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14. ABSTRACT

The most successful teleseismic discriminant is *Ms:mb*, and many studies are underway to try and extend surface wave magnitude (*Ms*) estimation to regional distances. A problem that is encountered at regional distances and small magnitudes is how to estimate *mb* so that the *Ms:mb* discriminant is meaningful and consistent with teleseismic measures.

Over the past several years, a regional *S*-coda wave methodology has been developed that provides for the lowest variance estimate of the seismic source spectrum. Thus, regional *MW* and *mb* estimates derived from *Sn* and *Lg* coda are very stable, even when only a single station is used. However, these *mb*'s are inherently biased for earthquakes because they are an *S*-based measurement, and explosions are relatively depleted in *S*-waves. Previous research projects have used region-specific *mb* scales based on direct measurements of *Pn* and *Pg* to improve the *Ms:mb* discrimination, even though the *mb* estimates often had a large variance.

The next obvious step to be implemented in the coda wave methodology is the use of *P* coda for *mb* estimates. This study focuses on developing a regional *P*-coda methodology to earthquakes and explosions on or near the Nevada, Shagan, Lop Nor, and Novaya Zemlya (NZ) test sites. We will use the *P*-coda spectra to derive estimates of *mb* and yield. The new *mb* estimates will then be compared with regional *Ms* measurements to examine possible discrimination improvements. As this project is new, we have only preliminary results using far-regional and teleseismic *P*-coda using Atomic Weapons Establishment (AWE) Blacknest data for NZ explosions and near-regional results for Nevada Test Site (NTS) explosions. Our goal will be to test whether *P*-coda magnitudes scale with the teleseismic *mb* for both earthquakes and explosions. Second, we want to know if these *P*-coda magnitudes exhibit less variance than their direct wave counterparts. Paths from NZ to NORSAR are still at regional distance and one might expect the *P*-wave and its coda to be comprised of waves that sample the crust and upper mantle over a range of take-off angles from the source. At teleseismic distances however, we might expect the averaging nature observed for local and regional coda waves to breakdown. At these distances, first arriving *P*-waves are likely emanating from a limited range of take-off angles near the bottom of the focal sphere. To investigate this, we processed roughly 30 NZ explosions recorded at the U.K. arrays, Eskdalmuir in Scotland (EKA) and Yellowknife in Canada (YKA) located at ~30 and 44 degrees from NZ, respectively.

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REGIONAL *P*-CODA FOR STABLE ESTIMATES OF BODY WAVE MAGNITUDE: EXTENDING THE M_S:m_b DISCRIMINANT TO SMALLER EVENTS

Kevin Mayeda, Jessie Bonner, and Heather Hooper

Weston Geophysical Corporation

Sponsored by Air Force Research Laboratory

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ABSTRACT

The most successful teleseismic discriminant is M_s:m_b, and many studies are underway to try and extend surface wave magnitude (M_s) estimation to regional distances. A problem that is encountered at regional distances and small magnitudes is how to estimate m_b so that the M_s:m_b discriminant is meaningful and consistent with teleseismic measures.

Over the past several years, a regional *S*-coda wave methodology has been developed that provides for the lowest variance estimate of the seismic source spectrum. Thus, regional M_W and m_b estimates derived from *Sn* and *Lg* coda are very stable, even when only a single station is used. However, these m_b's are inherently biased for earthquakes because they are an *S*-based measurement, and explosions are relatively depleted in *S*-waves. Previous research projects have used region-specific m_b scales based on direct measurements of *Pn* and *Pg* to improve the M_s:m_b discrimination, even though the m_b estimates often had a large variance.

The next obvious step to be implemented in the coda wave methodology is the use of *P* coda for m_b estimates. This study focuses on developing a regional *P*-coda methodology to earthquakes and explosions on or near the Nevada, Shagan, Lop Nor, and Novaya Zemlya (NZ) test sites. We will use the *P*-coda spectra to derive estimates of m_b and yield. The new m_b estimates will then be compared with regional M_s measurements to examine possible discrimination improvements. As this project is new, we have only preliminary results using far-regional and teleseismic *P*-coda using Atomic Weapons Establishment (AWE) Blacknest data for NZ explosions and near-regional results for Nevada Test Site (NTS) explosions. Our goal will be to test whether *P*-coda magnitudes scale with the teleseismic m_b for both earthquakes and explosions. Second, we want to know if these *P*-coda magnitudes exhibit less variance than their direct wave counterparts. Paths from NZ to NORSAR are still at regional distance and one might expect the *P*-wave and its coda to be comprised of waves that sample the crust and upper mantle over a range of take-off angles from the source. At teleseismic distances however, we might expect the averaging nature observed for local and regional coda waves to breakdown. At these distances, first arriving *P*-waves are likely emanating from a limited range of take-off angles near the bottom of the focal sphere. To investigate this, we processed roughly 30 NZ explosions recorded at the U.K. arrays, Eskdalmuir in Scotland (EKA) and Yellowknife in Canada (YKA) located at ~30 and 44 degrees from NZ, respectively.

