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A.J. Rodgers
W.R. Walter
C.A. Schultz
S.C. Myers

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REPRESENTING REGIONAL P/S DISCRIMINANTS FOR EVENT IDENTIFICATION: A COMPARISON OF DISTANCE CORRECTIONS, PATH PARAMETER REGRESSIONS, CAP-AVERAGING AND KRIGING

Arthur J. Rodgers, William R. Walter, Craig A. Schultz and Stephen C. Myers

Geophysics and Global Security,
Lawrence Livermore National Laboratory
L-205, P.O. Box 808, Livermore, CA 94551

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Short-period regional P/S amplitude ratios hold much promise for discriminating low magnitude explosions from earthquakes in a Comprehensive Test Ban Treaty monitoring context. However, propagation effects lead to variability in regional phase amplitudes that if not accounted for can reduce or eliminate the ability of P/S ratios to discriminate the seismic source. In this study, several representations of short-period regional P/S amplitude ratios are compared in order to determine which methodology best accounts for the effect of heterogeneous structure on P/S amplitudes. These methodologies are: 1) distance corrections, including azimuthal subdivision of the data; 2) path specific crustal waveguide parameter regressions; 3) cap-averaging (running mean smoothing); and 4) kriging. The "predictability" of each method is established by cross-validation (leave-one-out) analysis. We apply these techniques to represent Pn/Lg, Pg/Lg and Pn/Sn observations in three frequency bands (0.75-6.0 Hz) at station ABKT (Alibek, Turkmenistan), site of a primary seismic station of the International Monitoring System (IMS). Paths to ABKT sample diverse crustal structures (e.g. various topographic, sedimentary and geologic structures), leading to great variability in the observed P/S amplitude ratios. Subdivision of the data be back-azimuth leads to stronger distance trends than that for the entire data set. This observation alone indicates that path propagation effects due to laterally varying structure are important for the P/S ratios recorded at ABKT. For these data to be useful for isolating source characteristics, the scatter needs to be reduced by accounting for the path effects and the resulting P/S ratio distribution needs to Gaussian for spatial interpolation and discrimination strategies to be most effective. Each method reduces the scatter of the P/S ratios with varying degrees of success, however kriging has the distinct advantages of providing the greatest variance reduction and a continuous correction surface with an estimate of the model uncertainty. The largest scatter reductions are obtained for the lowest frequency P/S ratios (< 3.0 Hz).

Key Words: identification, discrimination, regional discriminants, path effects, kriging

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OBJECTIVE

The objective of this research is to evaluate several proposed representation methodologies of short-period regional discriminants and determine which representation methodology is best for correcting the discriminants for path effects. Short-period regional seismic phases will play an important role in monitoring the Comprehensive Test Ban Treaty (CTBT) for events with body-wave magnitudes, m_b, less than about 4.0. Because signal-to-noise is generally small for low magnitude events at teleseismic distances (distances greater than about 1500 km), discrimination strategies based on M_S:m_b, radiation pattern and/or source depth may not provide sufficiently reliable source characterization (e.g. National Research Council, 1997). Short-period P/S discriminants, e.g. Pn/Lg, Pg/Lg and Pn/Sn amplitude ratios, are effective at discriminating earthquakes and explosions at regional distances and small magnitudes (e.g. Walter et al., 1995; Hartse et al., 1997). However, the travel times and amplitudes of regional phases vary greatly due to acute sensitivity to highly heterogeneous lithospheric structure. An understanding of and correction for path dependent variations in these P/S amplitude ratios is necessary before they can be used reliably as discriminants. Many of the regional P/S discrimination studies to date have relied on simple one-dimensional geometric spreading and attenuation corrections. However, in complex regions these simple corrections are recognized as inadequate. There have been a number of recent empirical studies to correct regional phases for path effects.

This paper explores the effectiveness of various methodologies for representing the variability of short-period regional P/S amplitude ratios using a common data set observed at station ABKT (Alibek, Turkmenistan). For real-time monitoring of the CTBT there are several issues to consider. Firstly, the path propagation amplitude correction model must successfully represent the data. Secondly, the corrections for path propagation effects on regional phase amplitudes should vary smoothly and continuously as a function of location. This is required because event locations, especially regional locations, can have uncertainties on the order of 20-30 km. It is highly undesirable for corrections to change rapidly or for the correction to be undefined within the error ellipse of the estimated location. Finally, it is important for any amplitude correction to have a realistic uncertainty. For example, if a suspicious event occurs and its path propagation amplitude correction has a large uncertainty, then this needs to be included in the event identification process.

RESEARCH ACCOMPLISHED

Regional Waveform Data at ABKT and P/S Amplitude Ratio Measurements

Broadband waveform data (20 samples/sec) recorded at station ABKT were requested from the Incorporated Research Institutions for Seismology-Data Management Center (IRIS-DMC). Event parameters were taken from the National Earthquake Information Center-Preliminary Determination of Epicenters (NEIC-PDE). Because we are most interested in crustal earthquakes and phases, the reported depths were restricted to be less than 50 km. Distances were limited to 200-1500 km to avoid mis-identifying Pg as Pn at close range and upper mantle triplications at far regional distances. The reported body-wave magnitudes of the events used span the range 3.9-6.1. In this study we considered only vertical component data. A first-arriving P-wave was picked. We used about 200 regional events recorded at ABKT for the years 1993-1996. These events are plotted in Figure 1, along with the station location, topography and major tectonic features.

