CALIBRATION OF THE M_s(VMAX) TECHNIQUE IN EURASIA

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ABSTRACT

We continue to develop and test the Matlab program EVALSURF, which estimates variable-period ($8 < T < 25$ sec) Rayleigh-wave magnitudes using the Russell (2006) and M_s(VMAX) measurement technique (Bonner et al., 2006a) for comparison to the historical formulas of Marshall and Basham (1972) and Rezapour and Pearce (1998). The program uses the updated Lawrence Livermore National Laboratory (LLNL) group velocity models (Pasyanos, 2005) to identify, phase match filter, and extract the fundamental mode Rayleigh waves for analysis. During the past year, we have used EVALSURF to 1) estimate the surface wave magnitudes for the 9 October 2006 North Korean event, 2) examine the effects of large sedimentary basins on surface wave magnitudes, and 3) estimate surface wave magnitudes to periods as great as 40 seconds.

We applied the EVALSURF (Bonner et al., 2006b) technique to the surface waves generated by the reported nuclear explosion detonated in North Korea on 9 October 2006. We feel confident that Rayleigh waves were observed at 12 stations at distance up to 40 degrees. The M_s (VMAX) technique estimates a surface wave magnitude of 2.94 with interstation standard deviation of 0.17 magnitude units (m.u.). We found this estimate to be slightly above the Murphy et al (1997) event screening value (which is M_s=2.90) for an International Data Center (IDC) m_b of 4.1. If the m_b is indeed accurate, this could suggest a convergence of the populations at small magnitudes (Stevens and Day, 1985); however, Bonner et al. (2006a) saw no evidence of the convergence at the Nevada Test Site for events of similar and smaller m_b. We examined the three-component records at each station and found no conclusive evidence that Love waves were generated and recorded.

When Russell (2006) developed the surface wave magnitude formula used in EVALSURF, he used a single attenuation relationship derived from a North American dataset (Herrmann and Mitchell, 1975). Questions arose as to whether this formula would be valid for paths through large sedimentary basins where short-period ($T <20$ sec) attenuation was much higher than the model used to develop the magnitude formula. We have applied EVALSURF to Rayleigh waves recorded at stations just before and immediately after propagating through the thick sediments of the South Caspian Basin. There is less than 0.1 m.u. difference between the M_s(VMAX) estimates before and after the basin. These results do not support large differences in the M_s(VMAX) magnitudes due to propagation through thick basins.

We have also increased the upper limit of periods used in the EVALSURF technique from 25 to 40 sec. The results of a pilot study using the extended period range suggest that the longer-period surface wave analysis improved earthquake screening for deep (>35 km) events. We used the Murphy et al. (1997) criterion and screened 96%, 80%, and 78% of the earthquakes using extended-period EVALSURF, Marshall and Basham, and Rezapour and Pearce formulas, respectively.

OBJECTIVES

Developing a methodology for calculating surface wave magnitudes that is valid at both regional and teleseismic distances, applicable to events of variable sizes and signal-to-noise ratios, calibrated for variable structure and propagation, and easy to automate in an operational setting, is an important monitoring goal. Our objectives are to create such a methodology, and to use it to lower M_s estimation and detection thresholds. We hope that the method will provide a seamless tie between M_s estimation at regional and teleseismic distances.

We continue to develop and test the Matlab program EVALSURF (Bonner et al*.,* 2006b), which estimates variable-period (8 < T < 25 sec) Rayleigh-wave magnitudes using the Russell (2006) and M_s(VMAX) measurement technique (Bonner et al*.,* 2006a) for comparison to the historical formulas of Marshall and Basham (1972) and Rezapour and Pearce (1998). The program uses the updated LLNL group velocity models for Eurasia (Pasyanos, 2005) to identify, phase match filter, and extract the fundamental-mode Rayleigh waves for analysis. During the past year, we have used EVALSURF to 1) estimate the surface wave magnitudes for the 9 October 2006 North Korean event, 2) examine the effects of large sedimentary basins on surface wave magnitudes, and 3) estimate surface wave magnitudes to periods as great as 40 sec.

RESEARCH ACCOMPLISHED

Updates to Group Velocity Models

We have updated LLNL group velocity maps (Pasyanos, 2005) for southern Asia using new data recorded at several stations in the region. Rayleigh-wave dispersion curves (at periods of 10 sec and greater) were generated and included in a new tomographic inversion. The tomographic inversions for southern Asia at T=15 and T=30 seconds are shown in Figure 1. The results highlight the Indian shield region as relatively fast compared to the slower regions associated with the Himalayas and Bay of Bengal.