OBJECTIVES

Our research will determine whether *P*-coda can be used to estimate stable m_b estimates. Our objectives include:

- Developing a new technique for estimating *P*-coda-based m_b's at regional and near-teleseismic distances for sparse networks or at a single station,
- Improving M_S:m_b discrimination at lower magnitudes based on combining new *P*-coda-based m_b's with the current regional, variable period M_s estimation technology, and
- Providing an estimate of yield from *P*-coda-derived spectra that can complement similar estimates based on *Lg* and *Sn* coda.

We are in the preliminary phases of this project and are currently examining the characteristics of *P-coda* for the NTS. The preliminary results are presented in the following paragraphs.

RESEARCH ACCOMPLISHED

Background

For sparse local and regional seismic networks, a stable method of determining magnitude is necessary for the development of discriminants, yield estimation, and detection threshold curves. Over the past several years, the Department of Energy (DOE) labs have developed a regional coda wave methodology that obtains the lowest variance estimate of the seismic source spectrum (Mayeda et al., 2003; Phillips et al., 2003; Mayeda et al., 2005). Unlike traditional magnitudes such as M_L and m_b, which are relative, narrowband measurements that often have regional biases, the coda methodology provides stable, absolute source spectra that are corrected for *S*-to-coda transfer function, scattering, inelastic attenuation, and site effects. The spectra have been used to calculate stable moment estimates (M_w), short-period magnitudes (m_b, M_L), explosion yields, and radiated seismic energy, E_R (Mayeda and Walter, 1996) from as few as one station. The coda-derived spectra are calibrated for the particular region of interest and are in turn used as input into the Magnitude and Distance Amplitude Correction (MDAC) discrimination procedure outlined by Walter and Taylor (2002).

In addition to MDAC's regional high frequency discriminants, the traditional teleseismic discriminant, M_S:m_b, is currently being extended to smaller events at regional distances. For example, detailed global group velocity measurements are being used to develop models for Rayleigh waves (Pasyanos et al., 2003; Stevens et al., 2001; Ritzwoller et al., 2002; Levshin et al., 2002) that aid in the development of phase-match filters. These models are now being extended to periods as short as 7 s. New surface wave magnitude formulas (Russell, 2006) and measurement techniques [M_s Variable-Period, Maximum Magnitude Estimation (VMAX)] by Bonner et al., 2006) are being developed that allow estimates at these shorter periods that are unbiased with respect to teleseismic M_s estimates. The problem that we are experiencing at the lower magnitudes ($m_b < 4$) is the lack of unbiased body wave magnitudes for discrimination purposes.

For small-to-intermediate sized events, we have found that the discriminant performance decreases because of variance in the m_b magnitudes. Figure 1 shows the difference in performance between United States Geological Survey (USGS) and International Data Center (IDC) magnitudes for earthquakes near the Lop Nor test site. The event screening lines are based on research by Murphy et al. (1997). Events above the line are assumed to be earthquakes, thus more would be screened using the IDC magnitudes than the USGS magnitudes. Rather than argue which m_b estimate is most correct, our objective is to find a more stable estimate of m_b using regional and near-teleseismic *P*-coda-wave data.

We could use *Lg* and *Sn* coda-derived m_b estimates; however, this *may actually hinder* the M_S:m_b discrimination performance. Though m_b derived from regional *Lg* (e.g., Nuttli, 1973; Patton, 2001) and *Lg* coda (e.g., Mayeda, 1993) have been calibrated for certain regions, both are *S*-based measures, and thus will be biased with respect to earthquakes. Figure 2 shows m_b(*Lg* coda) from Mayeda (1993) for NTS explosions. The same path and site corrections applied to earthquakes in the region would result in almost an order of magnitude bias. This bias is also observed for direct *Lg*. For example, the Little Skull Mountain earthquake at NTS had an M_w of 5.5, but would have an m_b(*Lg*) of ~6.5, whereas the National Earthquake Information Center (NEIC) and International Seismological Center (ISC) m_b's for this event are 5.3. Likewise, if we calibrate m_b(*Lg*) to teleseismic estimates of m_b for

earthquakes, we will underestimate the m_b's for explosions. The use of *S*-based m_b's in the traditional M_S:m_b discriminant significantly degrades the discriminant's performance, since it tends to move the explosion and earthquake populations closer together.