Regional phase amplitude ratios and signal-to-noise ratios were measured for these data in three frequency bands (0.75-1.5, 1.5-3.0 and 3.0-6.0 Hz). Phases were isolated with the following group velocities: Pn 8.0-7.6 km/sec; Pg 6.5-5.5 km/s; Sn 4.6-4.0 km/sec and Lg 3.6-3.0 km/sec. Noise measurements were taken for a window of length equal to the Pn, Pg or Lg window ending 5 sec before the first-arriving P-wave. Absolute amplitudes within each band were measured in the frequency-domain by computing the log-10 mean spectral amplitude of each individual phase from the smoothed broadband instrument-deconvolved displacement spectrum. Ratios were formed from the individual spectral amplitudes. Phase amplitudes were compared to pre-Pn background noise to form signal-to-noise ratios for each phase and frequency band. Only data for which the signal-to-noise ratio for each phase was greater than 2.0 were used in the analysis. Maps of the Pn/Lg amplitude ratios are plotted in Figure 2. The behavior of all Pn/Lg and Pn/Sn ratios is quite similar. The maps shows that the P/S ratios from the Hindu Kush region are often low (indicating strong S-wave energy) and the P/S ratios from the Zagros region are typically high (indicating weak S-wave energy). Note that due to poor signal-to-noise many events from the Zagros are discarded for the highest frequency band.

Distance Corrections.

Following Taylor and Hartse (1998), the instrument corrected absolute amplitude of a regional phase, A(f), can be represented in the frequency domain as:

$$A(f,\Delta) = S(f)\, G(\Delta)\, Q(f)$$

where f is frequency, Δ is the epicentral distance, S(f) is the source spectrum, $G(\Delta)$ is the geometric spreading factor, and Q(f) is the attenuation operator. Geometric spreading does not depend on frequency and is simply dependent on distance, $G(\Delta) = \Delta^{-\eta}$. The attenuation operator, Q(f), is:

$$Q(f) = \exp\,[\, - \pi\, f\, \Delta \,/\, q(f)\, U\,]\, ;$$

where U is the velocity of the phase and the quality factor, q, depends on frequency as $q(f) = Q_0\, f^{-\gamma}$. Forming the P/S amplitude ratio within the same frequency band explicitly cancels the source spectrum and yields a form that depends on the differential geometric spreading and attenuation:

$$A_P(f)\ /\ A_S(f) = \Delta^{-(\eta P - \eta S)}\ \exp\,[\, - \pi\, \Delta\, (\ 1/Q_{0P}\, U_P - 1/Q_{0S}\, U_S\,)\ f^{-(\gamma P - \gamma S)}\ ]$$

where subscripts P and S correspond to values for P- and S-wave phases, respectively. The above form assumes that source radiation pattern and depth affects both phases equally. Strictly speaking, this is probably not true, but there is no way to account for these because the effects of source depth and focal mechanism on short-period regional phases and the depths and mechanisms themselves are largely unknown. If there is sufficient sampling of depths and focal mechanisms, then hopefully these effects will average out. We plotted the P/S ratios versus the PDE m_b and found no significant trend with magnitude. This indicates that source-scaling and corner frequency effects are eliminated by forming the P/S ratio within the same frequency band. Thus, under the above stated assumptions, for a region where the elastic and anelastic structure is homogeneous, the amplitude ratio behavior for regional earthquakes should vary most strongly with distance as a result of geometric spreading and attenuation. In the following we model the P/S amplitude ratios by their linear trend with distance.

The $\log_{10}$[Pn/Lg] amplitude ratios are plotted versus distance and fit to a linear regression in Figure 3a. The data are very scattered and the linear correlations of these data with distance are rather weak. It is apparent from the maps of the P/S amplitude ratios (Figure 2) that paths coming from the Zagros Mountains result in higher P/S ratios than those emerging from the Hindu Kush. Because these source regions are at approximately the same distance from ABKT, this behavior must result from path effects that cannot be described by a single one-dimensional distance correction as shown in Figure 3a. When ratios are subdivided by sectoring the major source regions by back azimuth from the station as drawn in Figure 1, the resulting distance corrections are much more strongly correlated with distance and variance reductions are greater for the subdivided data relative to the entire data set (Rodgers et al., 1997a). In Figure 3b-d the linear regressions of $\log_{10}$[Pn/Lg] with distance are shown when the back-azimuths are limited to isolate distinct source regions with differing P/S amplitude behavior. The correlations shown in Figures 3b-d are much stronger than those seen in Figure 3a. This is most clear for the lowest frequency band (0.75-1.5 Hz). Furthermore, the slopes and intercept values are different for the Hindu Kush and Zagros regions, indicating that the propagation effects are different for these two source regions.

The effectiveness of the distance corrections on Pn/Lg ratios is apparent from cross-validation statistics. Cross-validation measures the effectiveness of a correction in a realistic manner by removing an observation and using all the remaining data to estimate a correction for the left out observation. This method insures that the correction for any single data point is not influenced by the point itself. Distance corrections based on data for all azimuths do not model much of the scatter (-3.9% for the 0.75-1.5 Hz band). However, rms reductions obtained by simply sub-dividing the data by back-azimuth are greater (7-30%). When the sectorized distance corrections are applied to the entire data set, greater rms reductions are obtained (39.0% for 0.75-1.5 Hz, 26.4% for 1.5-3.0 Hz). The distributions of the raw and cross-validated Pn/Lg ratios for the frequency band 0.75-1.5 Hz are shown in Figure 5a and 5b, respectively. Note that not all data were included in the sectorization. The cross-validated data are much less scattered and more normally distributed relative to the raw data.