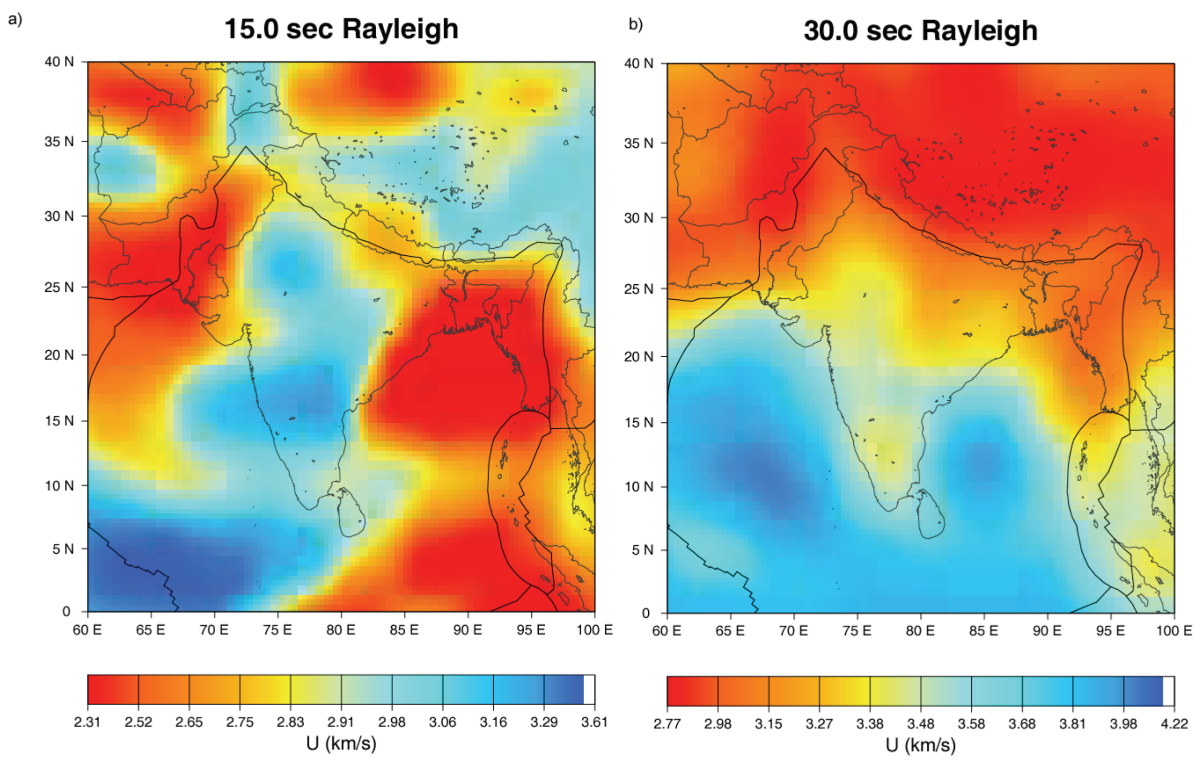

Figure 1. Tomographic inversion of Rayleigh wave group velocity in southern Asia for a) T=15 and b) T=30 seconds.

9 October 2006 North Korean Event

We applied the EVALSURF technique to the short-to-intermediate period surface waves generated by the reported nuclear explosion detonated in North Korea on 9 October 2006.

Data. The Incorporated Research Institutions in Seismology (IRIS) dedicated a data download page to this event. We requested the SEED format data for stations within 40 degrees of the reported epicenter from the dedicated IRIS web page. After we downloaded the data, we converted it to seismic analysis code (SAC) format. We then used the SAC “transfer from evalresp” option to correct for the instrument response and convert to displacement in nanometers. Data from KSRS were obtained from the US National Data Center and were corrected to displacement using the frequency/amplitude/response file. All horizontal components were rotated to the great circle azimuth. Examples of the data for the closest station (MDJ) are shown in Figure 2. At this distance (~370 km), there is a large amplitude Rayleigh wave arrival observed on the radial and vertical components. There was no significant Love wave energy in the surface wave analysis window.

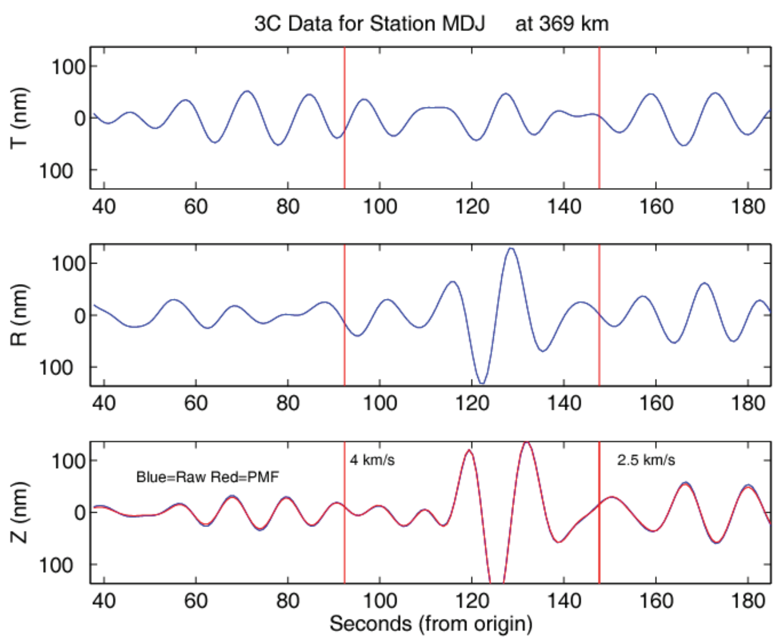

Figure 2. Three component seismograms, rotated to the true back azimuth, from the North Korean event recorded at MDJ. Both the phase match filtering (red) and raw (blue) seismograms are shown in the lower subplot.

