IDENTIFICATION OF DEEP EARTHQUAKES

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ABSTRACT

The objective of this project is to identify and apply seismic event discriminants that will reliably separate small, crustal earthquakes (magnitudes less than about 4 and depths less than about 40 to 50 km) from small, deep earthquakes (depths between about 50 and 300 km). These deep earthquakes are known to occur in the Asia-India continental collision zone, mostly north of the Indian subcontinent, including far western China. Not only are the depths of these subcrustal earthquakes difficult to reliably estimate using conventional arrival time location methods (when event-station distances are large), but they can also appear with explosion-like characteristics on discrimination plots designed to separate nuclear explosions from crustal earthquakes. Thus, reliably flagging these small, deep events is critical in improving discrimination performance, because deep earthquakes can immediately be removed from further event identification analyses. Further, reliably identifying subcrustal earthquakes will allow us to eliminate deep events (previously misidentified as crustal earthquakes) from research datasets, thereby refining event identification parameters for the Magnitude and Distance Amplitude Correction (MDAC) process, and ultimately leading to more robust capabilities for separating small, crustal earthquakes from explosions.

Our research approach involves 4 primary steps: (1) assemble a "control" data set of waveforms from reliably located, mostly larger earthquakes (both crustal and deep events) from the Hindu Kush region, (2) measure body-wave and coda-wave amplitudes of the "control" earthquakes, (3) experiment with amplitude ratios and other measurements as discriminants for separating crustal and deep events, and (4) apply the discriminants to a data set of small Hindu Kush earthquakes and assess discrimination performance. For selecting a subset of well-located, larger earthquakes we rely on depth constraint provided by the presence of teleseismic depth phases and/or centroid moment tensor (CMT) reports. We also select as "control" events some smaller earthquakes which were recorded by stations KBL and/or NIL, as these stations are within a few hundred km of the zone where deep earthquakes are known to occur. To date we have selected about 300 earthquakes for measurements under step 2 of our project. Wave amplitude measurements are under way. For step 2 we will also measure slownesses of deep and crustal earthquake waves as they cross the seismic arrays within Kazakhstan. We are especially interested in identifying far-local and regional depth phases at arrays and at three-component stations that can be used to constrain earthquake depths during the event location process.

The US National Data Center (USNDC) will be the primary user of these research results. The results of this study also have potential to benefit the current Administration's renewed interest in the Comprehensive Nuclear-Test-Ban Treaty by strengthening the verification regime. Our final research product will be an extension of the Event Classification Matrix (ECM), also known as the Event Categorization Matrix, which currently uses standard teleseismic discriminants to separate seismic events into populations of explosions, shallow earthquakes, deep earthquakes, or unresolved. As we move to regional, broad-area monitoring of smaller events, we will add discriminants to ECM that allow us to categorize deep earthquakes based on regional data alone. This will be essential to resolve small, deep events that may not be categorized as deep using teleseismic discriminants within the current ECM framework.

OBJECTIVES

To meet the United States Government (USG) nuclear explosion monitoring (NEM) requirements with high confidence and a low false-alarm rate, the monitoring community needs new and improved capabilities for analyzing small deep regional seismic events. Many features of regional seismograms can lead to confusion and possible miscategorization as explosions. The primary objective of this work is to identify and apply seismic event discriminants that will reliably separate explosions and small, crustal earthquakes (magnitudes less than about 4 and depths less than about 40 to 50 km) from deep earthquakes (depths between about 50 and 300 km) with particular emphasis on small deep earthquakes. Our end product will be the incorporation of regionally recorded waveform measurements and discriminants into the ECM such that US National Data Center operations can reliably identify and separate deep earthquakes from consideration as potential nuclear explosions.

