SOME INTERESTING SEISMIC EVENTS FROM WESTERN CHINA

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ABSTRACT

Over the past year we have investigated some interesting seismic events from western China. We have obtained records of small (about 2 tons), shot-hole chemical explosions from within about 350 km of station WMQ. These events allow us to test Pg/Lg discriminants down to magnitude levels between 2 and 2.5. We have also obtained records at WMQ of a seismic event from Qinghai Province that has an unusually strong Pn arrival. We have not yet identified the source of this event. Finally, we have worked with the late January, 1999 earthquakes from near the Lop Nor test site. Below, we briefly describe each of these investigations.

We have obtained information on shot locations, charge sizes, shot days, and approximate shot times pertaining to crustal-scale refraction profiles conducted in China during the years 1986-1989. We were interested in explosions from the summer of 1988, because these occurred at distances between 200 and 500 km from station WMQ in northwest China. We obtained lists of trigger times at WMQ for the months of July and August 1988 from the IRIS DMC. From the trigger lists, we determined that the 1988 explosions were detonated at the hours of 1700 and 1900 GMT. To date we have obtained WMQ were detonated between about 200 and 350 km from WMQ. We have measured Pg and Lg amplitudes from these chemical explosion records, from many nearby earthquakes, and from the September, 1988 Lop Nor nuclear explosion (mb near 4.6). We find that the single-charge chemical explosions (with mb's between about 2.0 and 2.2) and the nuclear explosion clearly separate from the small earthquakes when Pg/Lg (4-8 HZ) ratios are plotted versus magnitude.

On January 27, 1999 a seismic event from near the Chinese nuclear test site at Lop Nor was detected and located by the PIDC. The PIDC assigned a body wave magnitude of 3.9. On January 30, 1999 a second, larger seismic event from near Lop Nor was detected and located by the PIDC and by the NEIC. The PIDC assigned an mb of 5.3 and the NEIC assigned a preliminary mb of 5.8. We obtained regional waveforms for these events. Using the newly retrieved data and the previously processed events from NIL, we classify these events as earthquakes. We have also used the larger event to design phase-matched filters to enhance the surface waves of the smaller event as recorded at regional distances.

On December 6, 1997 a seismic event with mb near 4.5 occurred in a mountainous region of the east-central Qinghai Province, China. The event was detected and located by the PIDC and by the NEIC. Both organizations fixed the depth when estimating the event's location. The PIDC estimated an mb of 4.2 and an Ms (using only 2 stations) of 3.4. Using the PIDC mb:Ms event screening criteria this event falls within the earthquake population. We obtained regional waveforms for this event. In general, signal-to-noise ratios are poor for body waves at frequencies above about 2 HZ, except at stations WMQ (1350 km NE) and MAKZ (2000 km NE). We merged arrival times from regional stations with times from the NEIC and PIDC bulletins and relocated the event. Our relocation moved the event about 10 km farther south, but we could not constrain depth. Rayleigh and Love waves at periods between about 15 and 25 seconds generally have good signal-to-noise ratios at most regional stations. Because we do observe clear surface waves, we assume the event was not unusually deep. At WMQ we observe that Pn above 1 Hz is unusually strong relative to the shear phases Sn and Lg, and Pn is also unusually strong relative to the Love and Rayleigh waves. We do not know the cause for these observations. Possible explanations could include some combination of these factors: (1) some type of a large mining explosion, (2) an earthquake with an unusual source radiation pattern, (3) unusually strong Sn and Lg attenuation (or phase blockages) along the path to WMQ, (4) unusual focusing of Pn energy due to the geometry of the crust-mantle boundary along the path to WMQ.

Key Words: Special Events, Discrimination, Regionalization

OBJECTIVE

Over the past several years seismic verification research has emphasized the analysis of seismograms recorded at regional distances (between about 200 and 2000 km). The primary objective of this research has been to lower magnitude levels at which events can be detected, located, and identified. Our efforts have been directed at regional event identification in Asia. While conducting research in this field we have come across several interesting seismic events. In this paper we discuss three specific event identification situations, each of which provides unique examples of how regionalization and discrimination research efforts contribute to monitoring nuclear test ban treaties.

In our first example, we obtained records of small (about 2 tons), shot-hole chemical explosions from within about 350 km of station WMQ in northwest China. These events allow us to test Pg/Lg discriminants down to magnitude levels near mb 2.0. We are able to show that the Pg/Lg discriminant does separate explosions from earthquakes as magnitudes drop below mb 4.0. Our second example demonstrates why regionalization research is important in preparing for treaty monitoring. In late January 1999 an earthquake sequence from near the Lop Nor test site was recorded at NIL in Pakistan. We obtained autodrm data in near real time and measured these waveforms. Because we had done earlier regionalization work in this area, we were able to quickly classify the January 1999 events as earthquakes. Our final example shows that there are still regionalization research issues that must be resolved to effectively monitor treaties. We show waveforms from a seismic event that occurred in December 1997 in Qinghai Province, China. At WMQ the short-period records look explosion-like. However, we observe strong regional Love and Rayleigh waves, and we are currently unable to confidently classify this event.

