SEISMIC SOURCE AND PATH CALIBRATION IN THE KOREAN PENINSULA, YELLOW SEA AND NORTHEAST CHINA

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Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Development
Office of Defense Nuclear Nonproliferation

Contract Nos. DE-FC52-04NA25539[1] and W-7405-ENG-48[2]

ABSTRACT

Two significant seismic events were analyzed using the crustal velocity model developed under this contract. The M_W = 4.55 Korean earthquake of January 20, 2007, occurred in the Republic of Korea on land and within the dense digital seismic network. Using P-wave arrivals from 60 broadband, short-period and acceleration stations, the event occurred at 37.68N, 128.58E at a depth of 7.5 km at 20070120115653.8. Source inversion was performed using the accelerometer recordings in the 0.05–0.20 Hz band and the broadband data in the 0.02–0.10 Hz band, with identical focal mechanisms and source depths of 9 and 11 km, respectively. This is the largest event on land in South Korea since the Mw 4.7 event on December 13, 1996. Forward modeling of the waveforms at INCN and MDJ indicates the ability of the current model to match observations on the Korean Peninsula and the effect of significant pulse shape modification for paths that partially cross the Sea of Japan. The results of using the local network data provide a ground truth point for other studies analyzing seismic events on the peninsula.

The isotropic seismic moment of the October 9, 2006, North Korean explosion was estimated from the Rayleigh-wave spectral amplitudes observed at MDJ and INCN. Very little Love wave signal was observed, indicating weak tectonic release. The explosion yield was investigated using the Denny and Johnson (1991) model relating yield to the observed isotropic moment as a function of depth of burial and material properties. Sensitivity analysis highlights the strong effect of the assumed velocity and density structure in the upper kilometer of the Earth and the assumed depth of burial on the estimated yield. The crustal velocity model developed under this contract provides strong constraints on the expected shear-wave velocities in the shallow parts of the crust. Issues to be investigated include the effect of wave propagation through the Eastern Sea (Sea of Japan) to stations in South Korea, and the effect of attenuation on isotropic moment estimates over longer paths, e.g., to the station BJT in Beijing.

OBJECTIVES

The primary focus is the determination of moment magnitudes for earthquakes in the Korean Peninsula, Yellow Sea and Northeast China region for use in the calibration of coda based seismic moment determination. The source parameters are to be determined from the inversion of broadband waveforms of earthquakes in the region. To address the lack of large earthquakes, inversion of small earthquakes requires calibration of the shear-wave velocities in the upper crust in order to use the predominant signal in the higher frequency band of 0.05–0.2 Hz.

RESEARCH ACCOMPLISHED

In spite of the reduced level of effort during the past year, significant results include the initial use of the Korean Meteorological Administration (KMA) accelerometer network for broadband source inversion and travel time studies. In addition the surface waves generated by the October 9, 2006, North Korean explosion were used in combination with the Korean crustal structure developed under this effort to estimate source yield.

Moment Tensor Solutions for Korea Earthquakes

At the end of 2006, KMA changed their web site for access to digital seismograms. The positive aspect of this change is that digital waveforms for the velocity and acceleration sensors are available for all local earthquakes from 2001 to the present, and for many teleseisms from 2005 to the present. The waveforms data are in miniSEED, so that access is required to the station coordinate file. No station response information is provided though. The web page is designed in Javascript and works solely through the CGI interface, so that it is no longer possible to use the command *wget* to directly access the waveforms. The web site leading to the waveforms is http://www.kma.go.kr/neis/neis_01_02_01.jsp.

During the past twelve months only one earthquake, that of January 20, 2007, was large enough for source inversion. This was the largest earthquake on land since the Mw 4.7 event on December 13, 1996. Figure 1 shows the distribution of accelerometer and broadband stations used in the analysis. The locations given by different groups are as follows:

The St. Louis University (SLU) location uses the velocity model derived from the joint inversion of receiver functions and surface-wave dispersion developed under this contract for waveform studies (Herrmann et al., 2005). The SLU solution used 81 arrival times of P, S and Lg from 8 to 507 km.