Deep earthquakes present both a problem and an opportunity for seismic monitoring by the USNDC. The results of this study are intended to also benefit the current Administration's renewed interest in the Comprehensive Nuclear-Test-Ban Treaty by strengthening the verification regime. Standard methods of seismic location are routinely unsuccessful at tightly constraining event depth unless either (1) a number of clear depth phases (near source reflections) are observed, or (2) at least one seismic station reporting phase arrival times is at an epicentral distance no greater than 2 or 3 times the true event depth. Depth phases are extremely difficult to observe for small events as the reflections are often smaller than the direct (first arrival) phase and are either below the noise floor or lost in the reverberant coda of the direct arrival. Seismic event location is an iterative nonlinear least squares estimation problem, and the travel time sensitivity with respect to event depth diminishes rapidly for distances beyond several event depths, requiring manually constrained event depths for a location estimate. Asia has abundant deep seismicity from a number of tectonic collision zones as shown in the map of deep earthquakes in Figure 1. Until recently the seismic station distribution was not favorable for accurate depth estimation in the Hindu-Kush-Pamir deep seismicity region shown on the maps below. Recent installation of station KBL and improvements in the depth estimates of the Global Centroid Moment Tensor Project (based on seismic waveform modeling) finally make it possible for us to build a well-constrained ground truth dataset of deep events seismically recorded at regional distances. Once we construct the ground truth dataset, we can then systematically explore ratios of MDAC-corrected seismic amplitudes to form and test discriminants for deep events using the same tools and formalism we have used to study seismograms for shallow seismic events and explosions. Once we have developed and validated discriminants for categorizing deep events using MDAC and ECM technologies we can easily forward these to the USNDC for their evaluation and implementation.

Our objective is the creation of discriminants for use with the ECM method, which will identify deep earthquakes as separate population, distinct from explosions and normal depth crustal earthquakes using regional seismic data. This will augment the current teleseismic discriminants for deep earthquakes, and allow categorization of smaller events, which may be poorly recorded at teleseismic distances, but well recorded at regional distances. We need to develop a ground truth dataset of earthquakes at both normal crustal depths and earthquakes from subduction zones, below the overlying crust. Many earthquakes catalogs contain events with poorly constrained or fixed depth locations as well as events with well constrained depths, primarily from well recorded depth phases and waveform modeling. We have used the Centroid Moment Tensor (CMT) catalog for deep events as an additional source of ground truth.

RESEARCH ACCOMPLISHED

We first encountered problems with deep earthquakes early in the research program described by Hartse et al. (1997) prior to the development of MDAC and ECM methodologies. We have begun a systematic study regional discrimination of regionally recorded deep earthquakes for integration with MDAC and ECM, with a primary focus on the Pamir and Hindu-Kush zones of deep seismicity. Two recent summaries of the state of knowledge on deep earthquakes by Frohlich (2006) and H. Houston in Schubert (2007) while useful provide little insight into regional discrimination issues. Frohlich (2006) has a useful description of the deep seismicity of the Pamir and Hindu-Kush zones. Active research on the deep seismicity of the Pamir and Hindu-Kush zones spans decades [Roekcker et al. (1980); Chatelain et al. (1980); Verma and Sekhar (1985); Pavlis and Hamburger (1991); Zhao and Helmberger (1993); Fan et al. (1994); Mellors et al. (1995); Zhu et al. (1997); Pegler and Das (1998) and Chu et al. (2009)] but there are no ready answers to the problem of regional discrimination of deep earthquakes from normal crustal earthquakes or explosions. We will focus our efforts on identifying the regional characteristics of seismograms from

deep events that will distinguish them from regional seismograms of crustal earthquakes and explosions, with the goal of incorporating our results into the ECM suite of discriminants.
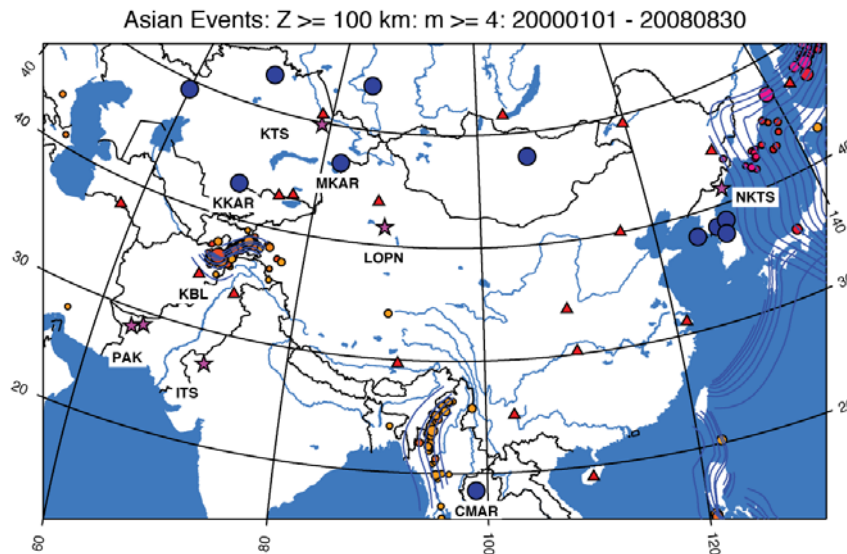

Figure 1. Locations of earthquakes deeper than 100km within the India-Asia collison zone. Also shown are nearby seismic stations and Asian seismic arrays. Blue contours are subducting slab depth associated with seismicity.