***M*$_s$(VMAX) Analysis.** Russell (2006) developed a time-domain method for measuring surface waves with minimum digital processing, using zero-phase Butterworth filters. The method can effectively measure surface-wave magnitudes at both regional and teleseismic distances, at variable periods between 8 and 25 sec.
For applications over typical continental crusts, the magnitude equation is:

$$M_{s(b)} = \log(a_b) + \frac{1}{2}\log(\sin(\Delta)) + 0.0031\left(\frac{20}{T}\right)^{1.8}\Delta - 0.66\log\left(\frac{20}{T}\right) - \log(f_c) - 0.43, \qquad (1)$$

where a_b is the amplitude of the Butterworth-filtered surface waves (zero-to-peak in nanometers) and $f_c \le \frac{0.6}{T\sqrt{\Delta}}$ is the filter frequency of a third-order Butterworth band-pass filter with corner frequencies $1/T-f_c$ and $1/T+f_c$. Examples of the filters for the surface waves at MDJ are shown in Figure 3. At the reference period T=20 seconds, the equation is equivalent to Von Seggern's formula (1977) scaled to Vaněk et al. (1962) at 50 degrees. For periods $8 \le T \le 25$, the equation is corrected to T=20 seconds, accounting for source effects, attenuation, and dispersion.

We refer to this technique as M_s(VMAX) for Variable-period, MAXimum amplitude magnitude estimates. The method has been extensively tested in the western United States and Eurasia (Bonner et al., 2006a). The magnitudes estimated for MDJ are shown in Figure 4 as a function of the evaluation period. Note how the excitation corrections in the Russell (2006) formula work well to flatten the Rayleigh-wave spectra at this particular station. The magnitude at the period of largest amplitude is recorded—in this case 2.77—for further use. EVALSURF also calculates Marshall and Basham (1972) and Rezapour and Pearce (1998) magnitude estimates at each station.

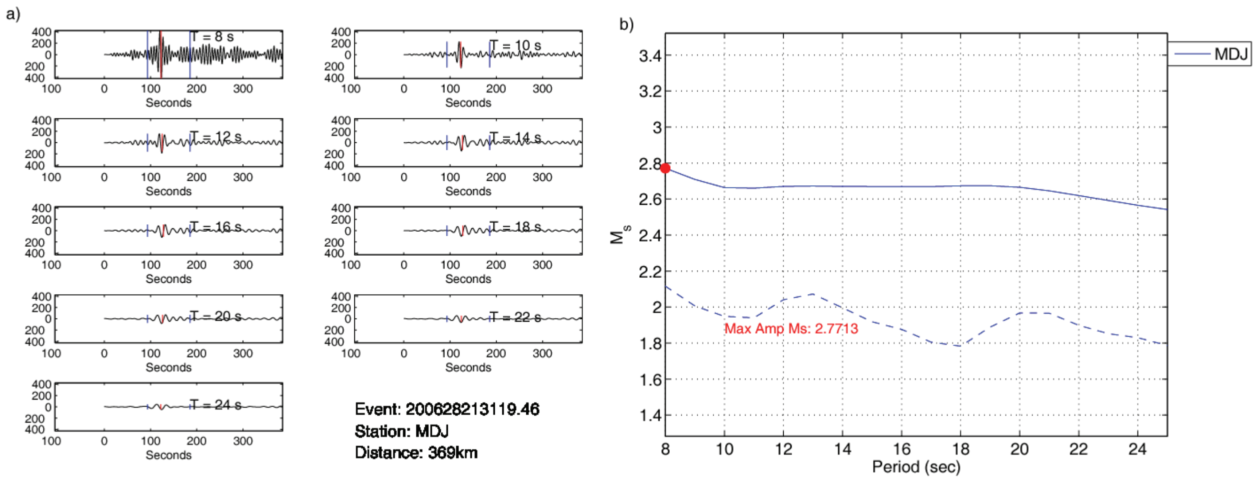

Figure 3. EVALSURF processing of the MDJ seismograms from the North Korean event. a) Narrow-band filtering for the North Korean event recorded at MDJ. b) Magnitude "spectra" estimated using M_s(VMAX) for the MDJ vertical component.

Magnitude Estimates. The results of the EVALSURF analysis for IRIS stations within 40 degrees of the North Korean event are summarized in Table 1 and Figure 4. We feel confident that Rayleigh waves were observed at INCN, ENH, TLY, HIA, BJT, MDJ, ERM, MAJO, and KS31. We also believe we observe longer period (>20 sec) surface waves at MKAR, LSA, and CHTO. We were unable to identify Rayleigh waves at NACB, YULB, YAK, MA2, YSS, and PET; however, we did calculate a noise-based M_s(VMAX) at each of these stations (Figure 4). A few other stations were available from IRIS in the regional distance range; however, there were instrument response problems that could not be resolved.