RESEARCH ACCOMPLISHED

Example 1: Small chemical explosions

When approaching the regional identification (or discrimination) problem, seismologists can often assemble data sets of large nuclear explosions (4.5 < mb < 6.2). For instance, Hartse et al. (1997) studied large nuclear explosions from the former Soviet test site in Kazakhstan (KTS) and the Chinese test site at Lop Nor by com-paring P/S ratios of the nuclear explosions to ratios of earthquakes. As the tectonically active regions of central Asia have high levels of natural seismicity, digital earthquake data sets that span a wide range of magnitudes (2.5 < mb < 6.0) can be assembled for these analyses. Even for regions of relatively low natural seismicity, digital records of at least a few small earthquakes can generally be assembled for discrimination studies (cf. Hartse, 1998). However, regional-distance records of known, low-yield nuclear tests for central Asia are not available. Therefore, it is difficult to assess the performance of the P/S regional discriminants when event size drops below mb 4.5.

We have recently obtained near-regional seismograms, recorded at WMQ, of chemical explosions detonated in 1988. These explosions provided the energy source of crustal-scale refraction profiles conducted in China (Figure 1, top) during the late 1980's (Li and Mooney, 1998; Mooney, 1998). Unlike delay-fired mining explosions, these were single-charge explosions shot in tamped holes. We assume that these single-charge chemical explosions can be treated as surrogate nuclear explosions. Our assumption is primarily based on results of the Department of Energy Non-Proliferation Experiment (NPE) conducted at the Nevada Test Site (NTS) in 1993. This experiment demonstrated that the seismic source functions for single-charge chemical and nuclear explosions are equivalent. (e.g. Denny et al., 1995; Stump et al., 1999). Thus, we expect single-charge chemical explosions to produce nearly identical seismic signatures and discriminants (Walter et al., 1995) as those from similarly-sized nuclear explosions when detonated under similar emplacement conditions.

We obtained all waveforms for our chemical explosion study from the IRIS Data Management Center (DMC). All data were recorded at WMQ, which began digital recording in late 1986. We requested waveforms recorded from late 1986 through mid-1998. All events fall within a box bounded from 34° to 52° north latitude and from 77° to 100° east longitude (Figure 1).

We obtained most of our data from PDE, REB, and SSB (Gao and Richards, 1994) event catalogs. We obtained our catalog of chemical explosions from a report by Mooney (1998) that describes interpretation

of crustal-scale refraction and reflection profiles in China. The report describes the chemical explosions used as the energy source for a refraction experiment conducted during the years 1986-1989. The report lists shot days and shot locations, but describes detonation times only as near midnight, which we assumed to be a local time. In 1988 the BH (20 sps) and the SH (40 sps) components at WMQ were operated in an event-detection mode. We therefore examined lists of WMQ SH and BH trigger times in an attempt to deduce the GMT explosion times. We found that the explosions occurred at near the hours 1900 or 1700 one day before the shot day listed in Mooney (1998). We obtained waveforms from three July explosions with good signal-to-noise ratios (Figure 1, bot-tom). Figure 1 shows example explosion and earthquake waveforms that have been bandpass filtered between 1 and 8 Hz. Note that for both the nuclear and chemical explosion Pg amplitude is about three times greater than Lg amplitude, while for the earthquake Lg amplitude is much greater than Pg amplitude. These basic patterns of relative P and S energy on the explosion and earthquake seismograms allow us to separate the explosions from the earthquakes on our discrimination figures presented below.

Before making any measurements we corrected each seismogram for instrument response into units of displacement in meters. We made time-domain phase amplitude measurements in several one-octave filter bands from 0.5-1 Hz up to 8-16 Hz. For measurements up to 8 Hz we used the BHZ component, whenever available. If BHZ was not available, we used the SHZ component. For all measurements above 8 Hz we used the SHZ component. After manually picking each regional phase arrival, we bandpass filter, cut appropriate data windows, and measure the RMS amplitude (in the LOG10 domain) for Pn, Pg, Sn, Lg, and pre-event noise. More details of our amplitude measurements are given in Hartse et al. (1997). Following amplitude measurements we corrected amplitudes for the effects of source and path using the MDAC method (Taylor et al., 1999).