Figure 1 shows a map of the deep seismicity of the Asian continent with the contours of event depths and the inferred subducting slabs in the Pamir Hindu-Kush area of Afghanistan/Pakistan as well as deep seismicity in Myanmar near India and in the Korea, Japan and Eastern Siberia regions. Our primary areas of concern are in the Hindu Kush resulting from the Indian subcontinent collision with the landmass of Asia.

Seismic bulletins commonly list seismic events with automatically or manually fixed depths (frequently 0, 10, 15 or 33 km are common) when the travel time location process is unable to estimate depth as a free parameter. Event depth trades off with origin time when depth (or origin time) is unconstrained. Seismic stations in areas of interest are rarely within 2 event depths, but a recently reinstalled station in Afghanistan (KBL) is within 2 event depths of a cluster of deep seismicity. With KBL, the USGS NEIC now locates events with improved accuracy depth estimates from travel times, allowing us to finally build a calibration dataset of well-constrained deep events. We can take advantage of USGS locations using KBL to devise waveform-based discriminants to identify the deep events. We can not reasonably expect KBL to be routinely available in the future given its politically unstable location, and long history of being unavailable. Figure 2 below shows a map of the deep seismicity and the depth contours for the Hindu-Kush region with the nearest available seismic stations. Station KBL is within 2 to 3 event depths of many of the deep events, and is helping constrain the event depths since its reinstallation. Station NIL has had a history of downtime and has not been as useful to constrain event depths. For event locations where KBL is either not close enough or not operating, we will examine the available seismic stations and estimate our own seismic locations using phase arrival time picks that we add and assess the depth from the new location for possible inclusion in out ground truth dataset. This will allow us to exploit our existing archive of event locations and assembled seismograms to create additional ground truth. We will also review and collaborate with the LANL seismic location effort to use existing LANL refined ground truth locations and contribute any additional ground truth locations we may generate.

Deep earthquakes of sufficient magnitude (approximately M > 5) are analyzed and published by the Global Centroid Moment Tensor Project (http://www.globalcmt.org/) which provides estimates of the event depth as well as source mechanism. These estimates are derived from waveform modeling, and have recently included more events with the depth estimated and not fixed. These CMT depth estimates provide another new source of ground truth for larger deep events. We have also used earthquake catalog sources include Earthquake Data Reports (EDR), Reviewed Event Bulletin (REB) and the Kazakh National Data Centre (KNDC) bulletin. We have required 4 or more distinct teleseismic depth phases, such as pP and sS for ground truth event depth. High quality ground truth

will be essential to developing discriminants for deep regional events and subsequent screening of existing event populations to recategorize events with poorly controlled depths. Figure 2a shows all available seismicity since station KBL began reporting and appearing in earthquake locations. Figure 2b shows a dramatically smaller subset of the the data which has had strict event depth criteria applied. We will need to add additional ground truth events over the course of this project.
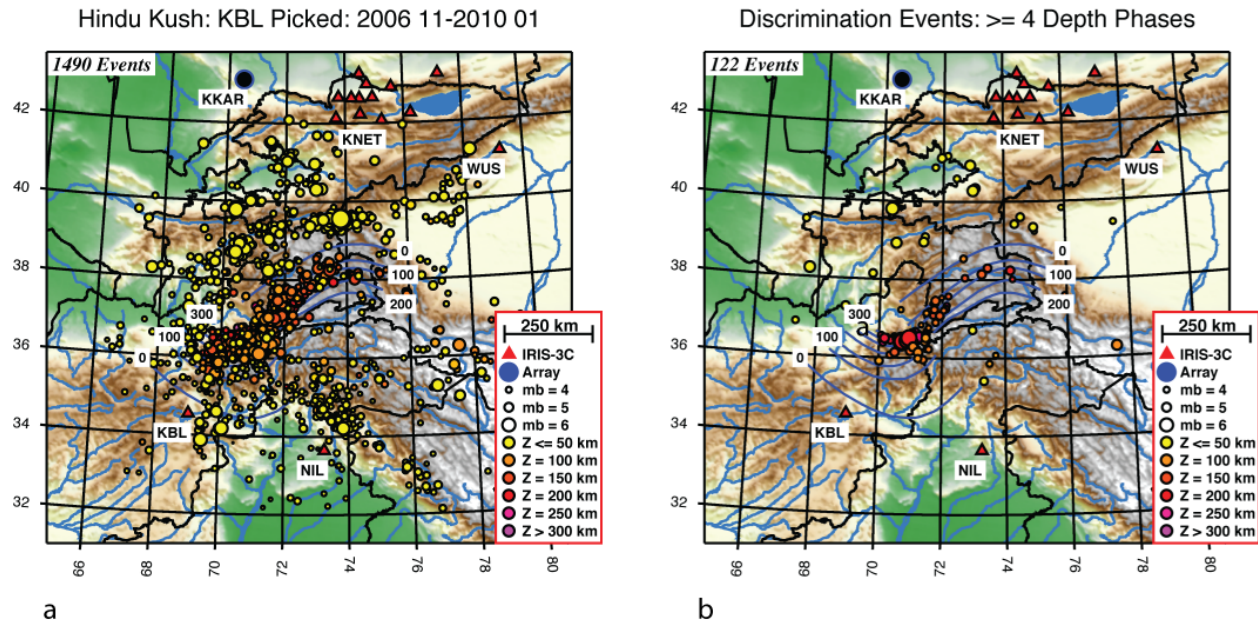