Table 1. M_s(VMAX) Results for the 09 October 2006 North Korean event.

Station	Distance (deg)	Period	*Ms*(VMAX)
MDJ	3.32	8	2.77
KS31	3.98	10	2.71
INCN	4.28	10	2.85
MAJO	8.53	20	2.82
BJT	9.92	12	3.16
HIA	10.33	8	2.97
ERM	10.53	11	2.93
ENH	19.31	13	3.2
TLY	20.26	15	3.23
LSA	32.76	23	2.91
MKAR	33.67	23	2.81
CHTO	34.14	20	2.89

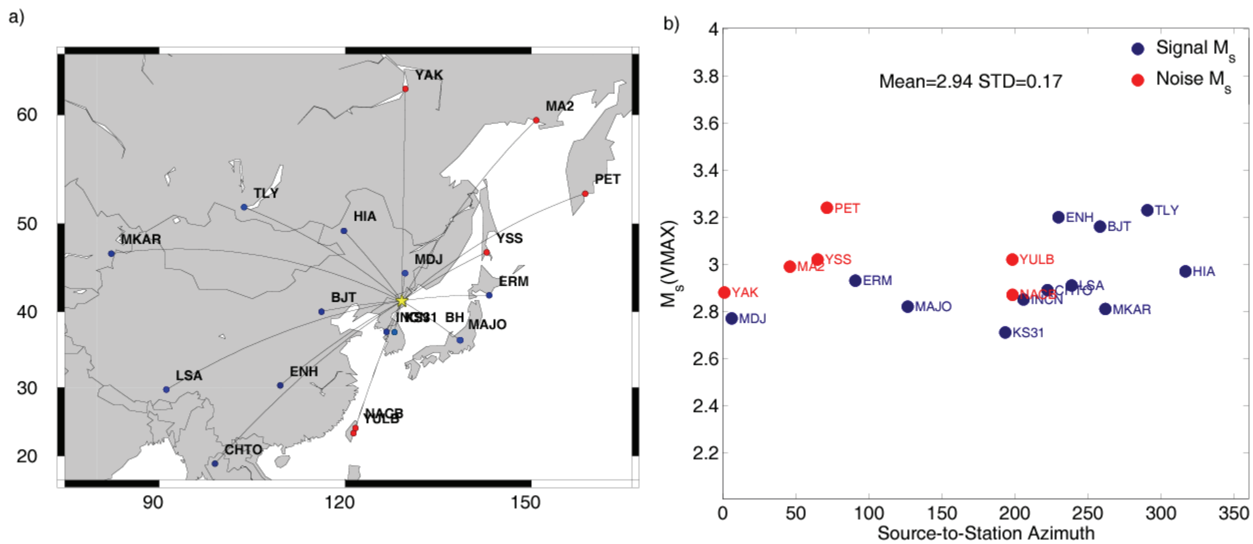

Figure 4. Signal- and noise-based M_s(VMAX) estimates for the 9 October 2006 North Korean event. a) Map of stations showing where noise-based (red circles) and signal-based (blue circles) surface wave magnitudes were estimated. b) Station magnitudes show a network average of 2.94, which considers only signal-based (blue) measurements.

The United States Geological Survey (USGS) and International Data Center (IDC) reported body wave magnitudes (m_b) of 4.2 and 4.1 respectively. The M_s (VMAX) estimates a network surface wave magnitude of 2.94 with interstation standard deviation of 0.17 m.u. We compared these data to our previous research (Figure 5) and found this estimate is slightly above the Murphy et al (1997) event screening value (which is M_s=2.90) for an IDC m_b of 4.1. If the m_b is indeed accurate, this could suggest a convergence of the populations at small magnitudes (Stevens and Day, 1985); however, Bonner et al. (2006a) saw no evidence of the convergence at the Nevada Test Site for events of similar and smaller m_bs. We note that three large magnitude estimates, at stations EHN, BJT, and TLY, are from similar back azimuths and are clearly separated from the other stations' estimates (see Figure 5). Future work must determine whether these larger estimates are due to source processes, un-modeled attenuation effects in Eq. 1, or instrument response problems.

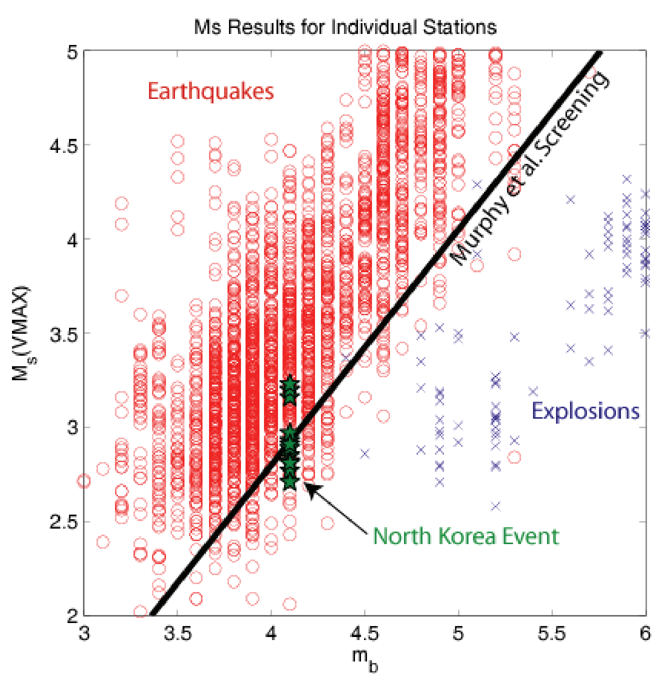

Figure 5. The North Korean event has an average M_s(VMAX) that falls slightly above the Murphy et al. (1997) screening line. The m_bs are from the IDC.

