Discrimination of Earthquakes and Explosions near Nuclear Test Sitesusing Regional High-frequency Data

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Introduction

We examine over 30 seismic events located by the CTBT IDC and its predecessor from 2000 through 2008 within 100 km of two known test sites -- Xinjiang, western China around Lop Nor test site and northeastern North Korea. 20 events with magnitude, mb > 3.4 were reported in the Reviewed Event Bulletin (REB) by the IDC near the Lop Nor test site. Only four seismic events were reported within 100 km of the North Korea nuclear explosion of 2006. The selected events are in the magnitude range of mb(REB) 3.4 to 4.4. For seismic events of magnitude > 4.0, focal mechanisms (CMT), mb:Ms, depth phases, and analysis of teleseismic body waves and long-period surface waves can be used to identify these events as reported in a companion paper by Sykes & Nettles (2009). However, regional phases Pn, Pg, Sn and Lg must be used to characterize the majority of small events with magnitude mb(REB) < 4.0 (~75% of the selected events). We analyze regional three-component seismic records to characterize those events and to seek the best regional phases and frequency bands that can help us to discriminate an explosion from the earthquake population.

Methods

To identify small earthquakes from the explosions, we use event characterization parameters laid out in the CTBT Protocol and its Annex 2 as listed below. Specifically, we will use spectral ratios of regional seismic phases on 3-component records to identify source types.

September 10, 1996

COMPREHENSIVE NUCLEAR TEST-BAN TREATY

ANNEX 2 TO THE PROTOCOL

List of Characterisation Parameters for International Data Centre Standard Event Screening

1. The International Data Centre standard event screening criteria shall be based on the standard event characterisation parameters determined during the combined processing of data from all the monitoring technologies in the International Monitoring System. Standard event screening shall make use of both global and supplementary screening criteria to take account of regional variations where applicable.

2. For events detected by the International Monitoring System ***seismic component***, the following parameters, inter alia, may be used:

- o location of the event;
- o depth of the event;
- o ratio of the magnitude of surface waves to body waves;
- o ***signal frequency content***;
- o ***spectral ratios of phases***;
- o spectral scalloping;
- o first motion of the P-wave;
- o focal mechanism;
- o ***relative excitation of seismic phases***;
- o comparative measures to other events and groups of events; and
- o regional discriminants where applicable.

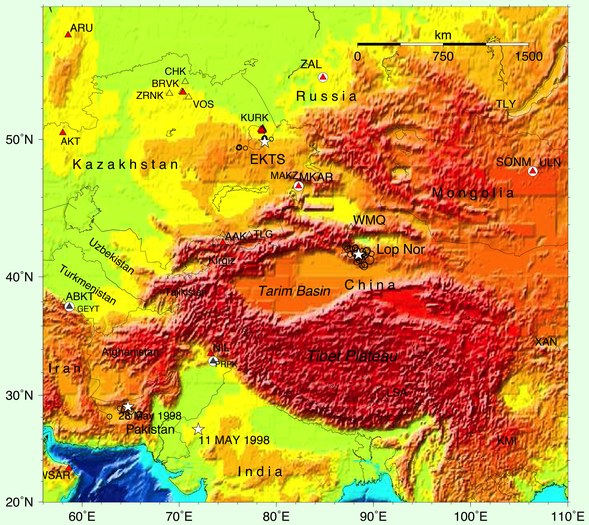

Figure 1. Known nuclear test sites in Asia (*stars*) and seismic events reported in REB that occurred within 100 km from the test sites (*open circles*). IMS primary network stations (*encircled red triangles*), auxiliary stations (*red triangles*) and ***open*** seismographic stations (*open triangles*) whose records are available in real time.