Regional m_b's have been calculated based on the *P*-based phases, such as *Pn* (e.g., Denny et al., 1987) and Pg (e.g., Tibuleac et al., 2001). However, Mayeda (1993) has shown that these regional measures have significant scatter associated with them, and thus significant numbers of recordings would be required to reduce the variance.

The questions that we are addressing through this research project include the following: Can we reduce the variance in regional m_b estimates using a sparse-station *P*-coda methodology, as opposed to using multitudes of direct *Pn* and *Pg* measurements, how will the stability of these m_b(*P*-coda) estimates compare to the highly successful and stable (but unfortunately biased) methods involving *Lg* and *Sn* coda, how many stations will be needed, and will the use of m_b(*P*-coda) improve M_S:m_b discrimination at regional distances?

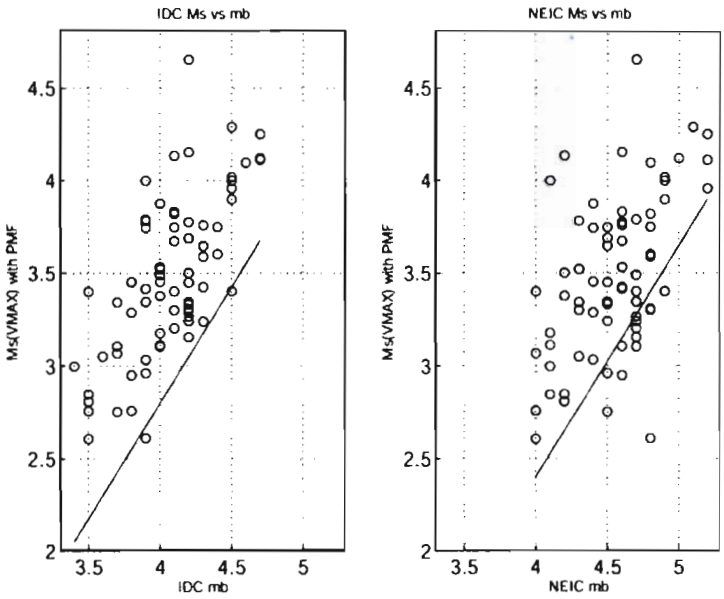

Figure 1. Comparison of event screening using M_s(VMAX):m_b(*P*) for small-to-intermediate sized events in Asia. (Left) IDC m_b. (Right) USGS NEIC m_b. The dashed line is the Murphy et al. (1997) criterion for event screening, which is $M_s = 1.25 * m_b$ (USGS)–2.6 and $M_s = 1.25 * m_b$ (IDC)–2.2.

Coda Window Length

Mayeda et al. (2003) showed that the variance of coda envelope measurements reached a constant value for *Lg* coda after a certain length of measurement window. Figure 3 shows the interstation variance plotted as a function of coda window length. This figure shows that any length of coda is preferable over measuring the direct phase. We plan to systematically test the regional and near-teleseismic *P*-wave coda's dependence on window length. Examples of the *P*-coda window lengths for NTS nuclear explosions recorded on the Livermore Network are shown in Figure 4. These windows show that approximately 20–30 s of coda can be used for magnitude estimates at these near-regional distances. Based on the results in Mayeda et al. (2003), using *P*-coda could reduce the interstation standard deviations in regional m_bs by between 20% and 50% depending upon the frequency band under consideration. We note that these percentages are based on *Lg* data, and may differ for P-coda.

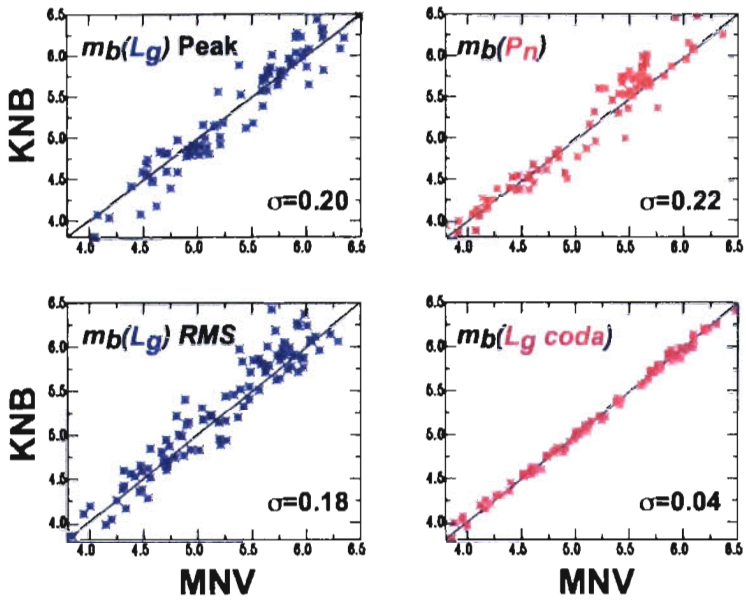

Figure 2. A comparison of four different m_b estimation techniques for NTS explosions recorded at MNV and KNB. The interstation standard deviation is roughly five times smaller for the m_b(Lg coda) than for the $m_b(Pn)$ and $m_b(Lg)$ methods.