Path Specific Crustal Waveguide Corrections

In recent years, several studies have explored the correlations between parameters which characterize the path specific crustal waveguide and regional phase amplitude ratios (e.g. Zhang and Lay, 1994; Baumgardt and Schneider, 1997; Rodgers et al. 1997b; Fan and Lay, 1998a,b ; Hartse et al., 1998). These studies report that the scatter in regional phase amplitudes can be reduced by applying either univariate or multivariate path corrections based on crustal waveguide parameters. The most important waveguide parameters vary with data set and region, but generally the strongest correlations are found for distance, mean elevation, mean sediment thickness and mean crustal thickness. An important conclusion from these studies is that often the observed scatter is reduced more by a crustal waveguide parameter (such as mean elevation, crustal thickness or sediment thickness) than by a standard one-dimensional distance correction. This suggests that path propagation effects in regions of crustal waveguide variability are more important than distance effects alone. Detailed statistical analysis of crustal waveguide effects on regional P/S ratios observed a station ABKT is described in a previous report (Rodgers et al., 1997b). That study reports that distance, mean elevation and mean sediment thickness are the most important single factors impacting the Pn/Lg and Pn/Sn ratios observed at ABKT for frequencies below 3.0 Hz. Regression on these three parameters (plus a constant) lead to rms reductions of up to 30%. Multivariate regressions which add rms elevation and mean crustal thickness to these parameters can improve the rms reduction by a few percent over that which is achieved with distance, mean elevation and mean sediment thickness.

Analysis of crustal waveguide effects on P/S ratios is repeated for the current data set to evaluate the effectiveness of the path parameter regression method relative to other methods. Crustal waveguide models are exactly the same as those presented in Fan and Lay (1998a,b) and Rodgers et al. (1998b). Topography was taken from the global topography model GTOPO30. This model represents continental surface elevation on a 30-second (0.93 km) grid. Sediment thickness (basement depth) and crustal thickness (Moho depth) were taken from maps produced by the Former Soviet Union Institute of Physics of the Earth (IPE) made available by the Cornell University Middle East-North Africa Project. Univariate regressions of the $\log_{10}$[Pn/Lg] amplitude ratios on mean elevation and mean sediment thickness are shown in Figure 4a and 4b, respectively. Linear correlations involving the Pn/Lg ratios (< 3.0 Hz) are stronger for mean elevation and mean basement depth than for distance and the scatter after the trends are removed is smaller (Figure 3a). It is interesting to note that the Pn/Lg ratios have a negative trend with mean sediment depth, indicating that Lg is stronger than Pn for paths with thicker sediment on average. For the ABKT data set, paths from the Hindu Kush pass through the thick sedimentary cover of the Turkmen Basin. This contradicts that idea that thick sediments will attenuate S-waves and lead to weak high Pn/Lg ratios. The correlations are weak for higher frequency ratios, probably because many high frequency data are lost due to low signal-to-noise and the variability of the path sampling is diminished. We regressed the low-frequency P/S amplitude ratios on five path parameters (distance, mean elevation, rms elevation, mean crustal thickness and mean sediment thickness) plus a constant. The effectiveness of these regressions is apparent in the cross-validation statistics. Rms reductions on the order of 20% are obtained for the low frequency P/S ratios using the path parameter regression method. The distributions of the raw and corrected ratios using cross-validation are plotted in Figure 5a and 5c, respectively. Although the scatter of the raw data is diminished, the distribution of the corrected data shown in Figure 5c appears to be bimodal. The available crustal waveguide characterizations appear not to capture the basic distinctions that allow the azimuthal sectorization to further reduce the scatter in Figure 5b.

Correction Surfaces by Cap-Averaging

Recently, Phillips et al. (1998) used a spatial averaging technique to construct geographic patterns of source- and distance-corrected absolute amplitudes of regional phases. These patterns (correction surfaces) were derived by computing the moving average (cap-average) of the amplitude residual observed at a single station and projected to the event location. Using the same amplitude ratio data as that presented in previous sections, we computed correction surfaces using the cap-average method. The data mean was removed before the correction surface was computed. We chose to use a cap-radius of 2.5 degrees and required there to be 5 or more observations within each cap. The Pn/Lg ratios in the 0.75-1.5 Hz pass band were cap-averaged to create a correction surface. The different mean values of the Hindu Kush and Zagros source regions are clear. These regions can be well defined by the 2.5 degree cap, and thus the cap-averaging method results in a surface that represents these features, however smaller-scale variability is not matched. An obvious problem of the cap-average method is that the surface can only be defined where there are a sufficient number of observations. Where there are observations but no defined surface it was not possible to compute a mean value using the stated cap-size and minimum number sampling. The predictability of this method can be seen from the histogram plotted in Figure 5d. The scatter of the corrected data is reduced by 37.1% and the distribution appears to be closer to a Gaussian distribution than the input ratios. Note that 24 observations (184-160) that were in the input data set were not corrected because of gaps in the cap-averaged surface.

Correction Surfaces by Modified Kriging

Kriging is an linear estimation technique which models non-uniformly distributed data as a continuous surface with uncertainty estimates. Recent modification of the kriging algorithm and application to seismic travel times by Schultz et al. (1998) make it possible for this technique to be applied to other types of seismic observables in a CTBT monitoring context. There are several distinct features of the modified kriging technique. Firstly, a continuous smooth surface is generated for a region of arbitrary size. Secondly, the observations and associated uncertainties drive the solution so that in areas of dense data coverage the resulting surface is close to the local average of the observations. In regions of sparse data coverage the surface returns to an *a priori* background model. The error estimates associated with individual observations are propagated through the process resulting in a correction surface that accounts for measurement uncertainty. The surface is generated from the data and a few statistical parameters. More precisely, these parameters are: 1) the correlation length, representing the spatial variability; 2) the background variance, representing the variability of the surface; and 3) the measurement error, representing the uncorrelated error in the measurements. In addition to these three parameters, the modified kriging algorithm also requires a blending range to determine how the surface is extrapolated in regions of sparse data coverage. These parameters are detailed in Schultz et al. (1998).