Seismic Events that Occurred near Lop Nor, Xinjiang, China

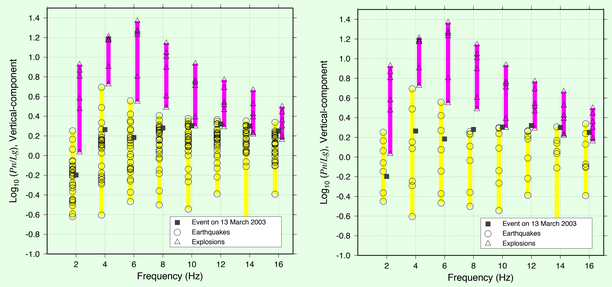

Figure 2. Measurements of the spectral amplitude ratio between P- and S-waves. Amplitudes were determined from eight frequencies using the crustal phases Pn, Pg and Lg, on vertical recordings. The known nuclear explosions (*triangles*, with the full range marked in pink) consistently have higher values than the earthquakes (*circles*, with the range in yellow). The event of 13 March 2003 (*squares*) clearly falls in the earthquake population, but show relatively strong ampliutdes at high frequency band 10 - 16 Hz. (left panel) 20 seismic events near Lop Nor test site reported in REB (mb > 3.4) and seven additional events from ISC bulletin (see list below) are plotted. (right panel) Seven seismic events with magnitude mb > 4.5 and six known underground nuclear explosions at Lop Nor test sites are plotted to examine for magnitude bias on spectral ratios.

Preliminary Results

Analysis of 20 earthquakes that occurred within 100 km from the Lop Nor Chinese test site reported in the REB indicates that vertical P wave to S wave ratios (Pn/Lg) of earthquakes are around 1.0 in the frequency band 1-16 Hz, whereas the same spectral ratios from six underground nuclear tests conducted at the Lop Nor test site during the 1990s are about 5.0 in the same frequency band without attenuation correction (see Figure 2). This suggests that the high-frequency P/S spectral ratios can be an efficient method to distinguish between explosions and earthquakes in the Lop Nor region, western China.

Regional records in the distance range 200 – 2,000 km are used for the preliminary analysis. The stations used include an IMS primary network station MKAR and three surrogate stations, NIL, ABKT and ULN as well as four IMS auxiliary stations in central Asia (see Figure 1).

In the case of the earthquakes and explosions around the North Korean test sites, the P/S spectral ratios from the earthquake and explosion population overlap significantly at frequencies of 1-7 Hz, but the spectral ratios from the two populations are fairly well separated in the range 9-15 Hz (Figure 5). These preliminary studies indicate that high-frequency P/S spectral ratio provides an efficient method to identify seismic source types for seismic events of magnitude < 4.0.

XINJIANG, CHINA

IDC REB (Reviewed Event Bulletin)

Date	Time	Lat	Long	h (km)	mb
2001-02-04	02:07:56.9	41.76	89.88	27	3.6
2002-04-09	14:38:18.8	42.08	89.65	0	3.4
2002-09-09	17:37:03.5	40.79	88.91	0	4.0
2003-01-22	13:33:04.4	42.28	87.51	23	4.0
2003-02-13	18:32:46.6	41.88	88.34	32	3.6
2003-03-13	15:07:08.3	41.78	89.08	25	4.3
2003-06-15	13:19:44.7	42.11	87.81	0	3.5
2003-10-01	09:01:19.6	41.80	89.17	34	3.7
2003-10-01	09:58:56.4	41.82	89.29	0	3.8
2003-12-19	15:01:20.0	41.88	88.90	0	4.2
2004-07-08	18:36:35.3	41.74	88.10	32	3.4
2005-10-11	14:48:12.1	42.13	88.71	0	3.5
2006-03-15	04:30:19.0	41.92	88.35	0	3.9
2006-03-23	12:25:11.0	42.12	87.73	0	3.9
2006-08-05	07:44:54.4	41.22	88.73	0	3.8
2006-09-21	07:42:45.3	41.13	88.39	0	3.6
2007-05-11	23:01:46.0	40.89	88.79	0	3.5
2007-08-25	11:12:58.9	41.16	88.28	0	3.9
2007-11-18	11:35:14.6	42.25	88.12	0	4.1
2008-08-16	12:21:19.6	42.27	88.09	0	3.7

Underground Nuclear Tests at Lop Nor test site

Year-mo-dy	hr:mn:sec	Lat	Long	h (km)	mb
1988-09-29	07:00:00.0	41.73	88.37	0.1	4.7
1994-10-07	03:26:00.2	41.57	88.72	0.6	6.0
1995-05-15	04:06:00.2	41.55	88.75	0.7	6.1
1995-08-17	01:00:00.1	41.54	88.75	0.6	6.0
1996-06-08	02:56:00.1	41.58	88.69	0.5	5.9
1996-07-29	01:49:60.0	41.72	88.38	0.1	4.9