The striking feature of the data set was the usefulness of the accelerometer channels for source inversion. We obtained separate source estimates using the broadband waveforms, the accelerometer waveforms and the surface-wave amplitude spectra from the broadband waveforms (Table 2). Figures 2 and 3 show representative fits to the low-pass filtered ground velocity for selected broadband and accelerometer waveforms. The large number of observations also provide a test of the velocity model. Figure 4 compares the P-wave first arrival picks to the model prediction. This is a valid comparison since our location is very close to the independent teleseismic USGS location.

Table 3 shows the earthquake source parameters determined for this and other events in the region under this contract.

Yield Estimation of the October 9, 2006, North Korean Explosion

The recent North Korean event of October 9, 2006, highlights both the opportunities of regional monitoring and the difficulties of working with a smaller than expected event. Seismic signals were observed regionally and teleseismically by open networks, permitting accurate location and determination of magnitude. The test was not automatically detected and located by the current NEIC system (Koper et al., 2007) although NEIC analysts were able to use P waves in the 3.3–81.0 degree distance range once they knew where to look. Subsequent studies demonstrated that large research arrays discerned the P wave and that signal stacking can be used to enhance the signal (Ammon and Lay, 2007).

Yield estimates are typically performed using a stable monitoring network and carefully constructed source-station corrections to estimate m_b, together with a regionally calibrated magnitude-yield relationship. Yield estimation is not trivial because the magnitude-yield relation depends upon source medium properties, depth of burial and the teleseismic propagation parameters, especially anelastic attenuation parameter t*.The final yield estimate is couched in terms of being valid for a normal depth of burial. Presumably an under-buried explosion is not a problem since it might blow out. An over-buried shot is problematic since it would have a lower than expected signal for a given yield and can be misinterpreted if assumed to be at a normal depth.

Koper et al. (2007) approached yield estimation for this test from the regional surface-wave signals at the stations MDJ (370 km) and INCN (475 km) to determine the isotropic moment. This was done using a Korea-specific crustal model developed for earthquake source inversion from surface-wave and receiver function observations (Herrmann et al., 2005) to create synthetic seismograms for a point explosion source. Spectral amplitudes of the observed and synthetic seismograms at periods between 10 and 30 seconds were obtained through multiple filter analysis (program *do_mft* of the Computer Programs in Seismology package). A simple regression determined the isotropic moment to be

$$M_I = 3.10\ (\pm 0.62)\ x10^{21}\ \text{dyne-cm}. \qquad (1)$$

These two stations were used since the paths from the test to the station did not significantly cross the Sea of Japan (Figure 5). The BJT station (1,103 km) at Beijing, China, was not used because of the greater distance, lack of knowledge of anelastic attenuation coefficients for the surface wave, and concern about path dependent effects for propagation through the sedimentary basins near Beijing. The paths are shown in Figure 5. Walter et al. (2007, these Proceedings) found a very similar isotopic moment using a slightly different velocity model and stations MDJ, TJN, INCN and BJT.

To estimate yield, the relations developed by Denny and Johnson (1991) were programmed in a general way in an Excel spreadsheet to permit an easy investigation of the relationship of changes in the material properties, yield, and depth of burial upon the seismological seismic moment estimate. Figure 6 shows the result of asking the question "What are the combinations of yield and emplacement depth compatible with the observed isotropic moment?" Two velocity models were considered for the upper kilometer—a generic Nevada Test Site (NTS) model characterized by a density of 2,000 kg/m^3 and S-velocity of 1,000 m/s, and a Korean model with a density of 2500 kg/m^3 and an S-velocity of 3,000 m/s. The NTS model was included since the Denny and Johnson data set included many events from NTS and since NTS is a well used reference model for explosions. The Korean model is based on the upper kilometer of the Herrmann et al (2005) model, and is thought to be representative of the mountainous shot region in North Korea.