The mean of the data is removed before kriging, so corrections near zero correspond to the mean or expected value of the entire data set. We chose a correlation length of 6.0 degrees, a measurement error of 0.2 $\log_{10}[Pn/Lg]$ units and background variance of 1.0 $\log_{10}[Pn/Lg]$ units. The kriged surface follows the trends of the data more closely than the cap-averaged surface, especially on scales smaller than the cap radius. In regions where the sampling is poor the kriged surface returns to the background in a smooth fashion. The estimated error is small near data points but large where the coverage is sparse. Thus, for a new event in a region of poor coverage, the kriged correction will be near the background model and the estimated error will be large. However, corrections for new events in regions of good coverage will be near the local mean of the data with smaller error. Kriging does an excellent job of reducing the scatter in the observed Pn/Lg ratios. Cross-validation of the corrections derived with the kriging method reduces the rms by 46.7% and results in a normally distributed population shown in Figure 5e.

The pattern of the kriged correction surface appears to have a distance trend. As shown in Figure 3a, the low frequency Pn/Lg ratios have a positive slope distance trend. We removed this trend and kriged the residual amplitude ratios. Cross-validation of the data using this approach resulted in a slightly larger rms reduction (49.1%, Figure 5f) than the kriging method without removing the distance trend. An important effect of removing the distance trend is that the background model used for determining the residual amplitude ratios for kriging is probably more appropriate than simply de-meaning the data before kriging.

Conclusions and Recommendations

Short-period regional P/S ratios hold much promise for identifying low magnitude seismic events. However, path propagation effects lead to variability in the P/S ratios that can inhibit isolation of the seismic source. The regional P/S observations presented above show great variability due to path effects. In this paper we investigated four strategies for representing path propagation effects on regional P/S discriminants. While each strategy succeeds in reducing the discriminant scatter, the kriging method provides the greatest scatter reduction (Figure 5) and has several advantages that distinguish it from the other methods. In the following sections we discuss the results along with the features and short-comings of each method. The advantages and disadvantages of each method are summarized in Table 1. Finally, we will discuss the more general applicability of these results to regional seismic discrimination.

Distance Corrections

Distance corrections have a well founded theoretical justification because geometric spreading and attenuation lead directly to a distance dependence for ratios of regional P- and S-wave phase amplitudes. For regions where elastic and anelastic structure are approximately constant, it is expected that P/S ratios vary most strongly with distance. The Pn/Lg ratios observed at ABKT are highly scattered and show only a weak dependence on distance when data from all azimuths are grouped together. However, when the data are subdivided by azimuth to isolate distinct source regions and path properties, the distance trends are stronger (Figure 3). The case of ABKT is unique because this station is situated near a major tectonic boundary, so paths from different azimuths sample completely different crustal structures. Although the sectorized distance corrections significantly reduce the scatter of the P/S ratios observed at ABKT, there are certain problems that can arise with this method. If a tectonic region is poorly defined or aseismic, then it may be difficult to define the sector boundaries. If tectonic boundaries are oblique to great-circle paths of regional events to a given station, then azimuthal sectorization may not succeed in reducing P/S ratio scatter. Because of uncertainties in event location (typically less than 30 km), one must be cautious when associating an event with a sector when the event is near the sector boundary. It is probable that the corrections do not vary smoothly across a sector boundary, which is an undesirable feature of the sectorization method. Finally, the only way to assess the uncertainty in a distance correction is from the formal errors of the regression, which will not represent the true uncertainty if the data are not Gaussian distributed.

Path-Specific Crustal Waveguide Corrections

Regressions of P/S discriminants on path-specific crustal waveguide parameters provide a continuous parameterization of the data and they succeed in reducing the observed scatter. However, the rms reductions are not as significant as the other methodologies. The fact that certain waveguide properties are better predictors of P/S behavior than distance alone supports the azimuthal sectorization strategy presented above. Crustal waveguide parameter regression studies report that P/S ratios behave differently at each station, so that corrections derived for one region may not be transportable to another region. For example, the univariate regression parameters reported by Fan and Lay (1998a) for P/S ratios observed at WMQ are different from the values obtained by regressing P/S ratios observed at ABKT. However, the slopes of the trends are generally in agreement. This issue is investigated further in the multiple station path parameter regression analysis reported by Fan and Lay (1998b). The relative importance of each parameter in multivariate path parameter regressions is dependent on the station. This observation suggests that path parameter regressions will be most successful if done for individual stations. It is possible that scatter reductions result because the path specific parameters are surrogates for the true controlling factors and there are correlations between the parameters chosen and the true controlling factors. Another important issue that arises when employing this technique is the fact that models of sediment and Moho depth are either poorly constrained or completely unknown.

Cap-Averaging

Cap-averaging is a straight forward spatial averaging technique that results in a substantial reduction in the scatter of P/S discriminants. The method is easy to apply to any data set and does not require models of crustal structure. For densely sampled, smoothly varying data sets this technique may provide an excellent representation of the data. However, for the realistic seismic amplitude data sets we considered in this study, cap-averaging has a few disadvantages which severely limit its applicability. Cap-averaging provides no error estimate, other than the standard error of the mean or the actual spread of the data within each cap. Cap-averaging can not represent data that varies on spatial scales smaller than the cap-radius. Also, no model prediction is obtained for poorly sampled or aseismic regions.