Using the MDAC-corrected Pg and Lg amplitudes, we tested several ratios as discriminants. We found that the high-frequency Pg/Lg (4-8 Hz) ratio (Figure 1) separates the small chemical explosions from the small earthquakes, just as we had previously shown this discriminant separating larger (mb > 4.5) explosions and earthquakes in Hartse et al. (1997). Although we do not show the example in this paper, we also find that the Pg/Lg cross-spectral ratio separates the small explosions from the earthquakes. In general, the results of this study suggest that the discriminants derived from earthquakes and explosions at larger magnitudes (mb > 4.5) can be extra-polated to smaller magnitudes (mb near 2.0).

Example 2: January 1999 Lop Nor Earthquakes

On January 27, 1999 at near 06:25 GMT a seismic event from near the Chinese nuclear test site at Lop Nor was detected and located by the Prototype International Data Center (PIDC). The PIDC assigned an mb of 3.9 to this event. On January 30, 1999 at near 03:51 GMT a second, larger seismic event from near Lop Nor was detected and located by the PIDC and by the USGS National Earthquake Information Center (NEIC). The PIDC assigned an mb 5.3 to this event and the NEIC assigned a preliminary mb of 5.8. As each event was reported in the seismic bulletins, we used email-based automatic data request manager (autodrm) commands to retrieve broadband waveforms from station NIL in Pakistan. NIL is about 1610 km from Lop Nor. CTBT seismic researchers at Los Alamos had previously retrieved and processed several seismic events from northwest China that were recorded at NIL, including four nuclear explosions from Lop Nor (Figures 2 and 3). Using the newly retrieved data and the previously processed events, we did a quick event identification analysis of the January 1999 events. As we had previously retrieved and processed NIL data for events from near Lop Nor, we were prepared to quickly classify these January 1999 event as earthquakes.

Figure 2 shows a detailed map of events near Lop Nor and a discrimination plot based on events from the region bounded by 35° to 50° N and 80° to 95° E. The discrimination plot uses Pn and Sn phase amplitudes measured in the 4-8 HZ band. The waveform plots (Figure 3, top) show that for the explosions, the earthquakes, and the 27 January event Sn and Lg are barely above noise levels. However, for all of these events, in the 4-8 HZ band, Sn signal does exceed prephase noise levels. Hence, we were able to include all of these events in the discrimination plot shown in Figure 2. The earthquakes and the January 1999 events have Pn/Sn ratios that reach a maximum of about 2.5, while the nuclear explosions have Pn/Sn ratios that reach a minimum of about 6. Based on our experience with regional discriminants, this is very good

separation between the earthquakes and the explosions. Because the January 1999 events have nearly the same ratios as the earthquakes from near Lop Nor, we class the recent events as earthquakes.

We have tested other discriminants (that is, other combinations of phases and bands) using NIL data and obtained similar results. Also, we have tested these same discriminants using data from station AAK in Kyrgyzstan and again obtained similar results. These January 1999 events will prove extremely useful for future discrimination studies, path calibration research of regional body waves and surface waves, event location investigations, and other seismic regionalization efforts now underway at LANL. For example, we measured the group velocities of the larger event and, based on these group velocities designed phase-matched filters to enhance the surface waves of smaller nearby events. Figure 3 (bottom) shows how the phase-matched filter effectively isolates the surface waves of the smaller event as recorded at regional station AAK.

Example 3: An Unusual Seismic Event From Qinghai Province, China
On December 6, 1997 at near 04h53m GMT a seismic event occurred in a mountainous region of the east-central Qinghai Province, China (Figure 4). The event was detected and located by the PIDC and by the NEIC. Both organizations used only teleseismic records when estimating the event's location, and neither organization attempted to estimate an event depth. The PIDC assigned an mb of 4.2 and an Ms (using only 2 stations) of 3.4. The NEIC assigned an mb of 4.5. Using the PIDC mb:Ms event screening criteria, this event falls within the earthquake population.

We analyzed regional waveforms, mostly recorded by the CDSN, for this event. Unfortunately, stations LZH and XAN were not operating on December 6, 1997. In general, signal-to-noise ratios are poor for body waves at frequencies above about 2 HZ, except at stations WMQ (1350 km NE) and MAKZ (2000 km NE) (Figures 4 and 5). At WMQ we see an unusually strong Pn arrival, and the shear wave phases Sn and Lg are weak. Rayleigh and Love waves at periods between about 15 and 25 seconds generally have good signal-to-noise ratios at most regional stations (Figure 5, middle). We merged arrival times from the regional stations with times from the NEIC and PIDC bulletins and relocated the event. Our relocation moved the event about 10 km farther south, but we could not constrain depth. Because we do observe clear surface waves, we assume the event was not unusually deep.