Figure 6 serves several purposes. First, the importance of shot media is obvious because of the difference between the NTS and Korean curves. Since shots are typically within one kilometer of the surface, this highlights the importance of knowing near-surface velocity structure when studying buried explosions. A second aspect is more forensic in nature. If the yield is known independently, such as from a magnitude-yield relation, then Figure 6 can be used to estimate the depth of the shot. This is actually an important consideration for the North Korea shot since it is presumed to be smaller than expected for a first-time shot. If it were designed for a larger yield and buried at a normal scaled depth, then this event would be overburied with implications on the use of regional phase corner frequency to constrain yield.

There are many seismic stations that have observed this event. South Korea has roughly 20 broadband and 80–100 digital accelerometer recordings that have not been released. There is an International Monitoring System array in Wanju (roughly halfway across the peninsula, east of Inchon). As these data become available, there will be new challenges, specifically the effect of the mixed ocean-continent path across the Sea of Japan to most stations in South Korea. This will affect not only the low frequency surface-waves but also the high frequency regional signals.

Interestingly the high frequency signals at MDJ, TJN, and INCN were very impulsive. Richards and Kim (2007) compared MDJ recordings of explosions in and near North Korea to similarly located earthquakes and chemical explosions from the point of view of discrimination. The impulsive nature of the North Korean explosion P-wave at MDJ was obvious. Walter et al. (2007, these Proceedings) compared P to S amplitudes at several different high frequencies for stations MDJ and TJN and find good discrimination of the test from earthquakes in the region. Figure 7 presents the filtered vertical components at MDJ and INCN. The MDJ background noise was very low. Because of the higher noise level at INCN, the bandpass of 0.5–3.0 Hz was used for this comparison. The MDJ trace has a very strong Pn followed by a crustal P-wave arrival or Moho reflection. The INCN record has a sharp P_n. Since the P_n spectra can be used to estimate the source corner frequency, which is related to yield, source material, and depth of emplacement (Denny and Johnson, 1991). There should be concerns about the effect of crustal and upper mantle structure on the P_n spectra, especially given the very impulsive nature of these regional arrivals since synthetic seismograms would never give such sharp P_n arrivals for a simple layer-cake velocity model.

As mentioned, the surface-wave signal at BJT (1,100 km) was not used. There was a good surface-wave at longer periods; however, without correction for Q-effects, the estimated moment was significantly smaller than those from MDJ and INCN. This path effect must be understood for completeness.

CONCLUSIONS AND RECOMMENDATIONS

Because the path from the North Korea explosion to the INCN station was partially through the Eastern Sea (Sea of Japan), the question of the specific path effect on the surface-wave amplitude spectrum is important for yield estimation. The effects might be estimated by considering the reverse path from the January 20, 2007, earthquake north to the station MDJ. The general issue of source depth might be resolved by including the accelerometer waveforms in the location of larger events in the southern half of the peninsula in order to provide more ground truth events in the region. These same data may provide constraints on the crustal velocity model that produces such impulsive high frequency P waves for the explosion.

ACKNOWLEDGEMENTS

Maps were created using GMT (Wessel and Smith, 1995).

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Table 1. Location estimates of the January 20, 2007 earthquake.

Year	Month	Day	Hour	Min	Sec	Lat	Lon	Depth	Mag	Auth
2007	01	20	11	56	54.3	37.64	128.47	10	4.4	USGS
2007	01	20	11	56	51	37.75	128.69		4.8	KNEIC
2007	01	20	11	56	53.9	37.68	128.59	7.4	4.55	SLU

Table 2. Source parameters of the January 20, 2007 earthquake

Date set	H (km)	Strike (deg)	Dip (deg)	Rake (deg)	Mw
Accelerometer Waveform	9	115	85	-5	4.55
Broadband Waveform	11	115	85	-5	4.56
Surface-wave spectra	10	115	90	0	4.61

Table 3. Source parameters for earthquakes in the Yellow Sea Korea Peninsula region.

