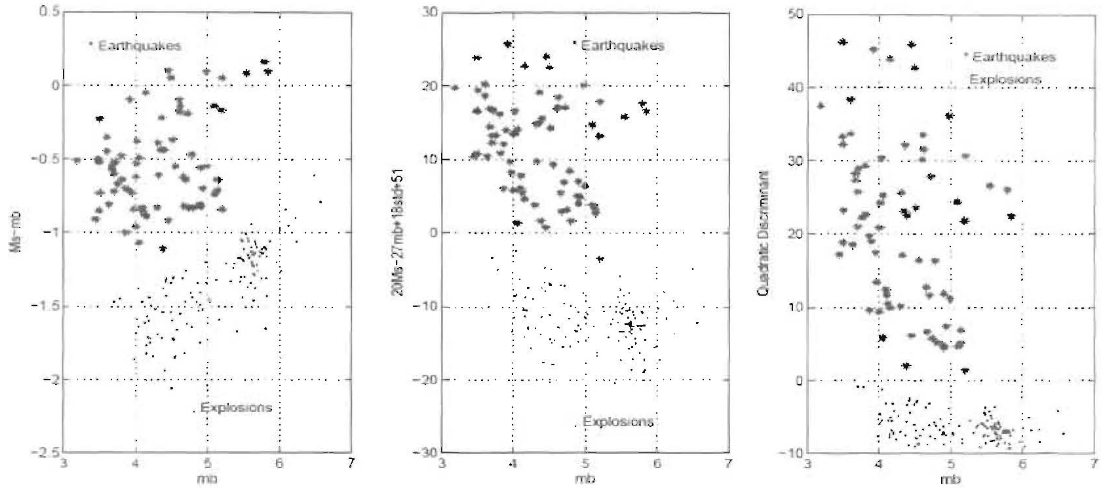

Figure 9. Conventional multivariate discriminant analysis combining M_s(VMAX)-m_b (left), M_s(VMAX), m_b and STD (middle), and multivariate linear-quadratic discriminant analysis (right) for 73 Western U.S. Earthquakes and 131 Explosions.

A New Metric for Intrastation Complexity

We have also studied the complexity of the "magnitude spectra" at each station. Our hypothesis is that explosion spectra should have fewer focal mechanism-produced complexities in the magnitude spectra than earthquakes (Figure 10). We have tried several different methods, including the intrastation std as a function of period shown in Figure 10 and a "differencing" approach. For periods between i=9 and 25 seconds, we estimate:

$$\Delta_{Ms} = Ms(i)-Ms(i+1). \quad (2)$$

We start at i=9 seconds to minimize edge effects. This results in n=17 new magnitude differences, Δ_{Ms} for each station. It may be fewer if estimates at some periods fail a signal-to-noise ratio test.

We then have estimated several different metrics, M, from Δ_{Ms} for comparison of the differenced magnitudes. Thus far, we have settled on:

$$M = \frac{\Sigma\left|\Delta_{Ms}-\overline{\Delta_{Ms}}\right|}{n} \quad (3)$$

Figure 11 show the histograms for the earthquake and explosion populations M while Figure 12 shows the cumulative distribution functions of M. The metric M works well for the application of trying to separate complexity of source spectra. At 90% explosion confidence, around .02 M, there is about a 30% earthquake confidence. explosion ground truth populations.

CONCLUSIONS AND RECOMMENDATIONS

Preliminary research shows that Love wave magnitudes for earthquakes are often equal to or larger than Rayleigh wave magnitudes. Conversely, for explosions, Love-wave magnitudes are typically smaller than Rayleigh-wave estimates, or below background noise levels. However, we observe a number of smaller events with reversed pattern. Interestingly enough, this peculiarity is observed for the Middle East dataset, but not for Korean dataset. We will continue to examine this phenomenon, possibly incorporating M_s maximum likelihood estimates, with hopes of porting the results, theory, and statistical p-values into the Event Classification Matrix (ECM; Anderson *et al.*, 2007). Additional aspects of surface wave propagation, including a new intrastation complexity metric and differences in explosion and earthquake magnitude variances, also show promise for improved event screening.

We will also develop an improved formula for estimation of $M_s(VMAX)$ using Love waves. Equation 1 was developed using empirical relationships using the Rayleigh waves, which may or may not be calibrated for Love waves.