Forming Pn/Sn discrimination ratios using WMQ measurements emphasizes the unusually strong Pn energy of this event (Figure 5, bottom). Note that the 06 December event is high on the ratio plots and within the population of Kazakh Test Site (KTS) explosions. Furthermore, the other presumed earthquakes from the Qinghai area do not display these characteristics. We do not know the cause for these observations. Possible explanations could include some combination of these factors: (1) some type of a large mining explosion, (2) an earthquake with an unusual source radiation pattern, (3) unusually strong Sn and Lg attenuation (or phase blockages) along the path to WMQ, (4) unusual focusing of Pn energy due to the geometry of the crust-mantle boundary along the path to WMQ. Whatever the cause or causes for these observations, this area will require more research effort. We need to calibrate the paths from Qinghai Province out to the regional stations, allowing for estimates of regional mb and Ms. Furthermore, we need to study the geometry of the crust-mantle boundary between the event and the regional stations.

CONCLUSIONS AND RECOMMENDATIONS

We presented three examples of interesting seismic events from western China. Our first example demonstrates that small (1.6 to 2.5 tons), single-charge chemical explosions can be separated from small earthquakes in the mb 2 to 2.5 range using P/S amplitude ratios. We recommend that other crustal-scale refraction survey explosions be used to test discriminants at low magnitudes. Explosions from such surveys may have been recorded at several IMS sites around the world and at other modern digital seismic stations. Our second example, identification of earthquakes from near Lop Nor, demonstrates the importance of regionalization and discrimination research in preparing to monitor the CTBT. Further, because the January 1999, earthquakes occurred close to Lop Nor, they present an excellent opportunity to calibrate regional seismic paths. In our final example, and event from Qinghai Province, we have found a seismic event with some characteristics that indicate an explosion and some characteristics that indicate an earthquake. Our

last example demonstrates the need for more regionalization research. We need to calibrate regional magnitude scales and better under the regional seismic paths in this part of Asia.

REFERENCES

Denny, M., P. Goldstein, K. Mayeda, and W. Walter, Seismic results from DOE's Non-Proliferation Experiment: a comparison of chemical and nuclear explosions, in Monitoring a Comprehensive Test Ban Treaty, NATO ASI Series, Kluwer Academic, Hingham, Massachusetts, 355-364, 1995.

Gao, L. and P. G. Richards, Studies of earthquakes on and near the Lop Nor, China, nuclear test site, *Proceedings of the 16th Annual DARPA/AF Seismic Research Symposium*, 106-112, 1994.

Hartse, H.E., The 16 August 1997 Novaya Zemlya seismic event as viewed from GSN stations KEV and KBS, *Seismol. Res. Let., 69, No. 3,* 206-215, 1998.

Hartse, H.E., S.R. Taylor, W.S. Phillips, and G.E. Randall, Regional event discrimination in central Asia with emphasis on western China, *Bull. Seism. Soc. Am.,* 87, 551-568, 1997.

Li, S. and W.D. Mooney, Crustal structure of China from deep seismic sounding profiles, *Tectonophysics*, 288, 105-113, 1998.

Mooney, W.D., Crustal structure of China and adjacent areas: A final report of the detailed compilation of data and results, *DOE Report DE-A101-97NN20004*, 1998.

Stump, B.W., D. C. Pearson, and R.E. Reinke, Source comparisons between nuclear and chemical explosions detonated at Rainier Mesa, Nevada Test Site, *Bull. Seism. Soc. Am.,* 89, 409-422, 1999.

Taylor, S.R., A.A. Velasco, H.E. Hartse, W. S. Phillips, W.R. Walter, Amplitude corrections for regional seismic discriminants, Los Alamos National Laboratory, Los Alamos, NM, LAUR-99-3040, submitted to *PAGEOPH*, 1999.

Walter W.R., K.M. Mayeda, and H.J. Patton, Phase and spectral ratio discrimination between NTS earthquakes and explosions: Part I: Empirical observations, *Bull. Seismol. Soc. Am.,* **85,** 1050-1067, 1995.