M_s(VMAX) Evaluation in the Caspian Basin

When Russell (2006) developed the surface wave magnitude formula (Eq. 1) used in EVALSURF, he used a single attenuation relationship derived from a North American dataset (Herrmann and Mitchell, 1975). Questions arose as to whether this formula would be valid for paths through large sedimentary basins where short-period (T <20 sec) attenuation was much higher than the model used to develop the magnitude formula. To address this possible problem, we have quantified the M_s(VMAX) performance in a thick sedimentary basin using a dataset recorded in the mid-1990s around the Caspian Sea (Priestley and Mangino, 1995). Two of their stations, KAT and LNK (Figure 6), were on the same great circle paths for several large earthquakes recorded during the deployment. The stations were uniquely positioned on the edges of the South Caspian Basin, which is one of the thickest sedimentary basins on earth with 15–25 km of unconsolidated sediments that overlie 10–15 km of oceanic crust (Neprechnov 1968; Rezanov and Chamo, 1969).

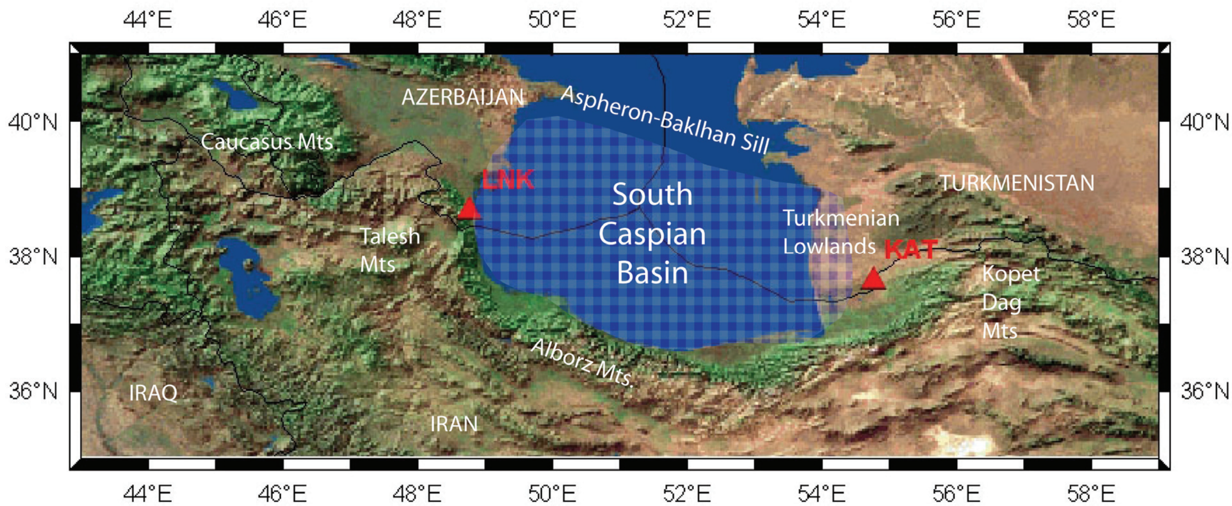

Figure 6. Map showing the South Caspian Basin and the locations of temporary seismic stations LNK and KAT. The checkered region shows where suspected "oceanic" crust underlies the South Caspian Basin based on previous deep seismic sounding data.

Figures 7a and b show vertical component seismograms for two earthquakes whose epicenters lie on the same great circle path as KAT and LNK. The data have been filtered between 0.01 and 0.1 Hz to highlight the surface waves. The pair of seismograms on the left show surface waves propagating from the west to the east from an m_b=5.6 earthquake along the Central Mid-Atlantic Ridge over 8900 km from station LNK. The pair on the right shows surface waves that are traversing from east to west from an m_b=5.6 epicenter in the Java Sea over 7700 km from station KAT. Each subplot has the same amplitude scale and shows data between group velocities of approximately 5 km/sec and 2 km/sec.

We estimated M_s(VMAX) for our dataset of earthquakes recorded at both KAT and LNK along the same great circle path (Figures 7c and d). The difference between the M_s(VMAX) estimates measured before and after propagating through the basin is less than 0.1 magnitude unit (m.u.) for four different earthquakes. For three of four events, the magnitude estimated for surface waves exiting the basin are ~0.1 m.u. smaller than the before-basin magnitude.