Additional Events around Lop Nor from ISC Bulletin

Year-mo-dy	hr:mn:sec	Lat	Long	h (km)	mb
1987-12-22	00:16:39.2	41.32	89.62	21	5.8 5.3 Ms
1988-11-15	16:56:45.0	42.04	89.35	26	4.9 4.3 Ms
1990-11-03	17:25:14.0	40.85	89.03	22	5.1 4.5 Ms
1992-11-27	16:09:09.3	41.96	89.26	14	5.2 4.8 Ms
1995-03-18	18:02:36.8	42.40	87.17	22	5.1 4.5 Ms
1999-01-27	06:25:03.0	41.55	88.35	41	4.2 3.2 Ms
1999-01-30	03:51:05.0	41.59	88.45	21	5.8 5.2 Ms

NORTH KOREA (REB)

Year-mo-dy	hr:mn:sec	Lat	Long	h (km)	mb
2002-04-16	22:52:38.6	40.68	128.63	0	3.9
2004-12-16	18:59:12.9	41.91	127.88	0	3.5
2006-10-09	01:35:27.5	41.31	129.02	0	4.1
2009-05-25	00:54:42.8	41.31	129.05	0	4.5

Seismic events that occurred around North Korean nuclear test site

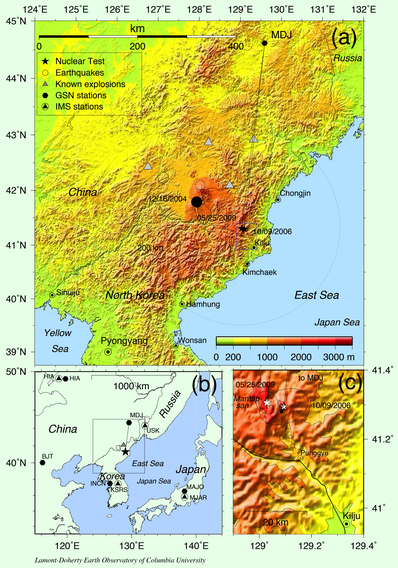

Figure 3. (a) Locations of recent earthquakes (circles), chemical explosions (triangles), nuclear tests on 9 October 2006 and 25 May 2009 (stars), and an ***open*** seismographic station MDJ (Mudanjiang, China; hexagon) in the North Korea-China, region.

(b) Map showing the North Korean nuclear test (stars), GSN stations (solid hexagons) and the International Monitoring System (IMS) of CTBT Organization (*encircled triangles*).

(c) Seismic locations of the nuclear tests (stars), tunnel entrance detected by surveillance satellites (filled square), suspected buildings for test (open square) around the Mantapsan (만탑산, 2205 m) site and villages (circles). Punggye (풍계)is a large village with railway station at the mouth of the valley and Kilju (길주)is a major city. Locations denoted by dates are given by NEIC/USGS. Error ellipse indicates 90% confidence interval for the final seismic location uncertainty.

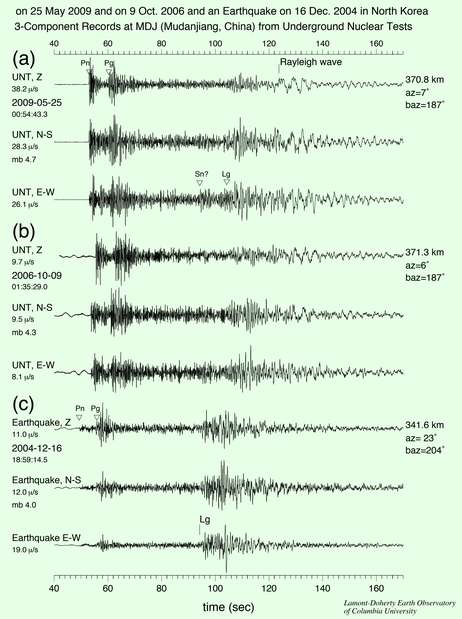

Figure 4. Three-component seismic records (Z, vertical; N-S, north-south; and E-W, east-west) at MDJ. (a) The nuclear test on 9 October 2006, (b) nuclear test on 25 May 2009, and (c) an earthquake on 16 December 2004. Traces are plotted with the origin time of each event. The event ID (UNT, underground nuclear test or Earthquake), component, peak amplitude of trace in micrometers per second, date and origin time, and magnitude are indicated. Peak amplitude of records from 25 May 2009 explosion are about 3 to 4 times greater than from those of 9 Oct. 2006.