Date	Time(UT)	Lat(N)	Lon(E)	Depth	Mw	Strike	Dip	Rake	Source
		37.2	128.8	8	4.63	30	80	160	Walter
12/13/1996	04:10			6	4.67	211	61	163	Herrmann
06/25/1997	18:50	35.8	129.2	11	4.34	130	55	35	Herrmann
03/05/1999	14:41	40.3	127.5	0	3.69	32	58	164	Walter
04/07/1999	14:32	37.2	128.8	2	3.70	110	75	-10	Herrmann
		40.5	123.0	10	4.84	36	84	-176	Walter
01/11/2000	23:43			15	5.06	27	43	-178	HRV
12/09/2000	09:51	36.6	130.0	12	4.06	10	25	75	Herrmann
11/21/2001	01:49	36.7	128.3	7	3.39	115	55	35	Herrmann
11/24/2001	07:10	36.7	130.0	12	3.81	220	71	164	Herrmann
03/17/2002	00:26	37.0	124.5	7	3.71	30	65	-120	Herrmann
		40.7	128.4	10	4.0	330	80	-30	Walter
04/16/2002	22:52	40.7	128.7	7.0	3.98	340	85	35	Herrmann
07/08/2002	01:49	35.9	129.7	19	3.75	130	70	25	Herrmann
07/23/2002	12:48	35.6	122.2	19	4.83	120	70	25	Herrmann
12/09/2002	22:42	38.9	127.3	6	3.62	25	65	-180	Herrmann
01/09/2003	08:33	37.4	124.2	5	3.83	355	65	-170	Herrmann
03/22/2003	20:38	35.0	124.4	14	4.80	30	80	-170	Herrmann
03/30/2003	11:10	37.6	123.8	13	4.57	25	80	-155	Herrmann
04/15/2003	17:55	36.4	126.2	9	3.21	300	35	50	Herrmann
06/09/2003	01:14	36.0	123.6	15	3.89	35	85	20	Herrmann
		43.8	119.6	25	5.27	220	78	166	Walter
				26	5.39	202	56	174	GS
08/16/2003	10:58			30	5.39	317	57	10	HRV

Date	Time(UT)	Lat(N)	Lon(E)	Depth	Mw	Strike	Dip	Rake	Source
10/13/2003	09:12	37.0	126.5	9	3.77	25	75	-175	Herrmann
01/05/2004	16:49	38.7	125.1	7	3.30	135	60	25	Herrmann
		45.4	118.3	8	5.46	158	29	80	GS
03/24/2004	01:53			13	5.35	167	28	86	HRV
04/26/2004	04:29	35.8	128.2	10	3.59	150	60	50	Herrmann
05/29/2004	10:14	36.7	129.9	11	5.08	350	30	70	Herrmann
06/01/2004	11:22	36.7	129.3	11	5.08	350	30	70	Herrmann
08/05/2004	20:32	35.9	127.4	8	3.18	206	85	-165	Herrmann
		41.9	127.9	10	3.84	30	85	-170	Walter
12/16/2004	18:59			8	3.94	48	75	-170	Herrmann
06/14/2005	22:07	33.2	126.1	8	3.78	270	80	-5	Herrmann
06/29/2005	14:18	34.5	129.0	11	4.13	145	45	30	Herrmann
10/09/2005	23:51	37.9	124.9	6	3.55	175	73	148	Herrmann
01/19/2006	03:25	37.2	128.8	8	3.50	200	75	-180	Herrmann
03/31/2006	12:23	44.6	124.2	5	4.71	334	44	52	Walter
04/29/2006	02:01	37.1	129.9	6	3.63	100	70	-10	Herrmann
01/20/2007	11:56	37.7	128.6	9	4.55	205	85	-175	Herrmann