Figure 2. Earthquakes of the Hindu Kush region. Note locations of stations KBL and array KKAR. Blue contours and labels represent depth in km of subducting slabs. In map a (left) are events which we have picked at KBL since KBL began sending data in late 2006. We believe many depths associacted with these reported locations are wrong. In map b (right) are only those events used for our preliminary discrimination analysis (see Figures 4 and 5). We used only events with 4 or more distinct teleseismic depth phases, such as pP and sS. There are 122 events on this map.

The array KKAR is not close enough to constrain event depth, but suffers from a large number of events that are problematic and probably poorly depth constrained. We believe the poor depth control has caused a number of deep earthquakes to be analyzed as if they were shallow crustal events, contaminating our dataset.

A robust quantitative depth estimate can be used to identify a seismic event as an earthquake (too deep to have been a nuclear explosion), reducing the operational burden at the USNDC. Alternatively, deep event discriminants could be formed and ECM could verify the utility of the discriminants for defining the population of deep earthquakes within a formal decision framework. We propose to build a ground truth dataset of events with well-constrained depths using stations close to pockets of deep seismicity, and waveform modeling results for event depth. With a well constrained set of events for both shallow and deep event populations, we will devise event depth discriminants, starting with our ground truth dataset and apply the depth discriminants to all our existing events, identifying and eliminating deep events that are contaminating out datasets for shallow crustal events. After successfully demonstrating useful deep event discriminants with our ground truth dataset, we will move on to look for other deep events in our data for which we do not have a nearby seismic station.

A demonstration of the probable effect of deep events at the array KKAR is shown in Figure 3 below which shows the Magnitude and Distance Corrected (MDAC) amplitude residuals for the P phase versus magnitude on the left and versus distance on the right. The MDAC corrections assume the event is shallow enough to be in the crust and applies corrections for geometric spreading, attenuation and source spectrum assuming a crustal propagation path to the station. Deep events would propagate mostly in the mantle with only a short crustal leg, and our attenuation models are not accurate for the hotter and more attenuating mantle. Also, our magnitudes are derived assuming a crustal path, and may also be incorrect. The vertical arrows show distinctive low residuals at two distance ranges, which we believe correspond to mislocated deep events. The horizontal arrow on the left shows the low residuals are

distributed over a range of magnitudes. In both plots the blue circles are the residuals after the assumed physics of the source, geometrical spreading and attenuation are removed and the red dots are the secondary residuals after linear trends are removed following the physical corrections. Any bias from deep events will contaminate the calibration data and alter the secondary correction.
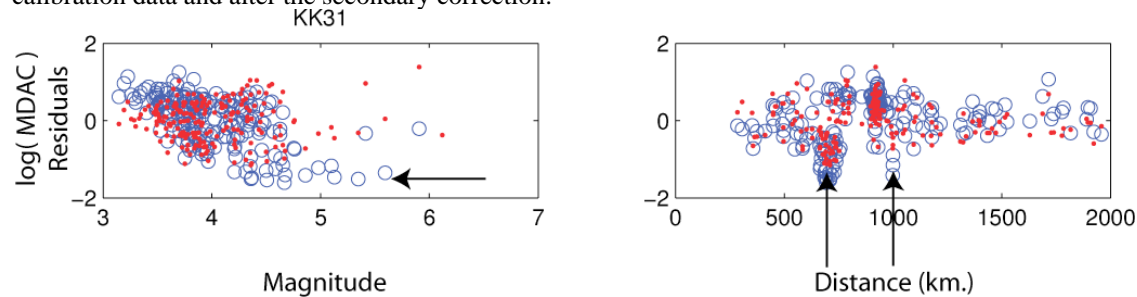
Figure 3. MDAC residuals versus moment magnitude (left) and versus distance (right) for KKAR array element KK31. Blue circles are residuals after removing physical effects of source and path. Red dots are residuals after a final regression. Note low residuals at 700 and 1000 km from KK31. We suspect many of these low-residual earthquakes are sub-crustal, but bulletins listed them at crustal depths.