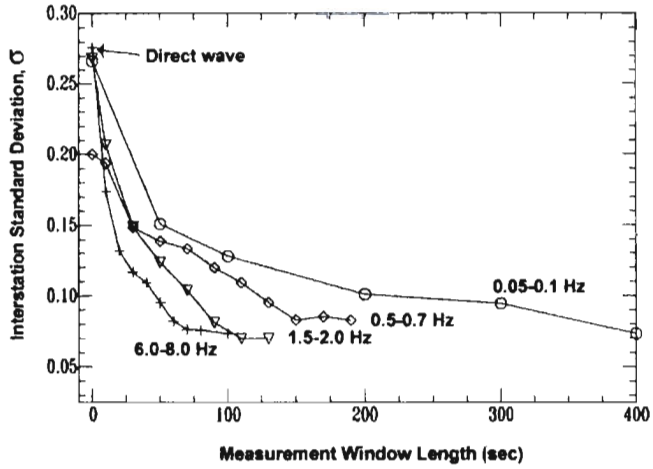

Figure 3. Interstation standard deviation, σ, is shown for a range of frequencies as a function of coda measurement window length using Gulf of Aqaba earthquakes. For longer periods, the critical window length, where further reduction in scatter is minimal, becomes larger, ranging from about 60 s at 6.0–8.0 Hz to about 200 s for 0.05–0.1 Hz.

What Composes *P*-Coda?

It is important to ensure that the *P*-wave coda is actually composed of coherent scattered *P*-wave energy and not direct arrivals or random scattered arrivals. Morozov and Smithson (2000) show that near-teleseismic coda phases can be explained by the excitation of short-period scattered waves within the crust by the waves incident from the mantle. Wagner (1997) found that the *P*-coda is a continuous succession of coherent, forward scattered/multipathed arrivals, not just the occasional deterministic regional phase immersed in "randomly" scattered coda. The number of coherent arrivals in the *P*-coda shown in Figure 5 is more than what would be expected from crustal multiples like *PmP*. Stacked coda envelopes from a Nevada earthquake (Figure 6) recorded on the Seismic Array in Mina, Nevada (NVAR) show that the *P*-coda has different characteristics (e.g., slopes) than the *Lg* coda, although both show little interstation scatter.

Characteristics of NTS *P*-Coda

We are processing over 240 nuclear tests from NTS using regional stations from the Lawrence Livermore National Laboratory (LLNL) digital seismic network along with far-regional and near-teleseismic stations (e.g., TUC, CMB, PAS, PDAR, TXAR). For NTS, we are in the process of examining the characteristics of the near-regional coda by deriving empirical envelope functions for selected regional and near-teleseismic stations. For this analysis, we have considered 5 narrow bands ranging between 0.5 and 3.0 Hz (e.g., 0.5 to 0.7, 0.7 to 1, 1 to 1.5, 1.5 to 2, and 2–3 Hz). Examples of the envelopes between 2 and 3 Hz are shown in Figure 7. We note that for this station (ELK) at approximately 400 km from most of the NTS explosions, the appropriate coda window starting time would be after *Pg*.

We are also compiling the characteristics of the *P*-coda spectra for NTS earthquakes and explosions (Walter et al., 2003). Corner frequency effects must be considered in our analysis, as must any possible differences in site response between stations. Since our proposed methodology will be to normalize each *P*-coda-derived source spectra to an absolute scale, site and path effects will be eliminated. In Figure 8, which shows coda spectra formed at ELK and MNV for Yucca Flat explosions, the corner frequency decreases as a function of increasing event size. We note however that the emplacement conditions also change with event size, since bigger events are shot at deeper depths where velocity and density are higher and gas-filled porosity is lower. As we continue this research, we plan to determine interstation magnitude scatter as a function of frequency band in order to find the optimal band for measuring m_b from *P*-coda spectra.

