# EMPIRICAL OBSERVATIONS OF EARTHQUAKE-EXPLOSION DISCRIMINATION USING P/S RATIOS AND IMPLICATIONS FOR THE SOURCES OF EXPLOSION S-WAVES

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## ABSTRACT

We continue exploring methodologies to improve earthquake-explosion discrimination using regional amplitude ratios such as *P/S* (ratio of P- and/or S-wave energy). The earliest simple source models predicted *P/S* wave amplitudes for explosions should be much larger than for earthquakes across the body wave spectrum. However empirical observations show the separation of explosions from earthquakes using regional *P/S* amplitudes is strongly frequency dependent, with relatively poor separation at low frequencies (~1 Hz) and relatively good separation at high frequencies (> ~3 Hz). We demonstrate this using closely located pairs of earthquakes and explosions recorded on common, publicly available stations at test sites around the world (e.g., Nevada, Lop Nor, Novaya Zemlya, Semipalatinsk, India, Pakistan, and North Korea). We show this pattern appears to have little dependence on the point source variability revealed by longer period surface wave modeling. For example regional waveform modeling shows strong tectonic release from the May 1998 India test in contrast with very little tectonic release in the recent North Korea test, but the *P/S* discrimination behavior is similar in both events, using the limited regional data available.

While accepted explosion *P*-wave models have been available for many years, the frequency behavior of the *P/S* discriminant has inspired a variety of competing models to explain how explosions generate *S*-waves. We briefly review some of these models in the context of the *P/S* discriminant observations. One hypothesis is that *S*-waves are generated mainly from conversion of *P*-waves and surface waves, so *S*-waves from explosions can be predicted from the *P*-wave models via a frequency dependent transfer function. A different hypothesis is that significant generation of S-waves comes from the CLVD (compensated linear vector dipole) component created by spall above the explosion. A recent model by Fisk (2006) shows the explosion *S*-wave spectra can be modeled using the *P*-wave spectra with the corner frequency reduced by the ratio of the wave velocities, which seems to imply a direct generation of *S*-waves in the source region. We examine a number of nuclear tests from around the world in light of these models. Given the importance of depth on some of the model predictions we reexamine some of the overburied explosions in Nevada. We also look at chemical explosions, including dedicated single shots at different depths and mining shots at adjacent open pit and underground mines to look at depth effects. Finally we examine a subset of Nevada data with signal above noise up to 16 Hz to determine if discrimination performance saturates at frequencies around 6 Hz as some models predict, or continues to improve at higher frequencies.

## OBJECTIVES

Monitoring the world for potential nuclear explosions requires characterizing seismic events and discriminating between natural and man-made seismic events, such as earthquakes and mining activities, and nuclear weapons testing. We continue developing, testing, and refining size-, distance-, and location-based regional seismic amplitude corrections to facilitate the comparison of all events that are recorded at a particular seismic station. These corrections, calibrated for each station, reduce amplitude measurement scatter and improve discrimination performance. We test the methods on well-known (ground truth) datasets in the U.S. and then apply them to the uncalibrated stations in Eurasia, Africa, and other regions of interest to improve underground nuclear test monitoring capability.

## RESEARCH ACCOMPLISHED

As part of the overall National Nuclear Security Administration Ground-based Nuclear Explosion Monitoring Research and Engineering program (GNEMRE), we continue to pursue a comprehensive research effort to improve our capabilities to seismically characterize and discriminate underground nuclear tests from other natural and man-made sources of seismicity. To reduce the monitoring magnitude threshold, we make use of regional body and surface wave data to calibrate each seismic station. Our goals are to reduce the variance and improve the separation between earthquakes and explosion populations by accounting for the effects of propagation and differential source size, and by optimizing the types and combinations of amplitude measurements used.