The residuals should ideally be zero mean if we have accurately removed the effects of the source based on the magnitude and the effects of distance based on geometric spreading and attenuation. These residuals, however, show systematic problems in our MDAC calibration data. We believe that if we can exploit the systematic patterns of residuals with other observables, based on a ground truth set of well constrained deep events, we can develop credible criteria to categorize the events as deep. This will improve the quality of our MDAC residual population, and our event identification results as propagated from MDAC through the ECM products. We anticipate that the shallow, refined event population will show less scatter and bias in terms of MDAC residuals, and will improve the ECM categorization. We also anticipate that we will define MDAC-based discriminants, and possibly other discriminants, that can be applied in the ECM framework, allowing us to recognize deep events based on regional information, even when a nearby station is not available. Hence, we will be able to identify deep earthquakes with small magnitude where teleseismic depth phases are not above noise levels.

As an example of the potential problems with deep events we show the waveforms for a shallow crustal earthquake, a deep sub crustal earthquake, and an explosion in the 1-2 Hz and 6-8 Hz bands all recorded at seismic station MAKZ (shown in Figures 4a and 4b), which is a surrogate for the nearby monitoring array MKAR, and has recorded underground nuclear explosions (UNE's) as well as earthquakes. In the 1-2 Hz band the typical crustal earthquake shows a P wave and a stronger Lg arrival, the deep subcrustal earthquake shows P and S but no discernable Lg, and the UNE shows P, Pg, S. and Lg.
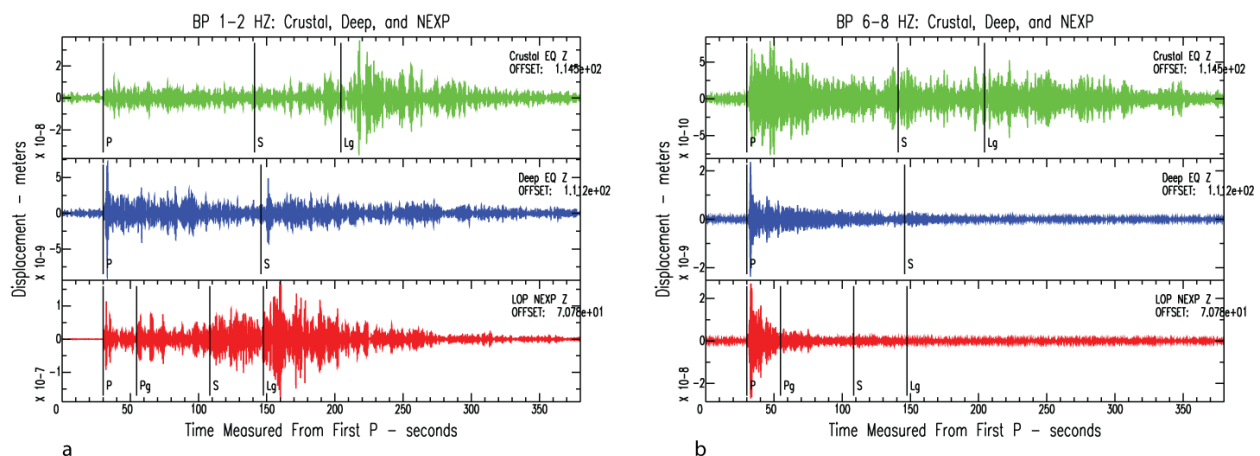

Figure 4. Examples of a crustal earthquakes, a subcrustal earthquakes, and a nuclear explosion from western China recorded at stations MAKZ in Kazakhstan. In (a) all are vertical component seismograms with a 1 to 2 Hz bandpass filter but in (b) bandpass filtered between 6 and 8 Hz. Note the lack of S and Lg for the deep earthquake and the nuclear explosion.