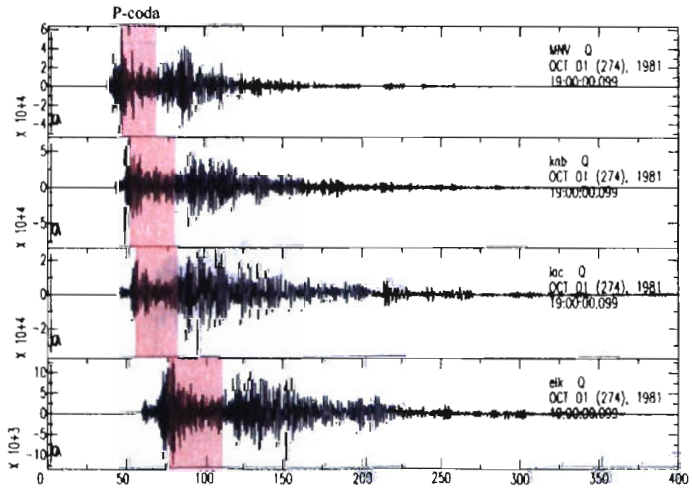

Figure 4. Plot showing regional *P*-coda windows for near-regional recordings of an NTS nuclear explosion.

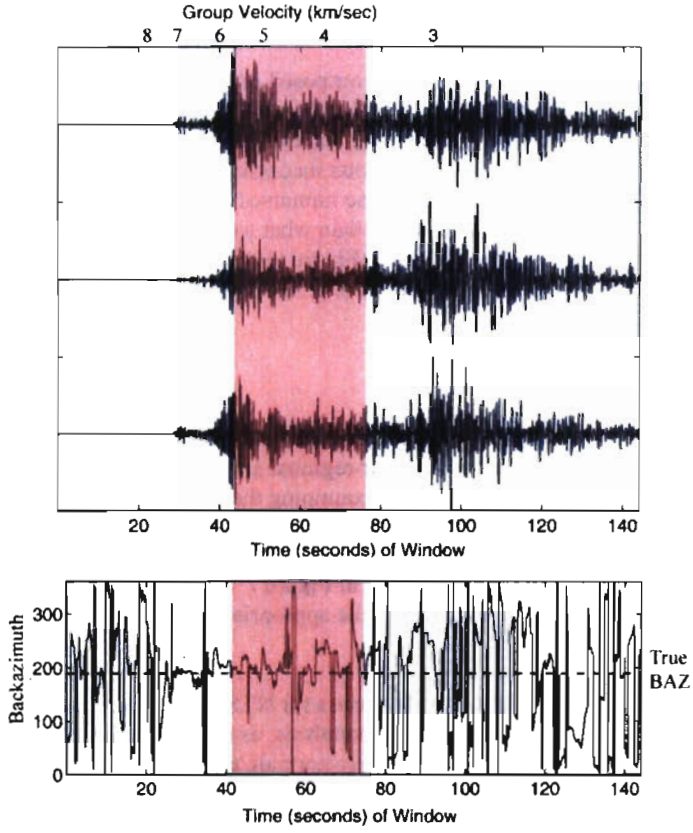

Figure 5. (Top) Seismic waveforms from an NTS nuclear explosion recorded at the ELK 3C station. (Bottom) A bearing-time recording for the three-component seismograms shows that the *P*-coda is not made up of random scattering with a few on-azimuth arrivals (the true back azimuth is the dashed line). Instead, the *P*-coda is composed of a continuous succession of coherent, forward scattered/multipathed arrivals, which will retain some "memory" of the original source strength.

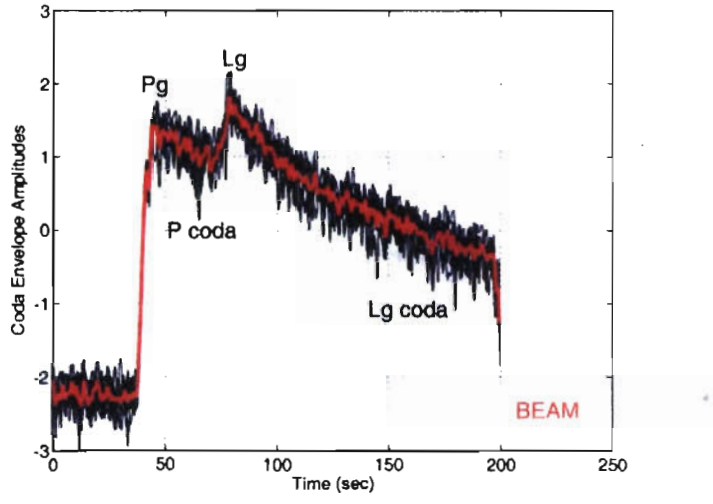

Figure 6. Coda envelopes at NVAR for a southern Nevada earthquake. The individual elements are shown as thin black lines, while the beam is shown as the red line. The results suggest that the *P*- and *Lg* coda are different, but both have small interstation scatter.