Modified Kriging

Modified kriging provides an excellent representation of the P/S ratio data observed at ABKT and has several important features which distinguish it from the other representation methodologies. Kriging provides the largest rms reduction and the corrected low-frequency Pn/Lg ratios (Figure 5e,f) are very nearly normally distributed. Kriging results in a continuous correction surface for all points in a specified region and returns smoothly to an *a priori* background model in sparsely sampled regions. An error estimate exists at each point based on data measurement error and other statistical properties of the data and is thus more realistic than formal errors from regression. Small-scale variability is better represented by kriging than by cap-averaging because cap-averaging is a low-pass filter. Spatial wavelengths of the kriged correction surface are controlled by the data and random sample error. Identified regions that block S-wave phases (Sn or Lg) can easily be incorporated into the kriged surfaces so that if a path is expected to have a blocked S-wave the correction will be flagged and the Sn or Lg amplitude will not be used to form a discriminant. A possible disadvantage of the kriging technique is that it is computationally intensive relative to the other methods. However, given the speed of modern computers and the significant advantages of kriging over other methods, the longer run time of this method relative to others should not limit its use.

General Comments

The path correction strategies presented here reduce the scatter in the low frequency (< 3.0 Hz) P/S amplitude ratios, while not significantly reducing the scatter in the higher frequencies in a consistent fashion. Many studies have reported that higher frequency P/S ratios discriminate better than lower frequency P/S ratios (e.g. Walter et al., 1995; Hartse et al., 1997). However, strong lithospheric attenuation can significantly reduce the signal-to-noise in the higher frequency bands for the smaller events ($m_b < 4.5$) at distances of 500 km or more that are of particular concern to CTBT monitoring. It is possible that for such events there will not be sufficient signal-to-noise to measure P/S ratios at frequencies above 3.0 Hz. Thus, if the strategies presented here can reduce the scatter in the low frequency P/S ratios they may enhance discrimination capabilities. We have included all paths for which the phase amplitude signal-to-pre-Pn-noise is greater than 2.0. It is certainly possible that we have included paths for which Sn or Lg are weak or blocked, given previous studies of regional phase behavior. The low-frequency Pn/Lg ratios show a continuous distribution (Figure 5a), suggesting that blockage cannot be easily identified by a maximum P/S ratio. However if blockage and/or attenuation is complete, blocked paths cannot be used for source discrimination. If paths with weak or absent S-wave energy were discarded, then the variability would be reduced and variance reductions might not be as strong. The representations presented here certainly describe the expected earthquake P/S behavior, including paths for which Sn or Lg is partially or totally blocked. So at the very least the analysis presented here helps us understand the regional phase propagation and predict the behavior of future earthquake P/S ratios recorded at ABKT. We are currently investigating techniques to separately map regions of Sn and Lg blockage. Once these regions are identified they can be incorporated into the correction surfaces. The test of whether variance reductions of earthquake measurements improves discriminant performance in this region requires explosion data. We are currently looking for evidence of mining explosions recorded at ABKT. The acquisition of waveform data recorded at ABKT for explosion sources at regional distances will allow us to investigate if path corrections enhance seismic source discrimination.

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References

Baumgardt, D. and C. Schneider (1997). Multivariate canonical correlations of P/S ratios and propagation path parameters for Iran, Proceedings of the 19th Annual Seismic Research Symposium on Monitoring a Comprehensive Test Ban Treaty, 23-25 1997, Defense Special Weapons Agency Report, 14-23.

Fan, G. and T. Lay (1998a). Statistical analysis of irregular waveguide influences on regional seismic discriminants in China, *Bull. Seism. Soc. Am.*, **88**, 74-88.

Fan, G. and T. Lay (1998b). Regionalized waveguide effects on seismic discriminants in western China, submitted to *Bull. Seism. Soc. Am.*

Hartse, H., S. Taylor, S. Phillips and G. Randall (1997). A preliminary study of regional seismic discrimination in Central Asia with emphasis on western China, *Bull. Seism. Soc. Am.* **87**, 551-568.

Hartse, H., R. Flores and P. Johnson (1998). Correcting regional seismic discriminants for path effects in western China, *Bull. Seism. Soc. Am.*, **88**, 596-608.

National Research Council (1997). Research required to support comprehensive nuclear test ban treaty monitoring, National Academy Press, Washington, D.C., 138pp.

Phillips, W. S., G. Randall and S. Taylor (1998). Path correction using interpolated amplitude residuals: An example from central China, in press *Geophys. Res. Lett.*

Rodgers, A., W. Walter and T. Lay (1997a). Calibration of distance and path effects on regional P/S discriminants at station ABKT (Alibek, Turkmenistan): azimuthal sector regionalization, UCRL-JC-128318.

Rodgers, A., T. Lay, G. Fan and W. Walter (1997b). Calibration of distance and path effects on regional P/S discriminants at station ABKT (Alibek, Turkmenistan): statistical analysis of crustal waveguide effects, UCRL-JC-129165.

Schultz, C, S. Myers, J. Hipp and C. Young (1997). Nonstationary Bayesian kriging: application of spatial corrections to improve seismic detection, location and identification, submitted to *Bull. Seism. Soc. Am.*

Taylor, S. and H. Hartse (1998). A procedure for estimation of source and propagation corrections for regional seismic discriminants, *J. Geophys. Res.*, **103**, 2781-2789.

Walter, W., K. Mayeda and H. Patton (1995). Phase and spectral ratio discrimination between NTS earthquakes and explosions. Part I: empirical observations, *Bull. Seism. Soc. Am.*, **85**, 1050-1067.