In the 6-8 Hz band (Figure 4b) the appearances change and while the shallow crustal earthquake still shows P and Lg, the S phase is now more visible. In contrast the deep subcrustal earthquake and the UNE now both show only the P wave and visually are not easily distinguished.

We believe that this visual similarity of the UNE and the deep subcrustal earthquake are also reflected in the MDAC residuals, and make the discrimination for ECM potentially complex, requiring additional MDAC ratios. ECM serves as a valuable framework to test hypotheses of a number of MDAC ratios for forming a population of deep subcrustal earthquakes. We can use the Centroid Moment Tensor (CMT) for ground truth estimates of depth (based on the CMT's waveform modeling) as well as the seismic Moment, Mo, and the moment magnitude, Mw, for events large enough for CMT results. The CMT modeling technique has been improved with the inclusion of more regional waveform data, constraining event depths, and producing fewer solutions with fixed depths to stabilize the solution. We may model some events that are too small for the CMT bulletin using our previously developed waveform modeling techniques for estimates of both seismic moment tensor (source mechanism) and event depth. For still smaller sub-CMT sized events, we will rely on accurate depths from events constrained by KBL travel times. Between these depth constraints, we can build a ground truth dataset, make phase amplitude measurements, choose potential MDAC discriminants, and test the utility of these discriminants with the statistically rigorous ECM framework, keeping the most successful discriminants. With CMT (and perhaps also with KBL-constrained events) we will build a set of deep but still crustal earthquakes (i.e., not in the subducting plate at mantle depths below the overriding plate) to test whether deep crustal earthquakes form a unique population or overlap with shallow crustal earthquakes.

In an example event identification plot of MDAC residuals (Figure 5) including the deep event (waveforms shown in Figures 4a and 4b) shown below, with a deep event as a black diamond, nuclear explosions at the Chinese Lop Nor test site as red stars, chemical explosions at the Former Soviet test site in Kazakhstan as blue stars, and earthquakes as yellow or green circles demonstrates the event identification risk of inadvertently including an unknown deep earthquake. The green circles represent earthquakes near the Chinese test site. The deep earthquake was deliberately added to the population for demonstration, as we do not routinely process known deep earthquakes. The MDAC residual for deep earthquakes is at the high end of the earthquake population, overlaps the nuclear explosion population, and exceeds the chemical explosion population. The deep event could be miscategorized as an explosion, and demonstrates that we may well have a number of other unrecognized deep earthquakes contaminating our study dataset. If we can systematically identify and segregate deep earthquakes as a unique population we will be able to provide enhanced event identification capability and improve the performance of ECM.
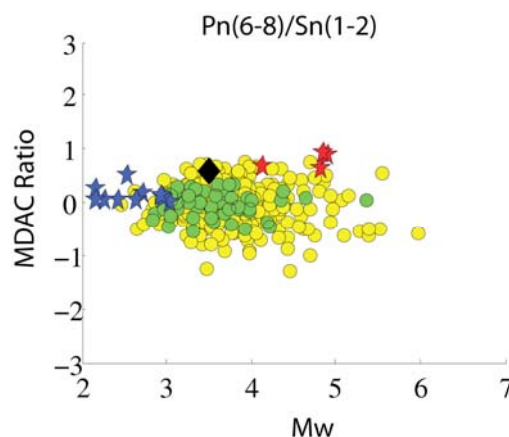
Figure 5. MDAC ratio of Pn in the 6-8Hz band to Sn in the 1-2Hz band for a deep event shown as a black diamond, nuclear explosions as red starts, chemical explosions as blue stars, and earthquakes as yellow and green circles. Earthquakes within 250 km of the nuclear explosions at the Chinese Lop Nor Test site are green. In these and following figures we use data from Global Seismic Network station MAKZ in eastern Kazakhstan, near the IMS array MKAR.

An additional example (Figure 6) for another event with depth ground truth backed up by CMT waveform modeling shows a larger event clearly above the bottom of the nuclear explosion population and in the upper limits of the earthquake population using another MDAC discriminant. This casts suspicion on the higher ratios in the earthquake