**Regional Phase Amplitude P/S Observations**

In the early days of underground nuclear testing the expectation, as shown in Figure 1, was that explosions would generate little S-wave energy and relative P/S wave amplitudes could be used as one technique to distinguish them from earthquakes. Prior to the advent of widespread digital seismometry in the 1990's observations of regional P/S amplitudes tended to be dominated by frequencies around 1 Hz. As shown in Figure 2 at a number of major nuclear test sites, these observations did not show clear separation between event types. Here we focus on closely spaced pairs of events to minimize any path effects.
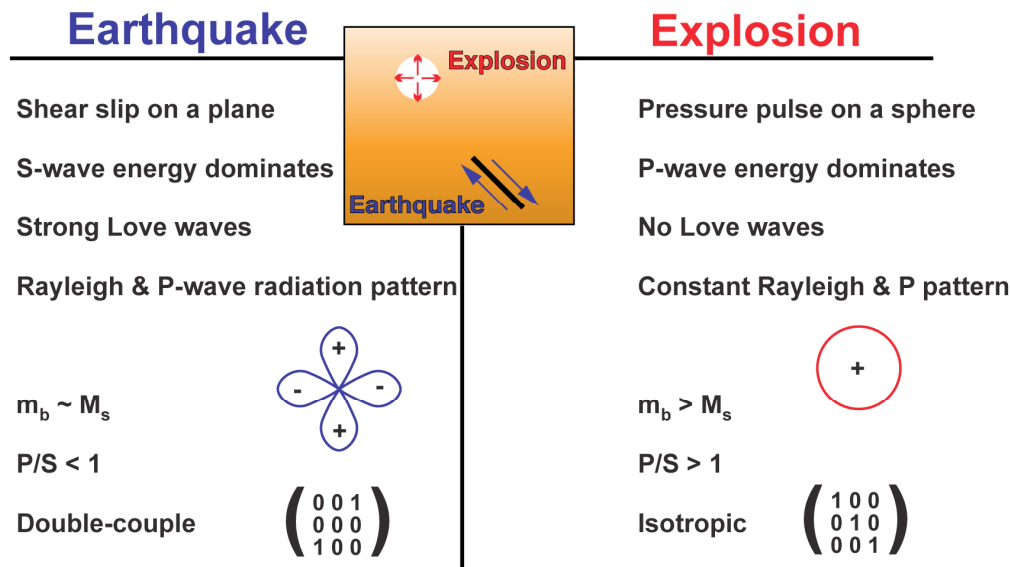


**Figure 1. An overview of the theoretical differences between a pure explosion and a pure earthquake leading to expected observational differences. Actual underground nuclear explosions are often more complex.**
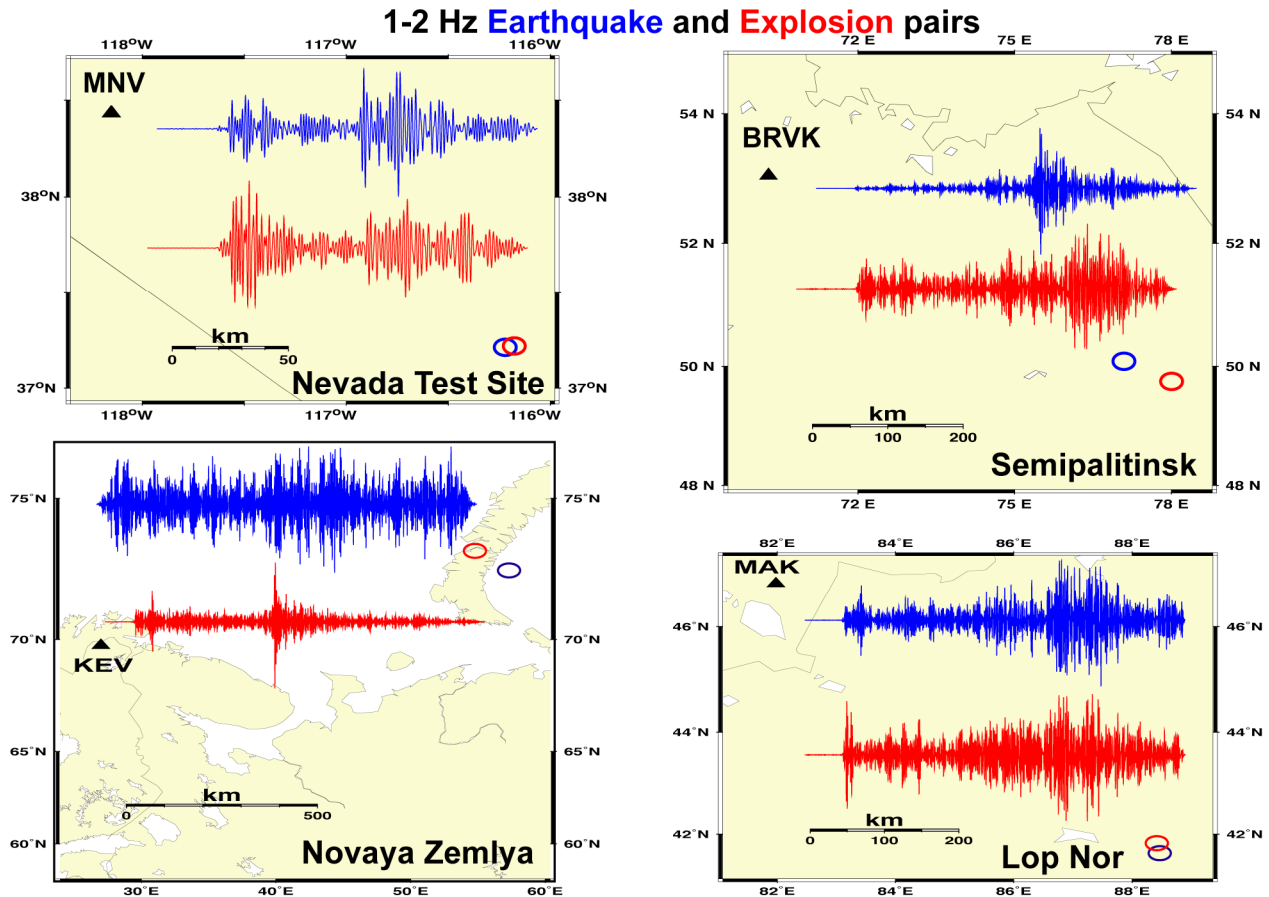
**Figure 2. Bandpass filtered 1-2 Hz seismograms of earthquake (red) and explosion (blue) pairs at nuclear test sites show little consistent relative P to S wave amplitude differences between the two source types. Low-Frequency P/S does not discriminate closely located events recorded on the same station at nuclear test sites.**