Zhang, T.-R. and T. Lay (1994). Analysis of short-period regional phase path effects associated with topography in Eurasia, *Bull. Seism. Soc. Am.*, **84**, 119-132.

Table 1. Summary Comparison of Methodologies for Representing P/S Discriminants

Method	Advantage	Disadvantage
Sector/Distance	works well	discontinuous
		difficult to draw sector boundaries
Path Parameter Regression	continuous	does not work very well
		crustal waveguide poorly known
Cap-Averaging	works well	poorly defined error
	easy to compute	surface undefined where no data
Modified Kriging	works best	computationally intensive
	continuous	
	well defined error	

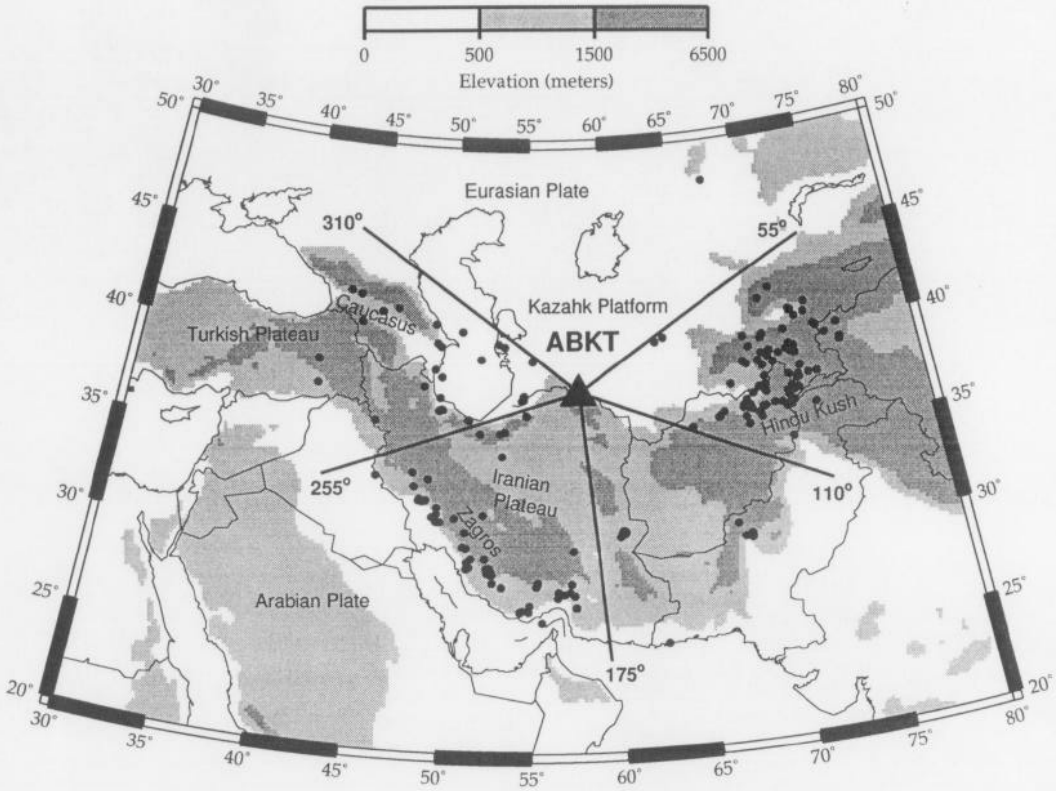

Figure 1. Map of earthquakes (circles), station ABKT (triangle) and regional topography and tectonic features. Thick lines represent boundaries used to subdivide the data by azimuthal sector.