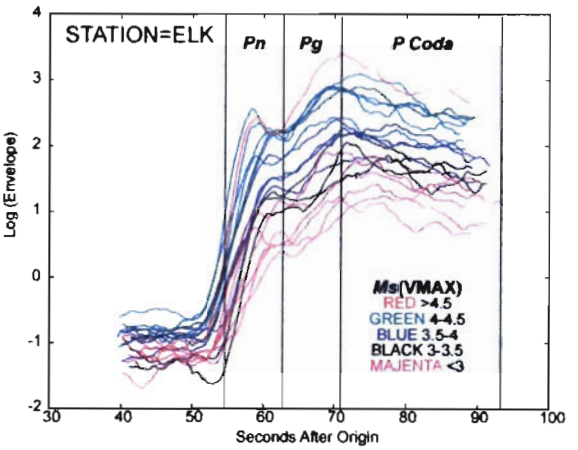

Figure 7. Narrowband envelopes (2–3 Hz) for *Pn*, *Pg*, and *P*-coda for explosions recorded at the Lawrence Livermore Network station ELK (~400 km). The envelopes have been binned based on M_s(VMAX) estimates for each event. We propose to use these coda envelopes to determine m_b.

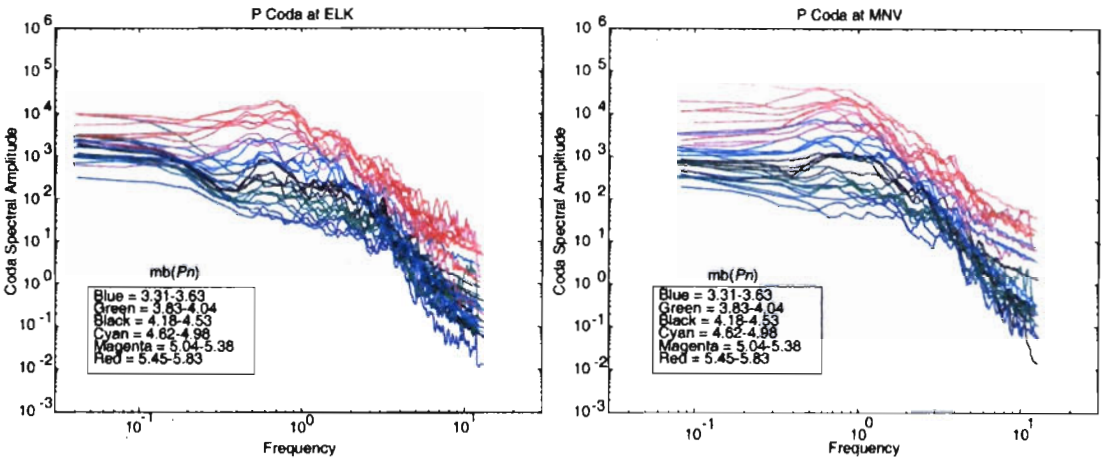

Figure 8. Observed *P*-coda spectra for Yucca Flat explosions at ELK (left) and MNV (right).

Characteristics of Novaya Zemlya *P*-Coda

The following section describes preliminary results using far-regional and teleseismic *P*-coda waveforms from the AWE Blacknest array stations. We specifically wanted to determine whether *P*-coda magnitudes would scale with the teleseismic m_b for both earthquakes and explosions. Second, we wanted to ascertain whether these *P*-coda magnitudes exhibited less variance than their direct wave counterparts. Figure 9 shows array-averaged envelopes (2–3 Hz) for two NZ explosions (m_b~5.8) recorded at NORSAR, at an epicentral distance of roughly 2200 km. Notice that both *P*- and *S*-codas are very similar in character. (Note: Pre-event noise level differences reflect seasonal variations.)

We measured relative *P*-coda envelope amplitudes using the October 24, 1990, NZ explosion as a reference event. By scaling narrowband envelopes between our reference event and the other explosions and earthquakes, we were able to tabulate relative coda amplitudes. Figure 10 shows coda envelope amplitude residuals (y-axis) relative to the maximum likelihood magnitude m_b(ML) for explosions (red squares) and earthquakes (blue triangles) (Lilwall and Marshall, 1986; Marshall et al., 1989; Bowers, 2002). This regression was done using roughly 100 s of *P*-coda in the 2–3 Hz band. These preliminary results are very promising in that earthquake m_b's are also in good agreement with m_b (ML). This is in sharp contrast to results from regional $m_b(Lg)$ and $m_b(Lg$ coda) (e.g., Mayeda, 1993). In those

studies, m_b was tied to explosions at the NTS, however applying the same formulas to earthquakes resulted in an overestimation of ~1 magnitude unit.