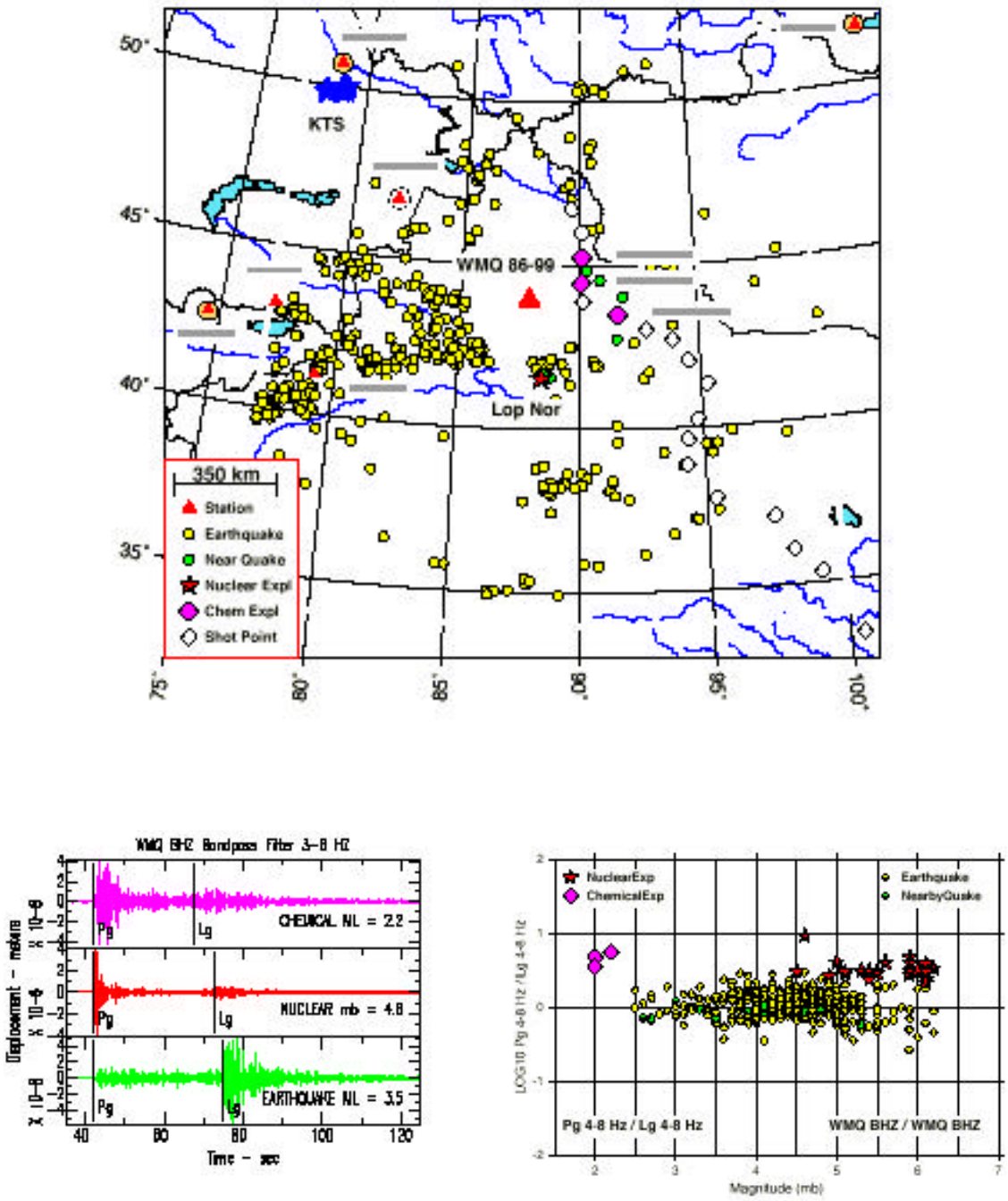


Figure 1. Map showing seismic events from northwest China (top), WMQ seismograms of a regional chemical explosion, a nuclear explosion, and an earthquake (bottom left), and the Pg/Lg (4-8 Hz) discrimination plot (bottom right). The diamonds on the map indicate refraction profile shot point locations and the dark diamonds indicate the explosions with seismic records at WMQ. Note that these small (2 ton), single-charge explosions can be separated from the small earthquakes.