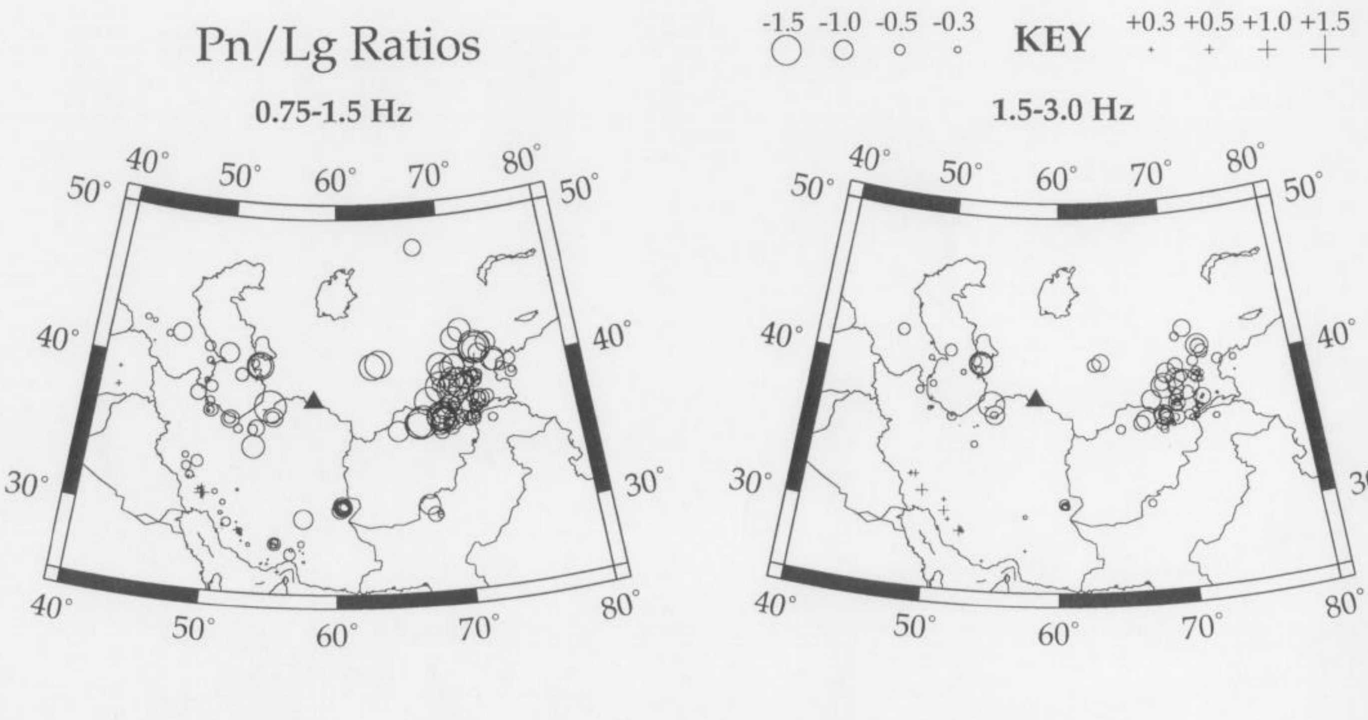

Figure 2. Log10[Pn/Lg] ratios for (left) 0.75-1.5 Hz and (right) 1.5-3.0 Hz plotted at the event location.

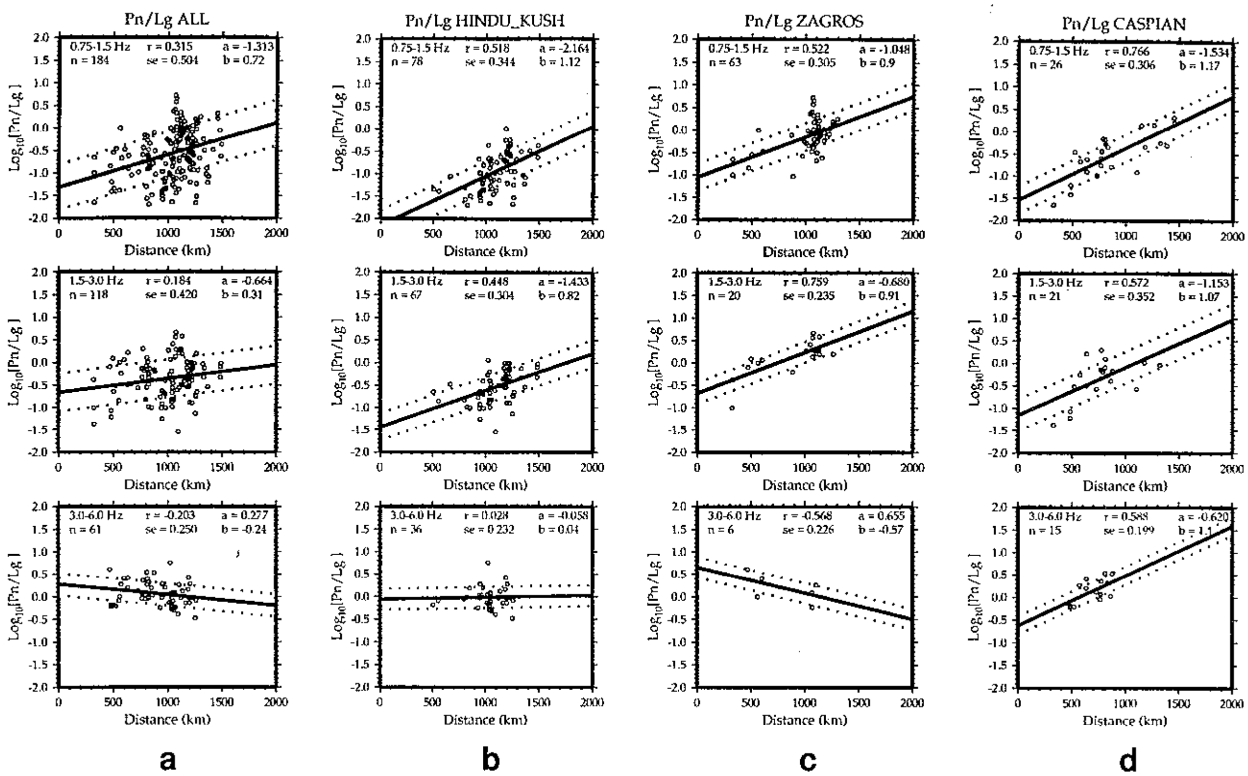

Figure 3. Log10[Pn/Lg] ratios versus distance for (top) 0.75-1.5 Hz (middle) 1.5-3.0 Hz and (bottom) 3.0-6.0 Hz. The regression fit (solid) and 1-σ error (dashed) are also shown. (a) Ratios for all back-azimuths; (b) ratios from the Hindu Kush; (c) ratios from the Zagros and (d) ratios from the Caspian.