With the advent of widespread digital seismometry in the late 1980's and early 1990's a large number of different researchers found that at high frequencies, greater than around 2-4 Hz, the regional P/S amplitude ratios did discriminate explosions from earthquakes (e.g., Dysart and Pulli, 1987; Baumgardt and Young, 1990; Kim et al., 1993; Walter et al., 1995; Taylor, 1996; Hartse et al., 1997; Battone et al., 2002). For example in Figure 3 we show the same events in Figure 2, except they are filtered at a higher frequency, 6-8 Hz. In this case the explosions clearly show larger P/S amplitude ratios than the earthquakes for all cases.

Examination of P/S ratios at high frequencies has now been done all over the world. As we show in Figure 4, the characteristic pattern of explosions have larger relative P-wave amplitudes than S-wave amplitudes appears to hold everywhere, provided that we filter the data at a high enough frequency and that we compare events with very similar paths. This is true even for the recently announced nuclear test by North Korea on October 9, 2006, as shown in Figure 4. In this case the nearest earthquakes for comparison are around 100 km away, but we can bracket the test with earthquakes and clearly see that it is deficient in high frequency S-wave energy.
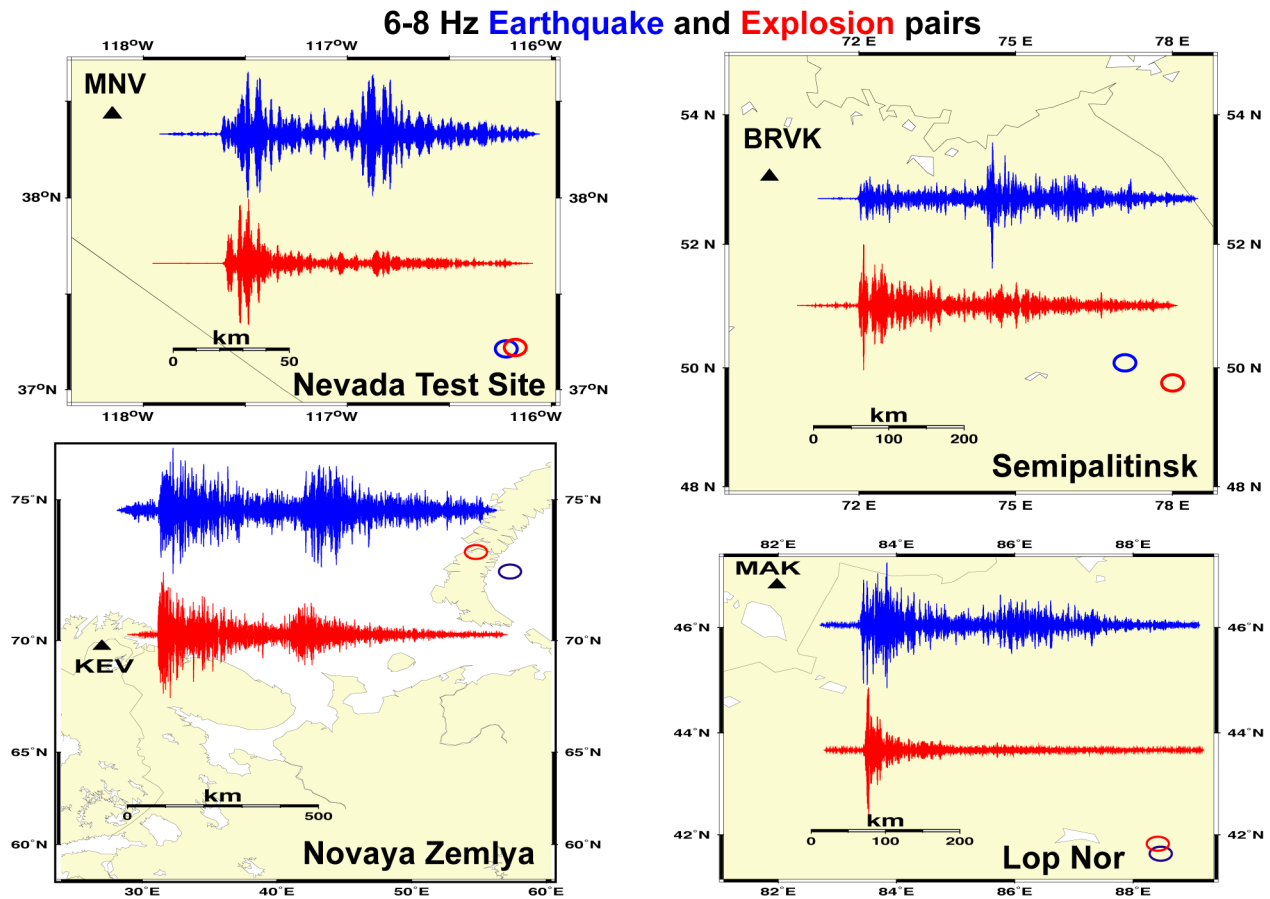
**Figure 3. 6-8 Hz bandpass seismograms of the same events in Figure 2 show significant and consistent relative P to S wave amplitude differences between the two source types. High-frequency P/S appears to discriminate closely located, similarly sized events recorded on the same station globally.**