Herrmann: http://www.eas.slu.edu/Earthquake_Center/MECH.KR/

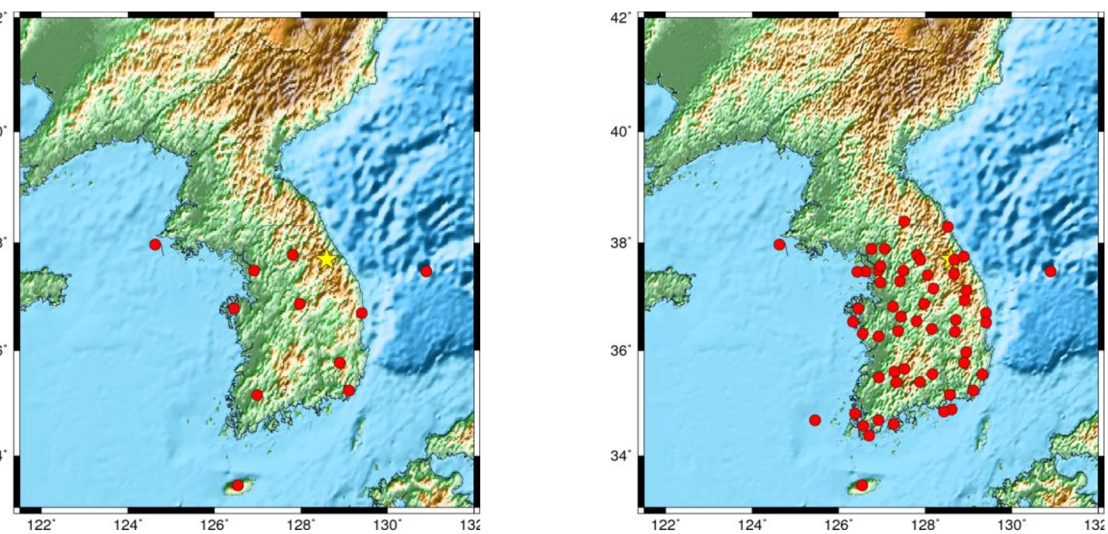

Figure 1. Location of the January 20, 2007 Korea earthquake (star) and the station locations for waveform analysis. Left: locations of KMA broadband sensors; right: locations of digital accelerometers.