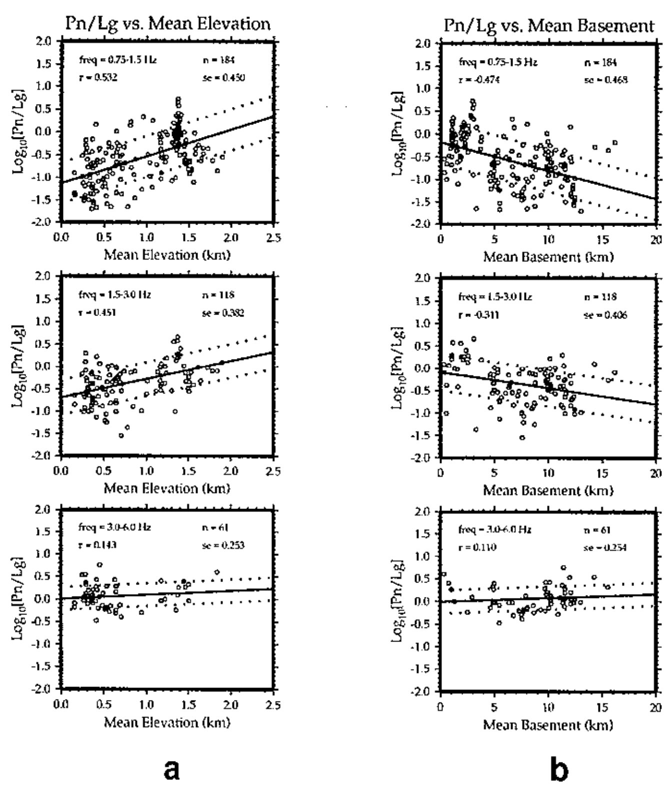

Figure 4. Log10[Pn/Lg] ratios for (top) 0.75-1.5 Hz (middle) 1.5-3.0 Hz and (bottom) 3.0-6.0 Hz versus along-path crustal waveguide parameters: (a) mean elevation and (b) mean sediment thickness. The regression fit (solid) and 1-σ error (dashed) are also shown.

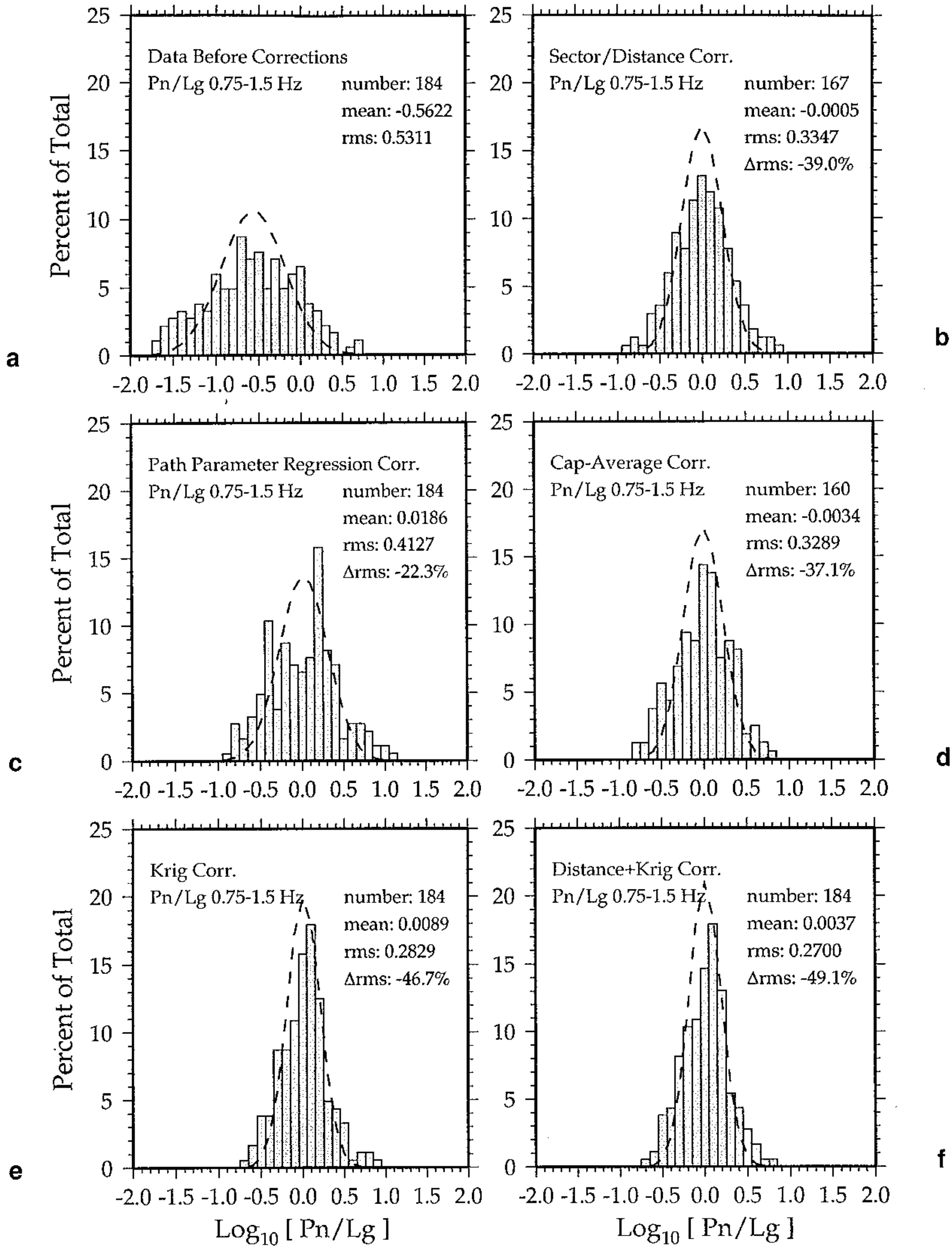

Figure 5. Histograms of Pn/Lg ratios (0.75-1.5 Hz) before (a) and after the various corrections for path effects were made (b-f). All distributions for data sets after corrections were removed were computed by cross-validation (b) sectorized distance corrections; (c) multivariate path parameter regression; (d) cap-averaging; (e) kriging; and (f) kriging after the distance trend was removed. A gaussian with equal mean and variance is plotted in each panel (dashed line) for comparison.