This North Korean test example shows the importance of accounting for path, as the S-wave energy in this case is partitioned into both Sn and Lg phases. The path of the recorded seismic energy crosses the Sea of Japan, a region of oceanic crust where Lg does not efficiently propagate. One can see that the earthquake with a greater proportion of its path in the Sea of Japan has stronger Sn than the other. In such cases it is important to correct for path effects and to consider P/S ratios for all the observable regional phases; in case one S-wave phase is attenuated to below the level of the noise.

When similarly sized earthquakes and explosions are nearly co-located, we can understand the observed seismic contrasts, such as the relative P-to-S wave excitation, in terms of depth, material property, focal mechanism and source time function differences. However, it is well known that path propagation effects (e.g., attenuation, blockage) and source scaling effects (e.g., corner frequency scaling with magnitude) can make earthquakes look like explosions and vice versa. We developed a technique called magnitude and distance amplitude corrections (MDAC) (Walter and Taylor, 2001) that can account for these effects with proper calibration. We use the earthquakes alone to determine the MDAC parameters such as geometrical spreading, frequency dependent Q and the average apparent stress. After calibration the MDAC formulation provides expected spectral amplitudes as a function of phase, frequency, magnitude and distance. These can then be subtracted from the actual observations. For earthquakes the corrected data should exhibit a close to zero mean, and no significant trends with magnitude and distance. Explosions should have significant non-zero mean residuals, leading to improved discrimination.
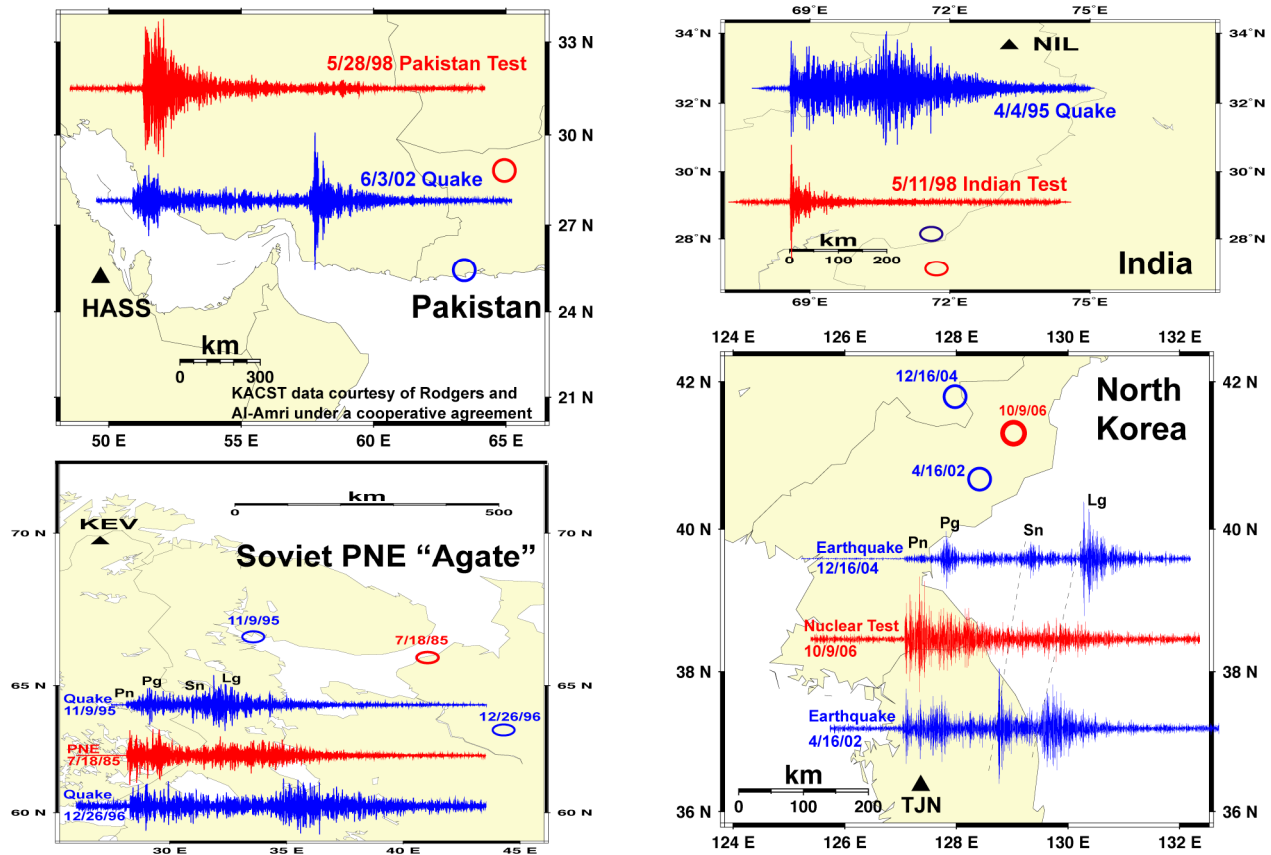
**Figure 4. Examination of high frequency filtered seismograms of closely spaced groups of earthquakes and underground nuclear explosions at many different locations around the world show a characteristic difference: explosions have relatively larger P/S amplitude values. High-frequency P/S appears to work everywhere.**