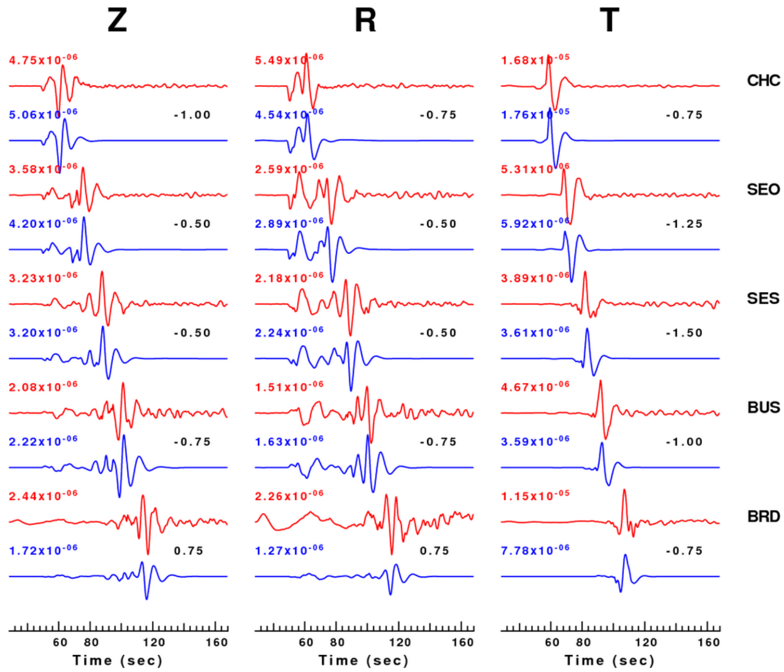

Figure 2. Selected broadband sensor recordings and model fit in order of increasing epicentral distance. All waveforms are ground velocity filtered with the sac/gsac commands *hp c 0.02 n 3* and *lp c 0.01 n 3*. For station/component pair (red is observed and blue is predicted) the same plot scale is used. The peak filtered velocity value is indicated adjacent to above the trace on the left. The number on the right indicates the time shift used for maximum correlation. Note that the time shift is with respect to the selected P-wave arrival and also that the Green's functions are computed with *DELTA=0.25* sec. The epicentral distances in *km* to the stations are CHC (70), SEO (150), SES (215), BUS (275) and BRD (350).

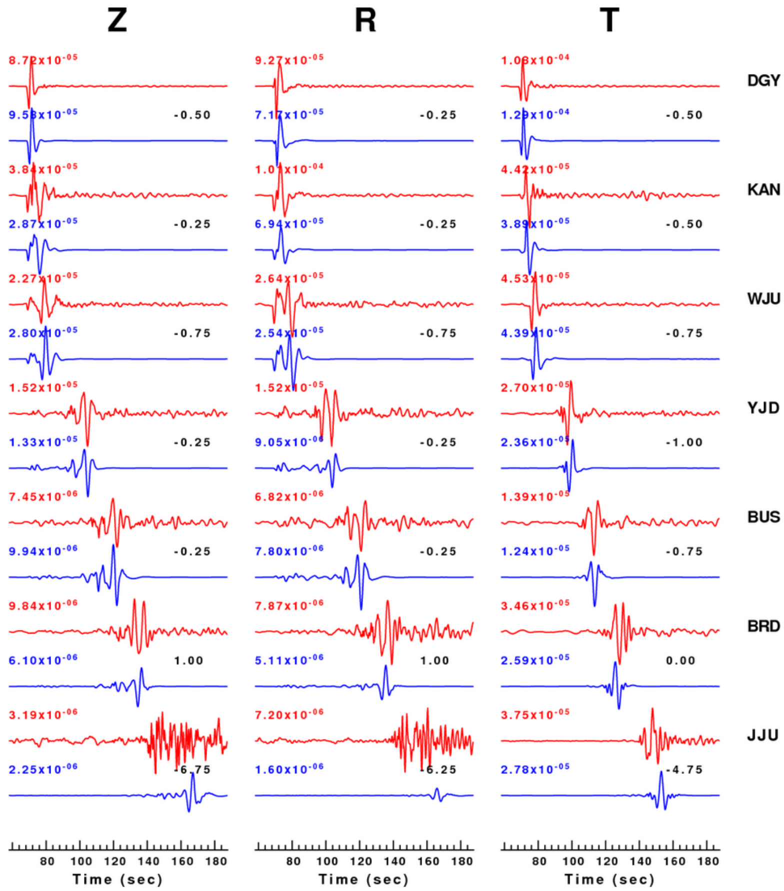

Figure 3. Selected accelerometer recordings integrated to round velocity (*m/s*) and filtered with the sac/gsac commands *hp c 0.05 n 3* and *lp c 0.20 n 3*. The epicentral distances in *km* to the stations are DGY (7), KAN (27), WJU (58), YJD (192), BUS (275), BRD (350) amd JJU (506). The trace display is discussed in Figure 2.