These results do not support large differences in the M_s(VMAX) magnitudes due to propagation through this basin. The observed differences of < 0.1 m.u. are smaller than the typical standard deviation from a network analysis, which is generally >0.2 m.u. (Bonner et al., 2006b). Note that the differences in the magnitudes for the two stations do not increase significantly at shorter-periods in the analysis. The small differences in the magnitudes are significant because the Q model in this basin (Priestley et al., 2001) is very different from the period-dependent Q models (Herrmann and Mitchell, 1975) used to develop the Russell (2006) equation.

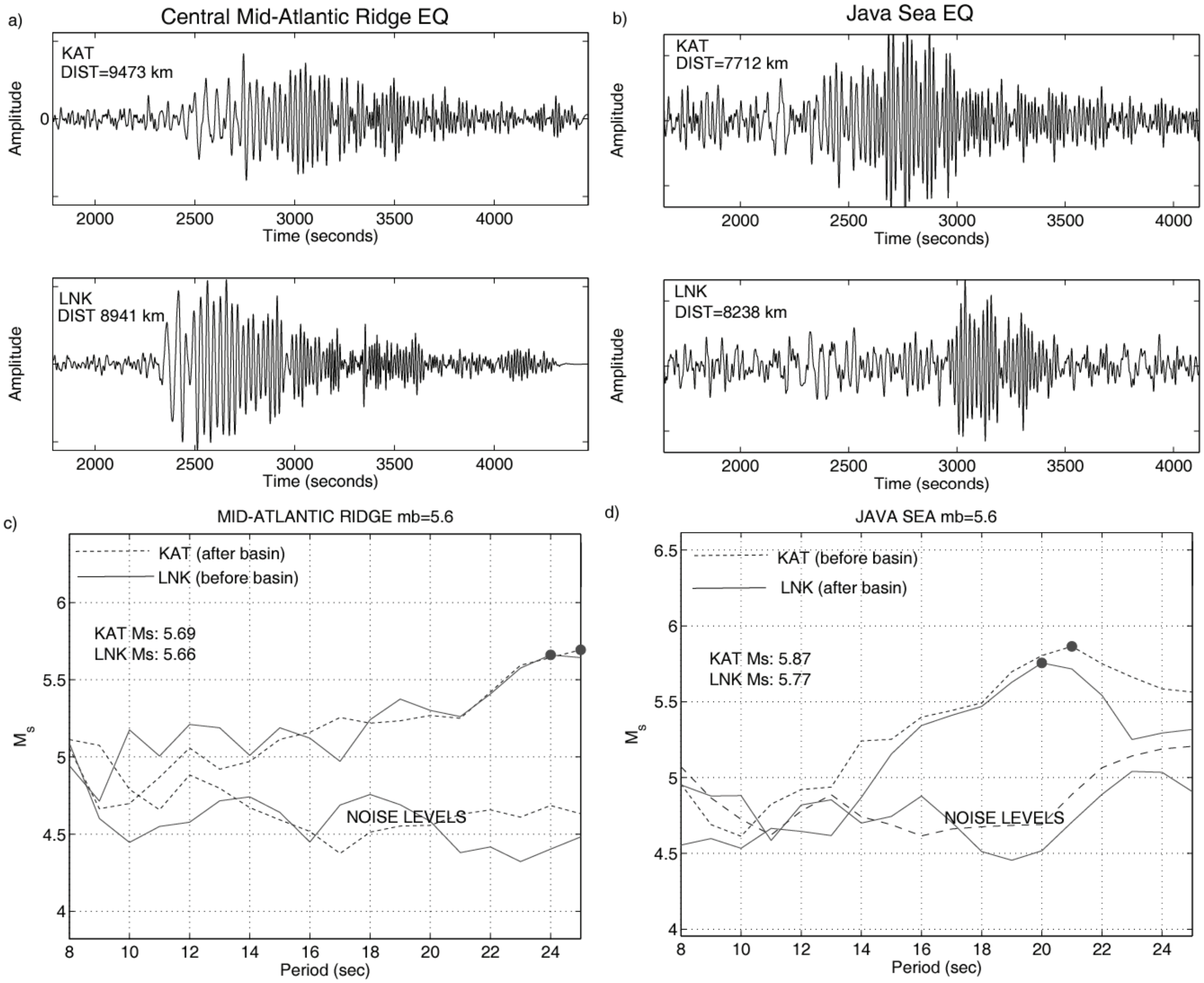

Figure 7. Examples of earthquakes recorded at stations KAT and LNK before and after propagating through the South Caspian Basin for events along the Mid-Atlantic Ridge (a) and Java Sea (b). The data have been filtered between 0.01 and 0.1 Hz to highlight the fundamental-mode Rayleigh waves. M_s(VMAX) "spectra" for the Mid-Atlantic Ridge (c) and Java Sea (d) earthquakes as recorded at KAT and LNK. The magnitudes estimated using the maximum amplitude surface waves before and after traversing the South Caspian Basin agree within 0.1 m.u. despite the anomalously thick sedimentary section in the basin.