Paths from NZ to NORSAR are still at regional distance, and one might expect the *P*-wave and its coda to be comprised of waves that sample the crust and upper mantle over a range of take-off angles from the source. At teleseismic distances however, we might expect the averaging effect observed for local and regional coda waves to break down. At these distances, first arriving *P*-waves are likely emanating from a limited range of take-off angles near the bottom of the focal sphere. To investigate this, we processed roughly 30 NZ explosions recorded at the U.K. arrays Eskdalmuir in Scotland (EKA) and Yellowknife in Canada (YKA) located at ~30 degrees and 44 degrees from NZ, respectively.

Figure 11 shows envelopes at EKA for 4 NZ explosions with roughly the same magnitude that were located within a few kilometers of each other. (Note: The pre-event noise is lower for the October 11, 1982, event because of improvements to the electronics in late 1979.) We see an immediate discrepancy for the September 24, 1979, event. Though it has the largest m_b(ML), it is roughly a factor of 3 smaller in amplitude (0.5 in $\log_{10}$) at EKA relative to the other three events. The direct *P*-wave, coda, and *PcP* phase (not shown) are all small. In fact, the EKA station magnitude for this event is low relative to the global m_b(ML) estimate, as well as the NORSAR and YKA estimates. Careful inspection of the raw data shows nothing unusual. The closest event is the September 27, 1978, event, but this event does not appear to be anomalous. Assuming that this anomalous behavior is real, it suggests a near-source process such as focusing directly beneath the event. Moreover, the scale-length must be small since a nearby event is not affected. This supports the notion that teleseismic *P*-codas will not have the same averaging properties that local and regional codas exhibit.

We also made relative coda envelope measurements for YKA and EKA for three bands (1.0–1.5, 1.5–2.0, and 2.0–3.0 Hz). In all cases we used the explosion envelopes for the August 18, 1983, event as our reference. The left side of Figure 12 shows *P*-coda amplitudes (relative to the reference envelope) for common events at YKA and EKA for all three frequency bands. We see that in general, there is good agreement between the *P*-coda amplitudes at the two stations (interstation scatter is ~0.17), though regional *Lg* coda at NTS has interstation scatter of only ~0.04 (see Figures 2 and 3).

The right side of Figure 12 shows *P*-coda amplitudes plotted against m_b(ML) for the 1.0–1.5 Hz band (again, these are relative amplitudes using the August 18, 1983, event as the reference). The solid line has a slope of 1. We note that 16 events at YKA and 10 events at EKA had clipped *P*-waves, however coda envelope measurements could still be made by measuring a few 10s of seconds past the clipped direct arrival.

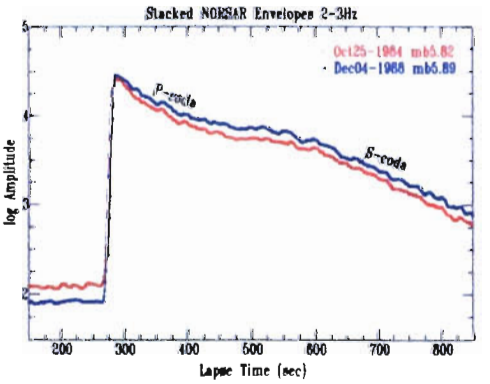

Figure 9. Array-averaged envelopes (2–3 Hz) for two NZ explosions (m_b~5.8) recorded at NORSAR.

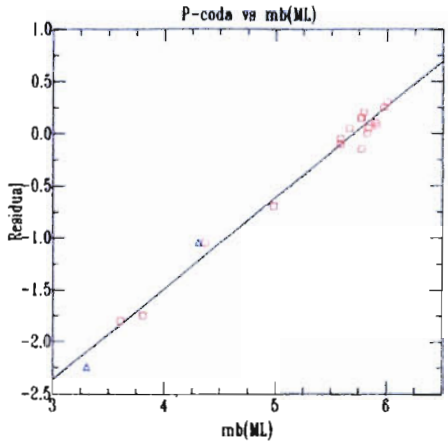

Figure 10. *P*-coda envelope amplitude residuals relative to the maximum likelihood magnitude m_b(ML) for NZ explosions (red squares) and earthquakes (blue triangles) measured at NORSAR.

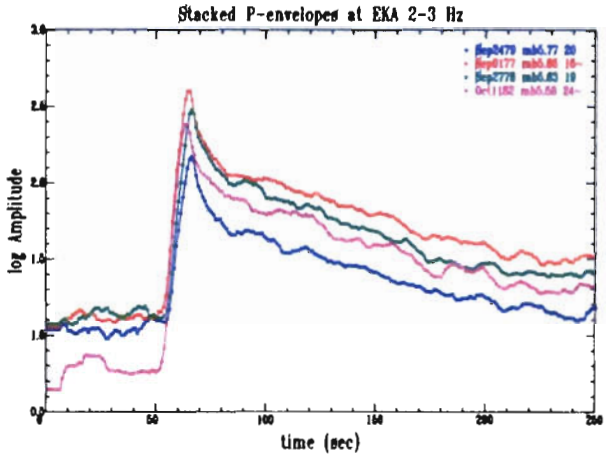

Figure 11. *P*-coda envelopes at EKA for 4 similar-magnitude NZ explosions.