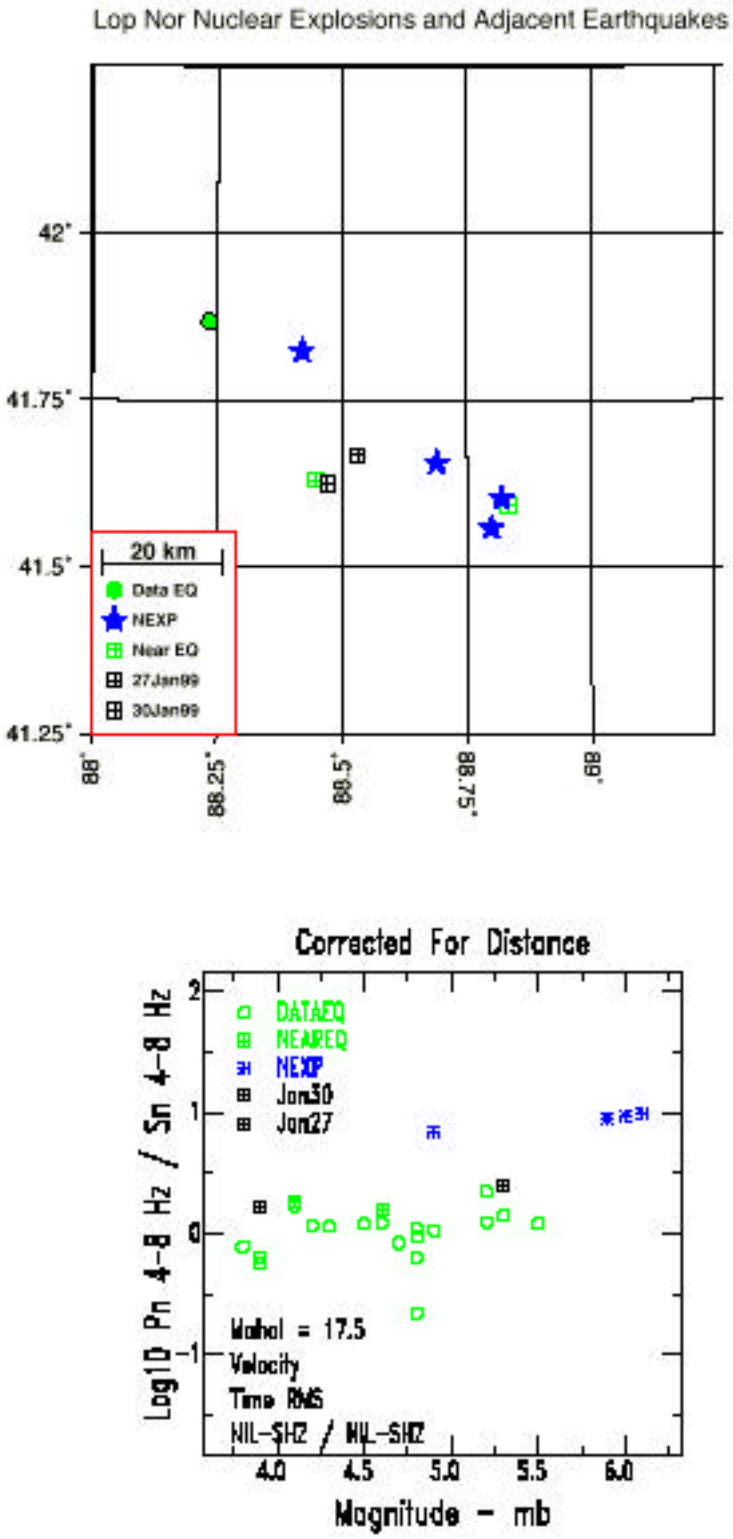
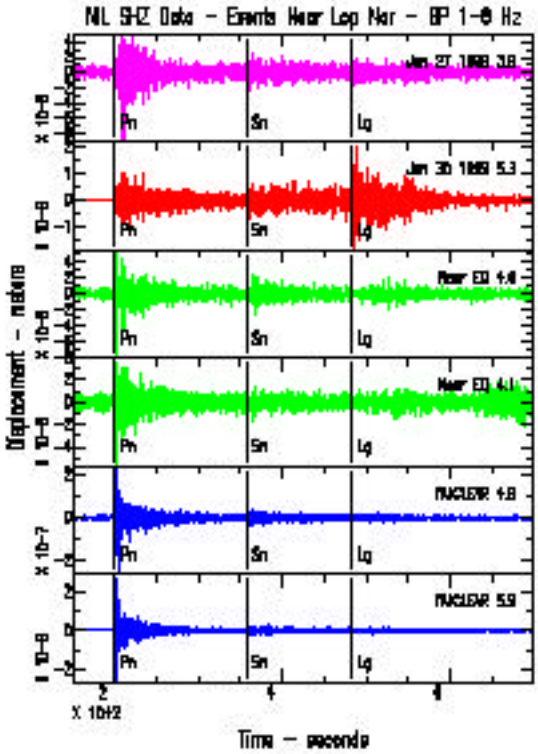


Figure 2. Map of the area around Lop Nor and locations of seismic events that have been recorded at NIL (top), and the Pn/Sn (4-8 Hz) discrimination plot of seismic events from the Lop Nor region (bot-tom). Note that the January, 1999 seismic events fall within the earthquake population. Waveforms are shown in Figure 3.