Extending M_s(VMAX) to 40 Seconds Period

We observed an edge effect associated with ending the surface-wave magnitude analysis at 25 sec (Bonner et al., 2006a). There are two explanations for this behavior. The Rayleigh wave spectral shape from earthquakes tends to favor longer periods when the events are deeper than the crust. In addition, we expect to observe a general trend of longer period measurements with increasing distances due to the nature of surface wave propagation. This trend is related to the rapid attenuation of shorter-period amplitudes compared to the longer periods at larger epicentral distances.

We are currently working to calibrate the Russell (2006) formula and M_s(VMAX) technique to periods up to 40 sec in order to determine whether the variance can be further reduced and event screening improved. To complete this task, we have determined that the terms in Eq. 1 are valid up to 40 sec including the source excitation dependence on period (-0.66 log (20/T)). To examine the performance at these periods, we compiled a dataset of surface wave recordings from events with a wide range of focal depths. Figure 8 shows our pilot study dataset, which so far includes 26 earthquakes in a small region of the Philippine subduction zone with depths ranging from 10 to 155 km as recorded on seven far-regional to near-teleseismic stations. Data from these stations and events were obtained from IRIS, corrected for the instrument response, converted to displacement in nm, and analyzed with EVALSURF extended to 40 seconds period.

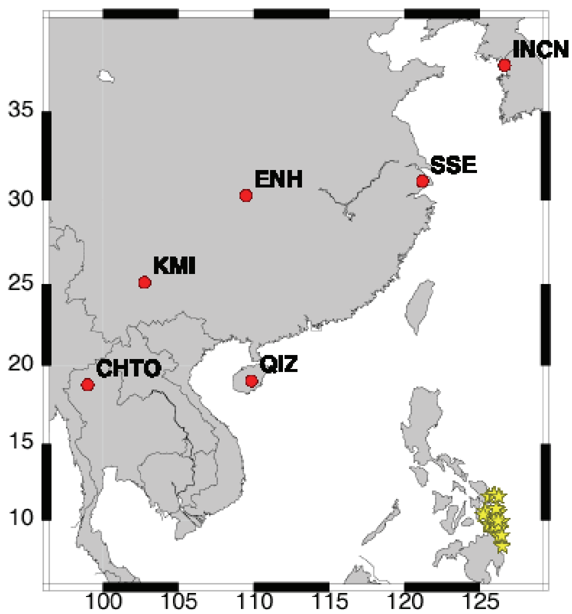

Figure 8. Pilot study database used for extending M_s(VMAX) to 40 seconds period. Thus far, we have analyzed 26 events with depths ranging from 10 to 155 km on seven stations at near-teleseismic distances.

We plotted m_b-M_s(VMAX) in Figure 9 to show how the discriminant is affected by focal depth. Increased depth causes the surface wave magnitudes to decrease faster than the m_b resulting in greater separation between the two magnitudes. This leads to possible contamination with the explosion population.

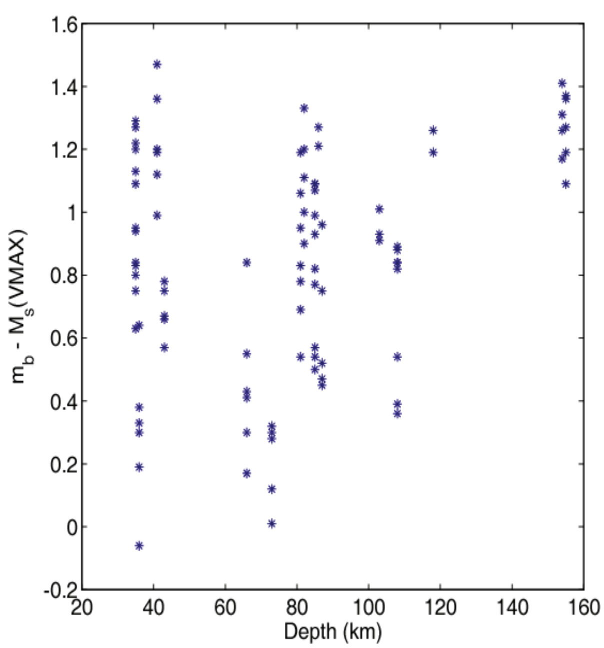

Figure 9. Depth effects on the m_b-M_s(VMAX) discriminant for the events shown in Figure 8.

In addition to M_s(VMAX), we estimated Marshall and Basham (1972) and Rezapour and Pearce (1998) magnitudes for each station-event pair (Figure 10). The data were plotted versus IDC m_b and evaluated against the Murphy et al. (1997) screening criterion. We calculated the number of earthquake M_s estimates that fell below the screening line, which were labeled as improperly screened, and tabulated them in each subplot. The results show that the M_s(VMAX) method has the fewest earthquakes that could not be screened. Only 4% of the individual station measurements fell below the Murphy et al. (1997) screening line, and after the network magnitudes were formed, none were incorrectly screened. This is in contrast to the Marshall and Basham (1972) and Rezapour and Pearce (1998) magnitudes which did not perform earthquake screening as well as M_s(VMAX), particularly on these deeper events.