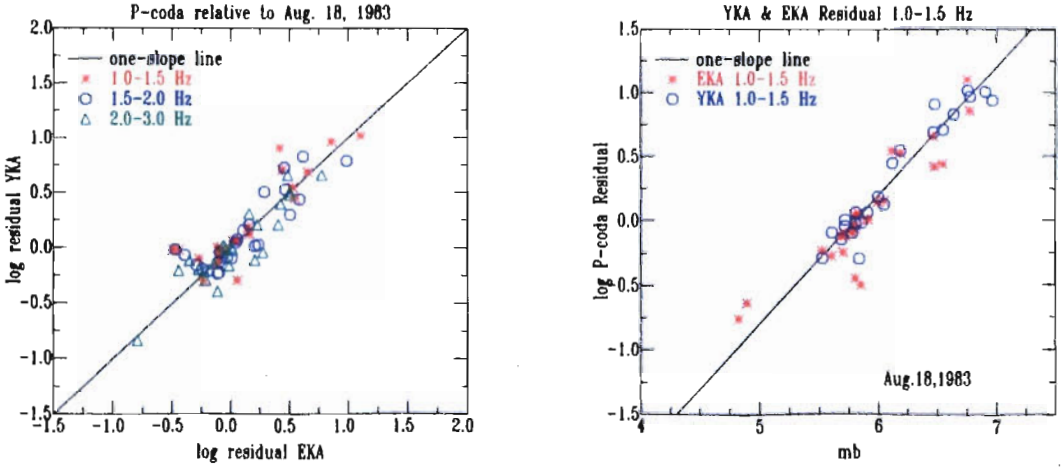

Figure 12. (Left) *P*-coda amplitudes (relative to the reference envelope) for common events at YKA and EKA for three frequency bands. (Right) *P*-coda amplitudes plotted against m_b(ML) for the 1.0–1.5 Hz band.

Our preliminary findings suggest that at regional distances the *P*-coda can be used as a surrogate for teleseismic m_b for both earthquakes and explosions based on the findings at NORSAR for NZ events (e.g., Figure 10). We plan to do a more rigorous test by looking at inter-station scatter and comparing directly with *P*-waves. To accomplish this, we will use NTS explosions and earthquakes recorded at multiple stations at progressively larger distances from NTS (e.g., BKS, YKA, EKA, NORSAR etc.). At teleseismic distances, the *P*-coda appears to share the same radiation pattern as the direct *P*-wave and does not appear to average over the focal sphere, as is observed for local and regional shear waves. Nonetheless, the derived body wave magnitude m_b(*P*-coda) at EKA and YKA for NZ explosions is in good agreement with the globally averaged results using direct teleseismic *P* (e.g., Figure 12). Furthermore, m_b(*P*-coda) can be computed on clipped data, which is quite common for the larger NZ explosions recorded at EKA and YKA.

CONCLUSIONS AND RECOMMENDATIONS

In our preliminary research, we have determined characteristics of *P*-coda, which suggest that we can use it to obtain regional body wave magnitudes with decreased interstation variance. During the next stage of the research, we will measure *P*-coda envelope amplitudes and derive path and site corrections. Since we will be considering events clustered at test sites, the corrections are expected to be minimal; however, for broad areas the corrections will be significant. We will compare interstation scatter of distance-corrected amplitudes as a function of window length. This will provide an empirical measure of error based on window length for each frequency band. For each frequency band, we will regress our coda envelope amplitudes against regional and teleseismic estimates of m_b (e.g., $m_b(Pn)$, $m_b(P)$) to determine which band provides the lowest variance. This will yield slope and intercept values for each frequency band. We will then derive $m_b(Pn)$ and $m_b(P)$ (following Denny et al. 1987) to compare against m_b(*P*-coda) to assess performance at the network and single-station level. Most of the nuclear explosions already have an $m_b(Pn)$ compiled by Vergino and Mensing (1989). Patton (2001) has estimated $m_b(Pn)$ for many historic NTS earthquakes. For recently recorded earthquakes, we will need to estimate $m_b(Pn)$ and $m_b(P)$. Finally, we will compute M_s(VMAX) from the regional stations and form an M_s(VMAX):m_b(Pcoda) discriminant; compare against teleseismic values and trends.

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