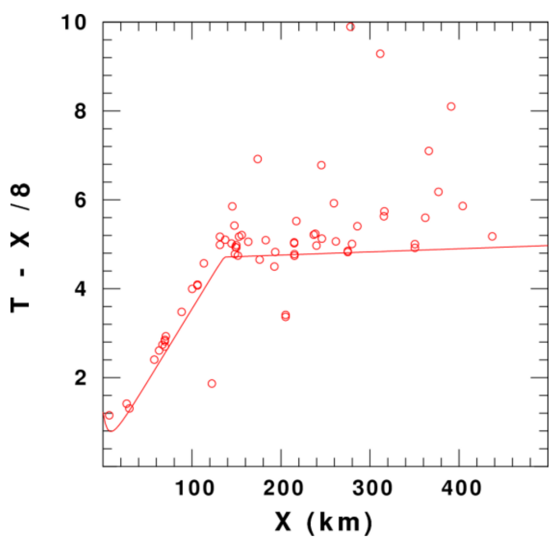

Figure 4. Observed and model predicted P-wave first arrival times for the relocated event.

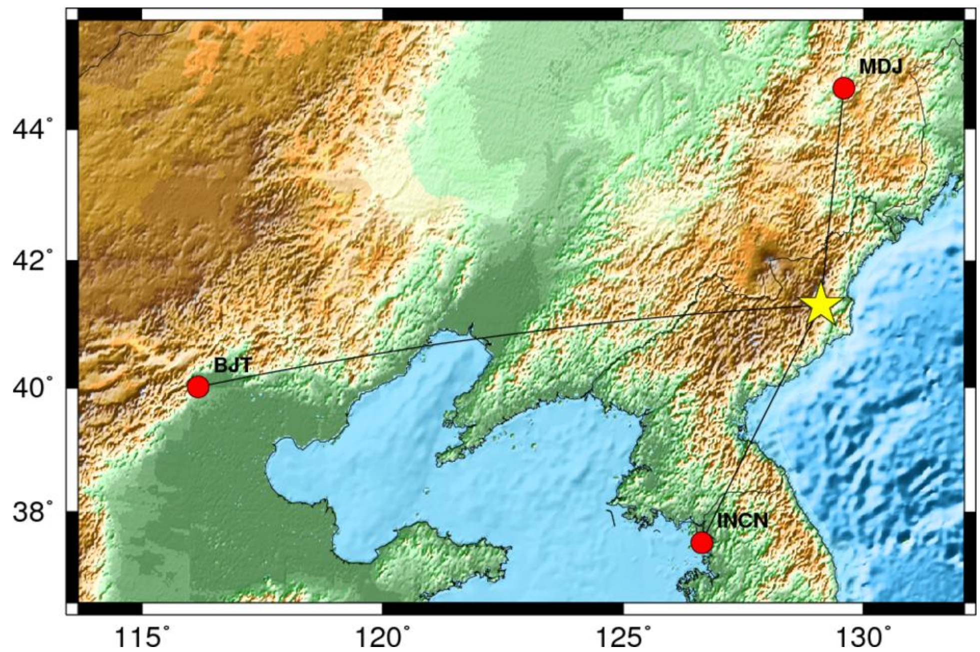

Figure 5. Paths to stations from the North Korean test.