As shown in Figure 5, we applied MDAC to correct for path effects for earthquakes all around the Korean Peninsula, Yellow Sea and Northeastern China region recorded at stations MDJ and TJN, which are publicly available through data centers such as the Incorporated Research Institutions for Seismology (IRIS) and the Ocean Hemisphere Project Data Management Center (OHPDMC). While the North Korean test is easily discriminated at both stations at high frequencies such 6-8 Hz, the two stations show slightly different frequency behavior, with MDJ discriminating well at all frequencies above 2 Hz, while TJN appears to keep improving as the frequency increases all the way to 8 Hz. We are analyzing the frequency dependence of the P/S ratios for a variety of regions in order to better quantify the effect.

A remarkable feature of the high frequency P/S ratios for discriminating underground nuclear tests is that they seem to work even in cases where the long period signals indicate that the explosions are complex. A case in point is the May 11, 1998 Indian test shown in Figure 4. That test shows significant Love waves and reversed Rayleigh waves (Walter et al, unpublished data, Selby et al., unpublished data) indicating a large amount of tectonic release and significant non-isotropic components of the moment tensor source. Despite the complexities in the source the S-waves disappear at frequencies of 1 Hz and higher and the test easily discriminates from nearby earthquakes as shown in Figure 4 and by Rogers and Walter (2002). In fact it looks very similar to the North Korean case, which as we show in the next section has almost no tectonic release. These two characteristics:
1) S-waves from explosions are strong at lower frequencies and diminish at frequencies greater than about 2–4 Hz,
2) S-waves from explosions at higher frequencies are independent of tectonic release and long-period character,