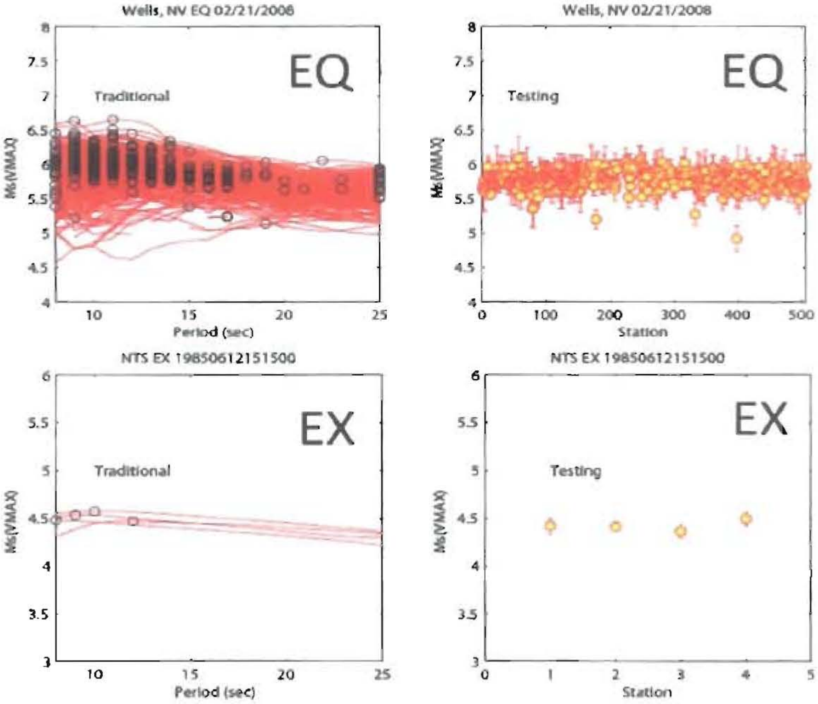

Figure 10. A proposed new approach for improved discrimination. (Left Column). Traditional M_s(VMAX) where the circle is the period of maximum amplitude. (Right Column). The mean of a station's estimate and its standard deviation are formed. Our results suggest that the intrastation standard deviation is typically less for explosions than earthquakes for our Western United States database.

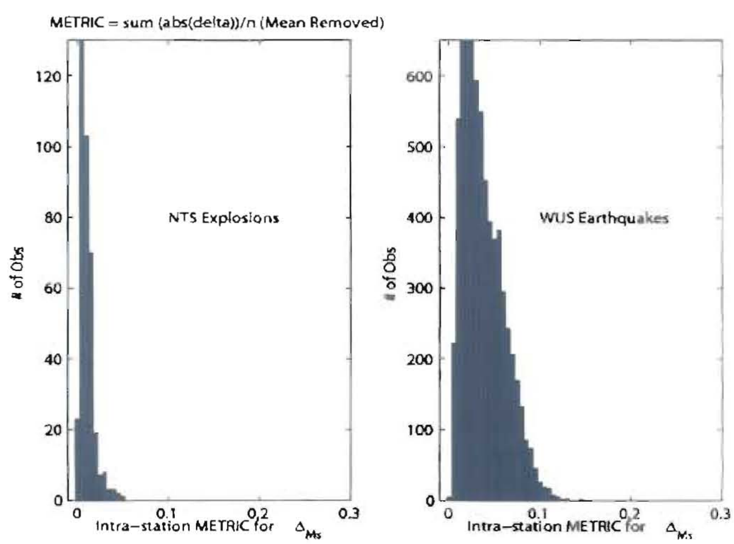

Figure 11. Comparison of the new intrastation metric Δ_{M_s} for NTS explosion (left) and Western United States earthquakes (right).

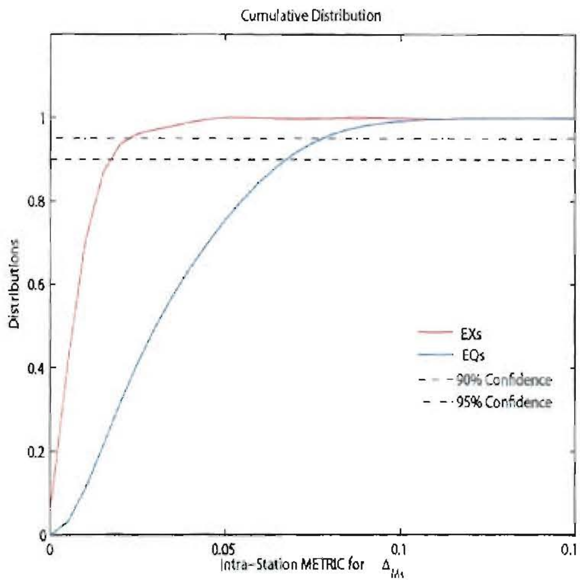

Figure 12. Cumulative distribution functions for metric M (Equation 3; Figure 11) for western United States earthquakes and NTS explosions.

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