population as potentially deep events, which have been mislocated as shallow. The chemical explosions are significantly lower in this example, and we presume that the highest ratio presumed earthquakes are unlikely to be chemical explosions. The lack of solid ground truth for deep events and the potential for significant differences in MDAC ratios for deep events demonstrates the need to carefully develop a ground truth dataset for deep events, and use MDAC ratios to define a separate population of deep events. These example figures show the potential problem of deep events overlapping nuclear explosion populations for these MDAC ratios, and a large population of presumed shallow earthquakes near the explosion population.
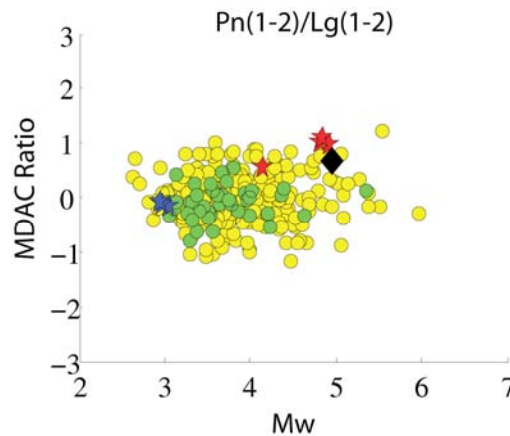
Figure 6. MDAC ratio of Pn 1-2Hz to Pn 6-8Hz which is a candidate for a deep earthquake discriminant. The ground truth deep event clearly is separated from the explosion populations and is near the extreme limits of the earthquake populations. The earthquakes (yellow circles) above the black diamond may be subcrustal events that have been mistakenly located with crustal depths.

In early attempts to find other potential discriminants for deep regional events we have examined other portions of the seismic waveform for amplitudes shown in Figure 7. We observe the lack of Pg relative to Pn for the deeper events.
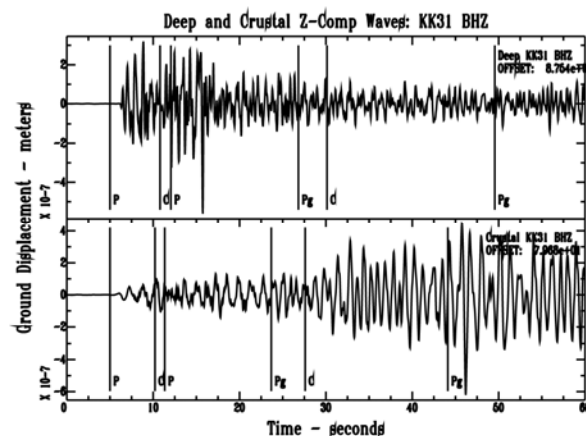
Figure 7. Sample P-waves from station KK31 showing (at top) a deep event (about 180 km) and a crustal event (about 30 km). Both events are about mb 4.8. The shallow event is about 650 km from KK31 and the deep event is about 730 km from KK31. Amplitude measurement windows are marked with "P" (8.2-7.6 km/s) to show the first-P window, "C" (7.7-6.4 km/s) to show the Pn coda window, and "Pg" (6.2-5.2 km/s) to show the Pg window.

We also observe a possible difference between the Pn and Pn coda for shallow and deep events possibly caused by differences in near source scattering. We will need to test all possible discriminants using MDAC for rapid preliminary testing we have used a distance correction which removes observed trends based on ground truth crustal earthquakes. Deep events will have a different propagation path with different attenuation. Figure 8 shows the amplitude ratios for distance corrected amplitudes as a function of both distance and magnitude for two candidate discriminants and shows separation of crustal and deep ground truth earthquake populations. We will want to test