are important constraints on any model that tries to explain how nuclear tests generate S-waves.
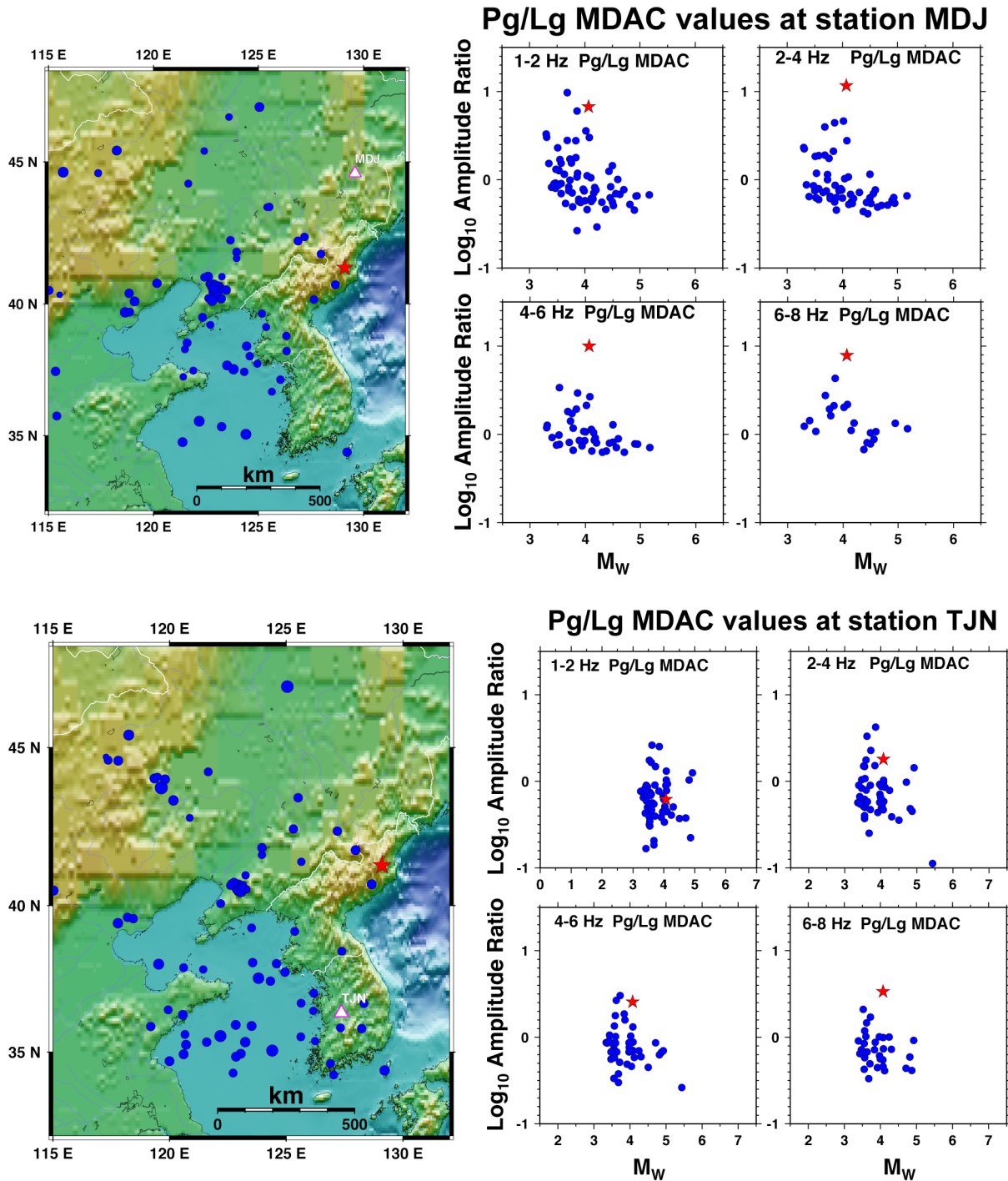


Figure 5. The maps show the earthquakes (blue circles) and the October 9, 2006, North Korean nuclear test (red star) observed at seismic stations MDJ and TJN. The scatter plots show the MDAC path corrected P/S ratios in four different frequency bands. For station MDJ discrimination improves as you move from 1–2 to 2–4 Hz but seems more or less constant at higher frequencies. In contrast for TJN the P/S discriminant seems to continue to improve as frequency increases up to 6-8 Hz.