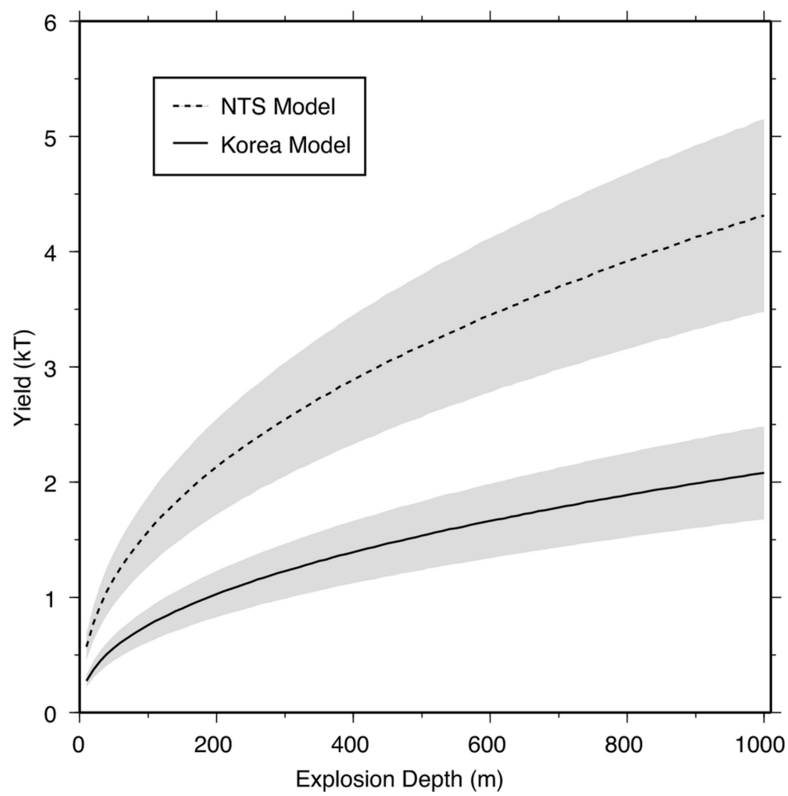

Figure 6. Yield estimates as a function of depth for the observed isotropic moment for two velocity models. The shaded regions reflect the variability due to the ± bounds of the observed moment (Koper et al., 2007).

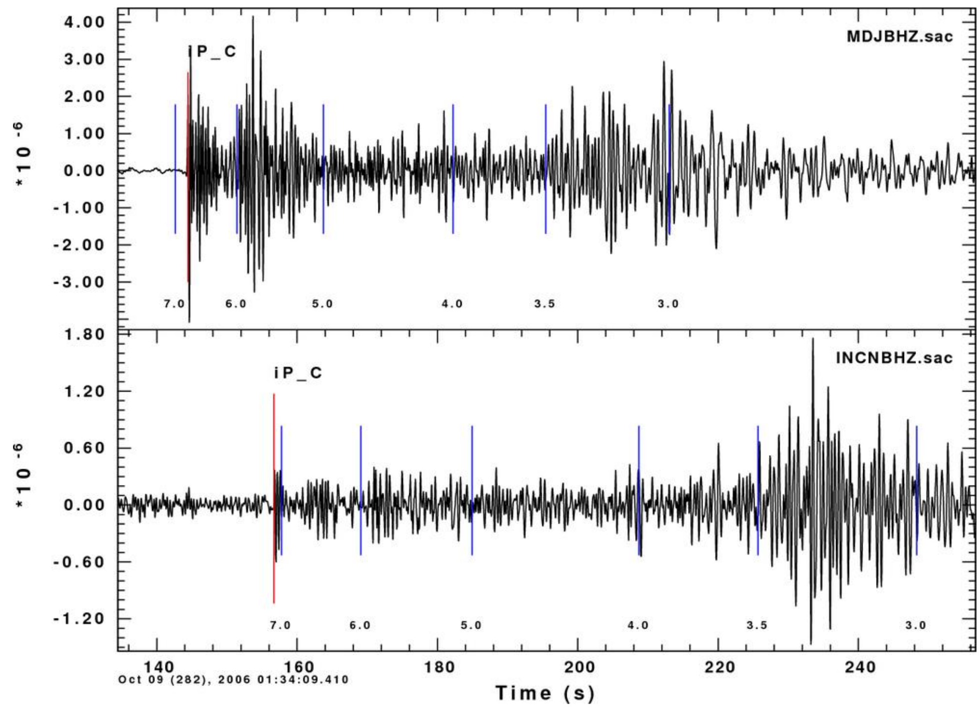

Figure 7. Comparison of bandpass filtered vertical component recordings at MDH (369 km) and INCN (475 km). These ground velocity traces (m/sec) had been filter using the sac/gsac commands: *hp c 0.5 n 2 p 2* and *lp c 3 n 2 p 2*. The *markt* command is used to show the group velocities of the signal.