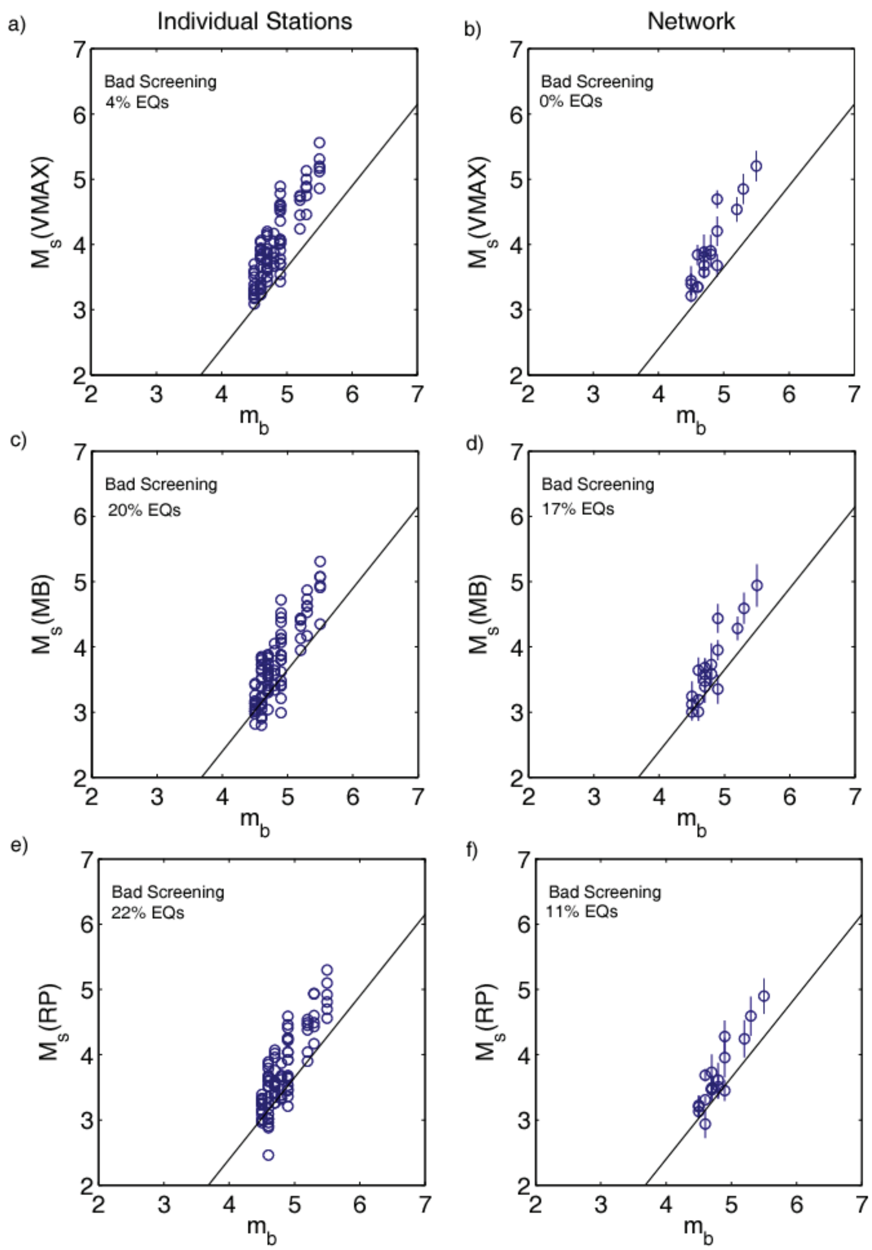

Figure 10. ***M_s* versus *m_b* for a set of earthquakes in the Philippine subduction zone (10-155 km depth). Individual station *M_s* estimates are shown in a) *M_s* (VMAX) c) Marshall and Basham and e) Rezapour and Pearce. Network magnitudes are shown in b) *M_s* (VMAX) d) Marshall and Basham and f) Rezapour and Pearce. The solid black line is the Murphy et al. (1997) screening line.**

CONCLUSIONS AND RECOMMENDATIONS

The variable-period surface wave magnitude M_s(VMAX) continues to provide a better and more consistent estimate of source size, particularly for smaller events and at shorter distances. During the past year, we estimated the 9 October 2006 North Korea event's surface wave magnitude as 2.94 with interstation standard deviation of 0.17 m.u. This magnitude was high relative to the reported m_b, resulting in the only explosion we have analyzed with network M_s(VMAX) that does not fall below the Murphy et al. (1997) screening line. Also during the past year, we have shown that estimates of M_s(VMAX) do not vary considerably (<~0.1 m.u) on opposite sides of the thick, highly attenuative sediments of the South Caspian Basin. Finally, preliminary results of extending the M_s(VMAX) method to 40 seconds shows improved event screening for deeper events. We do note that application of the M_s(VMAX) method to 40 seconds is limited. For small deep events, the longer period surface waves are difficult to observe above the background noise, and will most likely be screened based on depth phases or hypocentral location techniques.

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