these with full MDAC correction and ECM for performance, and assess datasets with no ground truth depths for possible recategorization of existing mislocated events with poor depth control.
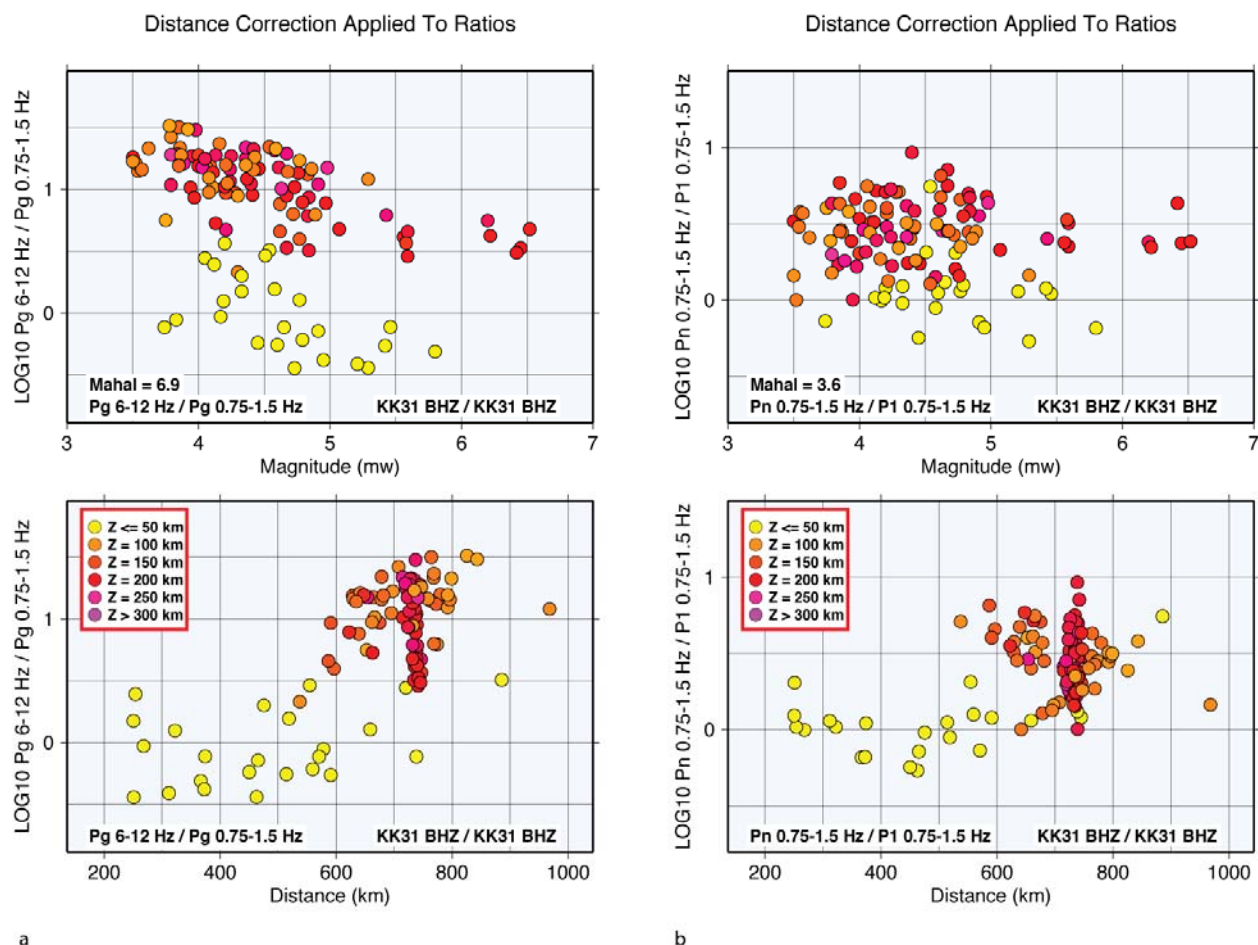
Figure 8. (a) Discrimination plots of Pg spectral ratio (6-12 Hz / 0.75-1.5 Hz) from RMS amplitude measurements (in displacement) made at KK31. Only events with 4 or more teleseismic depth phases were used to make this figure. A distance trend derived from the crustal earthquakes has been removed from all ratios. As the deep events have no true Pg phase, this plot is comparing a phase ratio for the crustal events to a P-coda ratio for the deep events. (b) Discrimination plots of the first-P amplitude in ratio with a P-coda amplitude. See Figure 7 for a description of the P-coda window. Because the P-coda decays more rapidly for deep events compared to crustal events, and because the first-P of the deep events are more impulsive that the crustal events, this discriminant separates the event populations. We will experiment with P-coda window positions and length to attempt to improve this discriminant.

In addition to the separation we continue to observe the systematic variation in residuals for events clustered in a narrow distance range. We will need to investigate this further as it may be an indication of source anomalies for at least a portion of the deep event population. If we can identify and exploit these anomalies, they lead to other candidate discriminants for further evaluation.

CONCLUSIONS AND RECOMMENDATIONS

We developed a small ground truth data set for deep events recorded at regional distances and shown potential discriminants for deep events. We need to develop additional ground truth data for both deep and crustal events in the Pamir Hindu-Kush region with screening events in published earthquake catalogs and merging catalogs with

additional information to relocate events for improved depth control. We also need to pursue all available seismic waveform signatures for deep events recorded at regional distances and test potential discriminants with MDAC and ECM for performance analysis. We further need to use successful discriminants to isolate mislocated deep events from existing calibration datasets and refine the MDAC analysis of those datasets for only the crustal earthquakes to remove any exiting bias from using mislocated deep events.

ACKNOWLEDGEMENTS

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