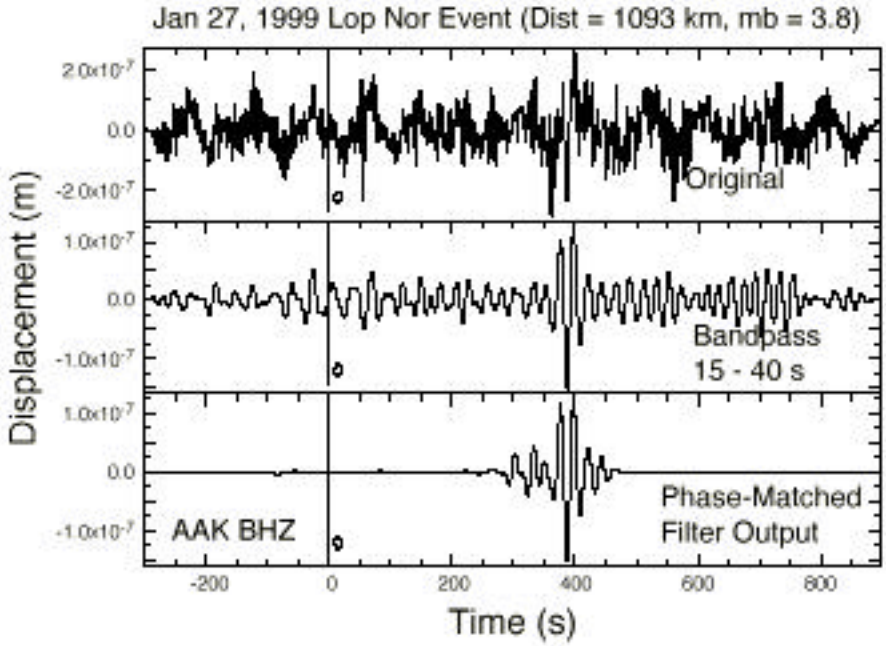


Figure 3. Short-period seismograms of four earthquakes and two nuclear explosions from Lop Nor recorded at NIL (top). The two top traces are the 27 Jan and 30 Jan seismic events. Also, we show the broadband, bandpass filtered, and phase-matched filtered seismograms of the 27 Jan event as recorded at AAK. We designed the phase-matched filter using the large Lop Nor earthquake (mb 5.2) of 30 Jan.

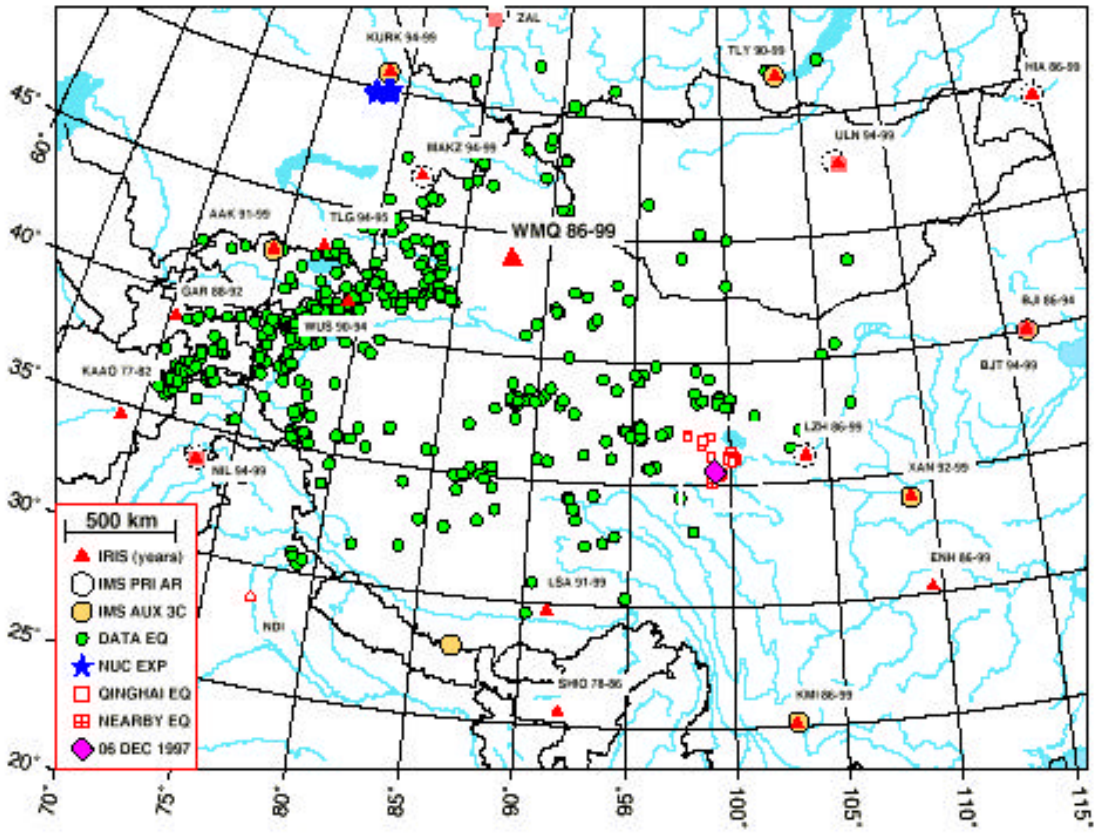


Figure 4. Map of western China showing the location of the 06 Dec 1997 Qinghai seismic event (diamond). The open squares near the diamond are earthquakes that occurred near the 06 Dec event. Waveforms and discrimination plots related to these events are shown in Figure 5.