In Figure 6 we show long-period waveform fits of the North Korean nuclear test compared with a nearby earthquake. This test shows little tectonic release and appears reasonably well fit at long-periods by a purely isotropic moment tensor.
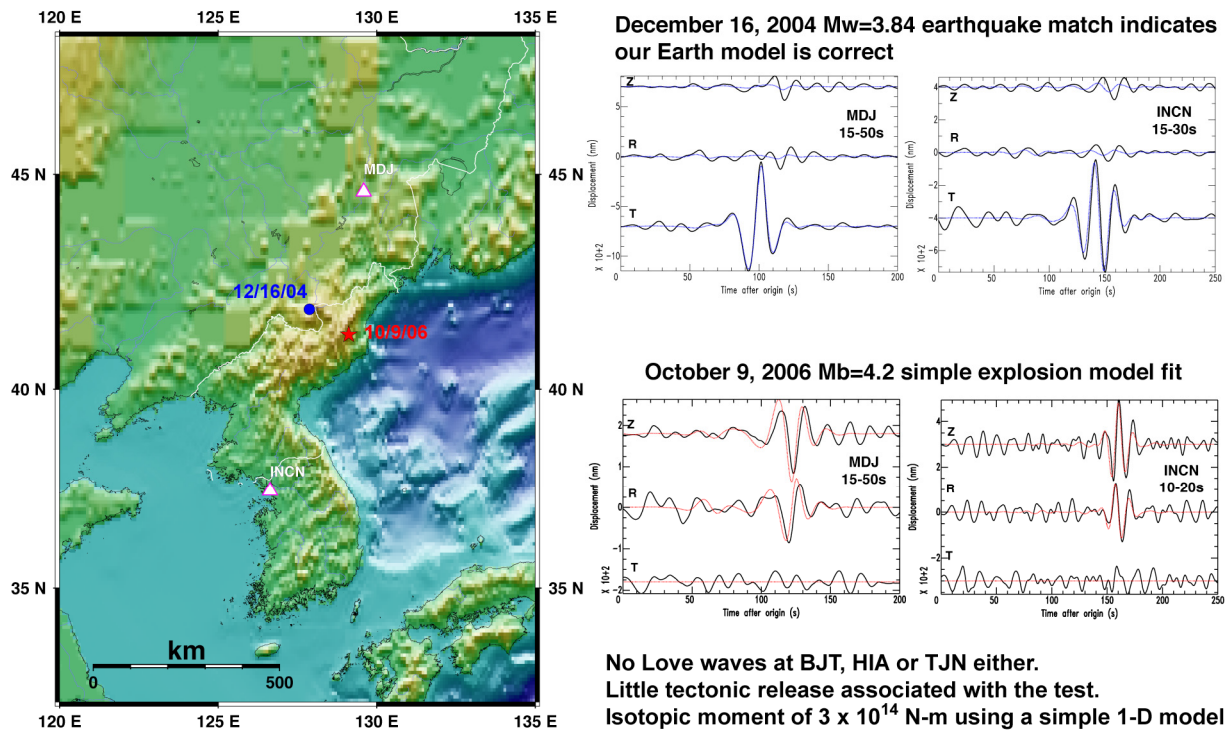


**Figure 6. Long-period waveform modeling for point source moment tensor parameters of the October 9, 2006, North Korean nuclear test and a nearby earthquake on December 16, 2004. Top plots show good waveform fits mainly to Love waves for the earthquake, which indicates we have a good earth model for synthetic seismogram generation. The bottom plots show that a pure isotropic explosion source provides a very good fit for the mainly Rayleigh waves observed for the nuclear test. The long-period waveforms are fit by a simple explosion without Love waves indicating minimal tectonic release.**

## Explosion S-waves Models

While there are long-standing explosion P-wave models that have been used for many years, there is still no widely accepted model to predict S-waves from nuclear tests. Here we show two different ideas about how S-waves are generated from nuclear explosions and in each case we are able to match some S-wave observations from the North Korean declared nuclear test of October 9, 2006.

We show in Figure 7 some very preliminary comparisons of parametric models with source spectra inferred from path corrected observations at station TJN. On the left we compare the Mueller-Murphy (1971) granite P-wave model with inferred P source observations. Note that we can have a variety of models with the same spectral level at low frequencies (< 2 Hz) depending upon depth and source size. As of this writing the North Koreans have not announced any information on yield and emplacement conditions. For this particular station subject to the assumptions (e.g., path correction is right, radiation is isotropic, Mueller-Murphy granite model is applicable, etc.), we are able to match the P waves reasonably well using the 100-m depth model, however the long period level is a bit high compared to the waveform modeling moment.
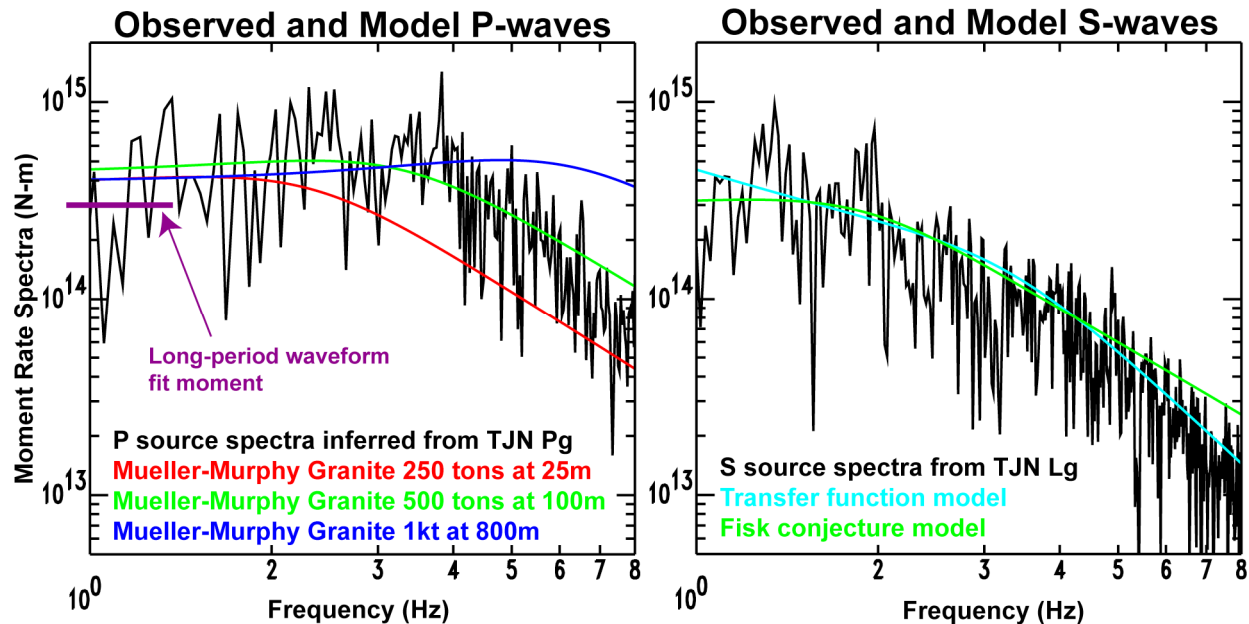
**Figure 7. We infer P- and S-wave source spectra from observed station TJN Pg and Lg spectra after correcting for path effects. On the left we compare the P-wave spectra with Mueller-Murphy granite models for yields from 250 to 1000 tons and depths from 25 m to 800 m. On the right we compare two models for S-waves with data. See text for discussion.**