Notice the strong P waves from the nuclear explosions, and clear Rayleigh waves on vertical records from explosions which indicate very shallow source depth. Notice the weak P waves and relatively strong S energy (Lg waves) on earthquake records, in particular, S waves on E-W component records (~ transverse wave motion) are nearly twice greater than vertical or N-S (~radial motion) components. This is a typical characteristics of an earthquake source as shear displocation along the fault plane.

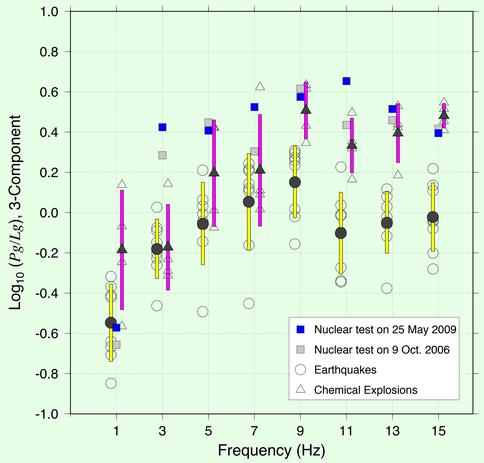

Figure 5. Three-component Pg/Lg spectral ratios at eight discrete frequency points used in discrimination analysis are plotted for earthquakes, chemical explosions, and the nuclear tests. A mean value at each discrete frequency point is plotted for earthquakes (solid circles) and explosions (solid triangles), with their colored arms representing the scatter (s.d.). The explosion have higher P/S ratios than the earthquakes and separation of two populations is better at high frequencies. The spectral amplitude ratios of the 9 Oct. 2006 (grey squares) as well as 25 May 2009 (blue squares) explosions fall in the explosion population.

How similar seismic records from the explosions on 9 Oct 2006 and 25 May 2009 are?

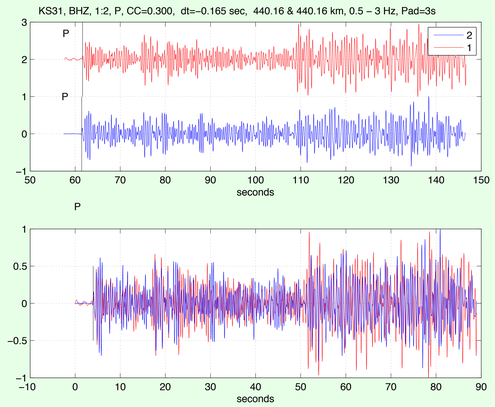

Figure 6. (top panel) Vertical records from the explosions on 2006-10-09 (red trace) and 2009-05-25 (blue trace) at KSRS (Wonju array, South Korea, ~440 km) are aligned to P arrivals, (bottom panel) two records are cross-correlated (0.5-3 Hz band) with the cross-correlation coefficient of 0.30, which suggests that two records are not quite similar. Since the distances are nearly the same, the poor waveform correlation may be due to deeper source depth for 2009 explosion.

Conclusions and Recommendations

Identification of small-sized earthquakes (M ~ 3) and low yield underground explosions (< a kiloton) can be done with very high confidence based upon vertical- and three-component P/S spectral ratios.

Identification of explosions in western China near Lop Nor test site and northern Korea can be done even down to a very small fraction of a kiloton provided seismic data from the IMS stations and other ***open*** seismographic stations are available.

The nuclear test carried out by North Korea on 9 October 2006, and the way in which objective data emerged that enabled it to be characterized, provided the first practical test for the CTBT monitoring regime.

References

Kim, W.Y. and P.G. Richards (2007), North Korean Nuclear Test: Seismic Discrimination at Low Yield, ***Eos Transactions AGU***, April 3, 2007.

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