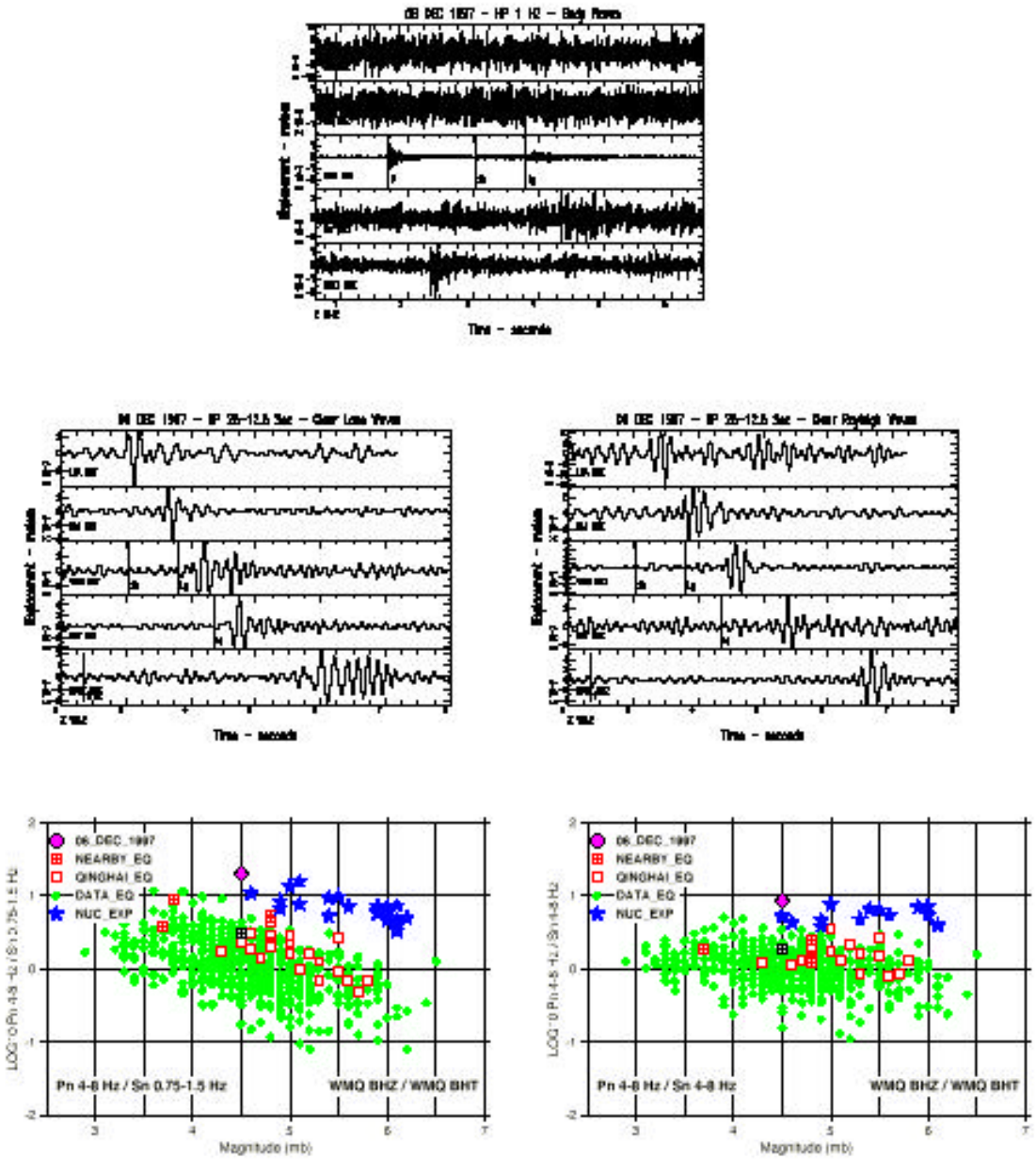


Figure 5. Short-period waveforms (top) and long-period waveforms (middle) of the 06 Dec 1997 Qinghai event recorded at several CDSN stations. The middle trace of each waveform display is data from WMQ. Note the Unusually strong Pn arrival at WMQ. The 06 Dec event is high in the nuclear explosion population on the Pn/Sn discrimination plots (bottom).