The S-wave case is shown on the right hand side of Figure 7. We follow the Walter et al. (1994) idea that the S-waves come mainly from conversion and can be matched by modifying the P-spectra, using a P to S transfer function. Here we simply assume a transfer function of similar form to that shown in Figure 6 of Walter et al. (1994) is applicable, that is strong conversion near 1 Hz and weaker conversion at higher frequencies. We used a simple linear relationship in log-amplitude versus log-frequency space, which decays about a factor of ten in amplitude from 1 Hz to 10 Hz. Multiplying by the assumed P-wave source model, in this case the Mueller-Murphy granite function for 500 tons at 100 meters depth, we get the light blue line shown in Figure 7. The result is a reasonable match to the observed data. This simply illustrates it is possible to predict explosion S-waves using simple parametric P-wave models and transfer functions, but it is not the only way to do so.

For comparison we can also apply the Fisk (2006) conjecture that the S-waves are matched by lowering the Mueller-Murphy corner frequency by the ratio of the P to S wave velocity. The implication of this model is that S-waves are generated close to the source and are tied to the elastic radius similarly to P-waves. The Fisk (2006) conjecture does not specify the absolute level so here we scaled it to match the data as shown in green in Figure 7. This is also a reasonably good match to the observed data. Within this frequency band and allowing arbitrary absolute scaling, both models are similar. However at higher and lower frequencies (or much larger or smaller, or much deeper explosions) there are significant differences between these two models. In particular the Fisk (2006) conjecture would say that P/S discrimination at these same frequencies (e.g., 4-8 Hz) would not work well for much smaller (or much deeper) explosions. Fisk (2006) states the frequency band must be above the S-wave corner for discrimination to be effective.

**Future Work**

To better address differences in predictions between the various models of S-wave generation we need to study events with very different source size, depth and emplacement conditions. For nuclear tests the few very overburied events offer a chance to examine effects that might be related to corner frequency effects. Similarly chemical explosions, to the extent they are similar to nuclear explosions offer a much wider range of source conditions. We are using both of these types of data to test and develop better understanding and better models for predicting nuclear explosion S-waves.

To better address practical explosion identification we are improving our MDAC source and path corrections and looking at optimal combinations of normalized regional amplitude measurements. For example given that there is often discrimination power in all of the frequency bands where P/S is observed, we are testing and quantifying the improvement provided by using multiband P/S ratios to discriminate explosions from earthquakes.

## CONCLUSIONS AND RECOMMENDATIONS

Regional discrimination algorithms require calibration at each seismic station to be used for nuclear explosion monitoring. We apply a magnitude and distance amplitude correction (MDAC) procedure to remove source size and path effects from regional body-wave phases. This allows the comparison of any new regional events recorded at a calibrated station with all available reference data and models. This also facilitates the combination of individual measures at multiple stations to form multivariate discriminants that can significantly improve performance over single station individual measures. We are working to quantify the performance of P/S ratio discriminants as a function of frequency and number of stations. We are using the Arizona Source Phenomenology Experiment (AZSPE) data to explore the use of industrial chemical explosions to help calibrate regional discriminants in areas where nuclear explosion data is not available.

## ACKNOWLEDGEMENTS

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