Eos, Vol. 88, No. 14, 3 April 2007

North Korean Nuclear Test: Seismic Discrimination at Low Yield

PAGES 158, 161

North Korea carried out a widely reported nuclear explosion on 9 October 2006 at 0135 UTC at a location about 40 kilometers northwest of the city of Kilju (Figure 1). The location of the test determined from seismic signals recorded at 31 stations around the world was given as 41.294°N, 129.094°E in Quick Determination of Epicenters (QED) by the U. S. Geological Survey's National Earthquake Information Center (NEIC), very close to Mantap-san (Mount Mantap, 2205 meters, see Figure 1c). Further, since the late 1990s, surveillance satellites have detected tunneling activity in this area suspected to be indicative of North Korea preparing to conduct nuclear tests at this site [*Broad et al.*, 2005].

The region around the test site consists of Cretaceous (65–140 million years old) granite intrusions and Precambrian (more than 540 million years old) granite gneiss and schist. The magnitude for the test based on body waves, m_b, was determined using 10 teleseismic observations (QED) to be 4.3. Its yield was approximately 0.6 kiloton, estimated using the equation 0.75 log (yield in kilotons) = $m_b - 4.45$, for hard rock, assuming a fully coupled explosion [*Murphy*, 1996]. L. R. Sykes (personal communication, 2006) estimated a yield of 0.4 kiloton with 1 kiloton for an upper 95% confidence limit with $m_b = 4.23$, and T. C. Wallace (personal communication, 2006) estimated a yield of 0.8 kiloton based on a spectral average of 18 teleseismic signals and an 800-meter depth in granite.

This event may typify the handling of problem events under the Comprehensive Test Ban Treaty (CTBT) monitoring regime, in that it could not be identified as an explosion based on teleseismic records (although these provided detections and a good location estimate). Fortunately, good regional records at distances of a few hundred kilometers were available in near real time from stations not part of any formal monitoring network.

Two questions were raised after detection of this event and its announcement by the North Korean government. First, can this seismic event be shown objectively to be an explosion or an earthquake? The answer was quickly shown to be affirmative based on seismic data. Second, was it really a nuclear test, or could it have been a chemical explosion? The seismic signals from the test were small, about 1 magnitude unit smaller than any previously known first nuclear test. It was therefore technically possible that the test was an explosion derived from conventional chemical explosives. Answering this question required an assessment of nonseismic issues, including the probability of being able to assemble hundreds of tons of chemical explosives clandestinely, install them underground, and fire them almost simultaneously [*Richards and Kim*, 2007].

Seven days after the test, the U.S. Office of the Director of National Intelligence (ODNI) reported detection of radioactive debris from air samples collected in international airspace close to the test site on 11 October 2006, objectively confirming that a nuclear explosion was the source of the seismic signal [*ODNI*, 2006]. On 25 October, the South Korean government confirmed the nuclear test based on radioxenon detection in air samples taken in South Korea.

For this article, we analyzed seismic records from the nuclear test and compared them with similar records from earthquakes and known chemical explosions in the region (Figure 2). We concluded that the event was explosive, based upon seismic records from two Global Seismograph Network (GSN) stations in the region—Mudanjiang, China (MDJ), and Inchon, South Korea (INCN)—and by comparison with records from known explosions and earthquakes (Figure 1). In addition, this article describes the identification of explosions and earthquakes in northeastern North Korea and suggests useful seismic discriminants for distinguishing between explosions and earthquakes near the North Korean test site, even for explosions much smaller than that of 9 October.

Seismic Observations of the North Korean Nuclear Test

The three-component seismic records at the nearest available station, MDJ (distance = 371.3 kilometers, azimuth = 6.1°), from the 9 October nuclear test (Figure 2a) show a strong initial *P* wave arrival (*Pn* phase) on vertical record, with positive (compressional) first motion followed about 7 seconds later by *Pg* waves (reflected multiple times within the Earth's crust between the test site and observing station). This impulsive nature of *P* waves is commonly found for an explosion source. Later in the trace, weak *S* waves (*Lg* waves) arrive with a group velocity of about 3.6 kilometers per second, followed by clear surface waves (Rayleigh waves) with a period of approximately 3 seconds and group velocity of about 3 kilometers per second, typical of a shallow seismic source (less than 3–4 kilometers). The Rayleigh waves are best seen on the north-south record (which is radial because the station is almost due north of the source), and also on the vertical record.

In contrast, the vertical record from a nearby earthquake on 16 December 2004 (Figure 2b) shows a weak first arrival *Pn* phase compared with the same phase from the 9 October record, followed by strong *Lg* wave arrivals with group velocity of approximately 3.6 kilometers per second. Although the earthquake ($m_b = 4.0$) and the nuclear test ($m_b = 4.3$) have nearly the same magnitude, no clear Rayleigh waves are excited by the earthquake due to its deeper source (~10 kilometers). Additional three-component seismic records at MDJ from a controlled chemical explosion (2 tons) on 19 August 1998 in the region (Figure 2c) are from a slightly shorter distance (289 kilometers) between the chemical explosion and station MDJ and of smaller source (magnitude 1.9), yet are very similar to those from the 9 October test.

The nuclear test records show strong and impulsive *P* waves (*Pn* and *Pg*), and weak *S* waves, whereas the earthquake records show weak *P* waves and energetic *S* waves (*Lg*). We quantify these differences to obtain a robust seismic discriminant for northeastern North Korea and northeastern China.

Identification of the North Korean Nuclear Test

Eight shallow earthquakes with magnitudes from 2.5 to 4.1 occurred between 1989 and 2005 within about 200 kilometers of the test site. Four chemical explosions were conducted in August 1998 near the test site (Figure 1). They were 1- or 2-ton (TNT equivalent) single-hole shots ranging in magnitude from about 1.0 to 1.9. Waveform data from MDJ are fairly good for all events. Other GSN stations, INCN, HIA, BJT, and MAJO (see Figure 1b), show weak seismic signals with relatively poor signal-to-noise ratio.

The *P* wave to *S* wave ratios (*P*/*S*) of rotated, three-component records are defined as $(P_Z^2 + P_R^2)^{½} / (S_Z^2 + S_R^2 + S_T^2)^{½}$ where subscripts indicate the component: vertical (*Z*), radial (*R*), and tangential (*T*). A single three-component *P*/*S* ratio is obtained for each narrow frequency band centered on different discrete frequencies. Distance corrections are ignored, because all events are within 200 kilometers from each other and the paths have very low attenuation. Three-component *P*/*S* spectral ratios at eight discrete frequency points used in discrimination analysis for earthquakes, chemical explosions, and the nuclear test show that the three-component *P*/*S* spectral ratios from the earthquake and explosion populations overlap significantly at frequencies of 1–7 hertz, but the spectral ratios from the two populations are fairly well separated at 9 hertz and above (Figure 3). The overlap and separation of high-frequency spectral ratios from these two populations are also generally observed for other regions, such as the Nevada test site [*Walter et al.*, 1995] and southern Russia [*Kim et al.*, 1997].

By W.-Y. Kim and P.G. Richards

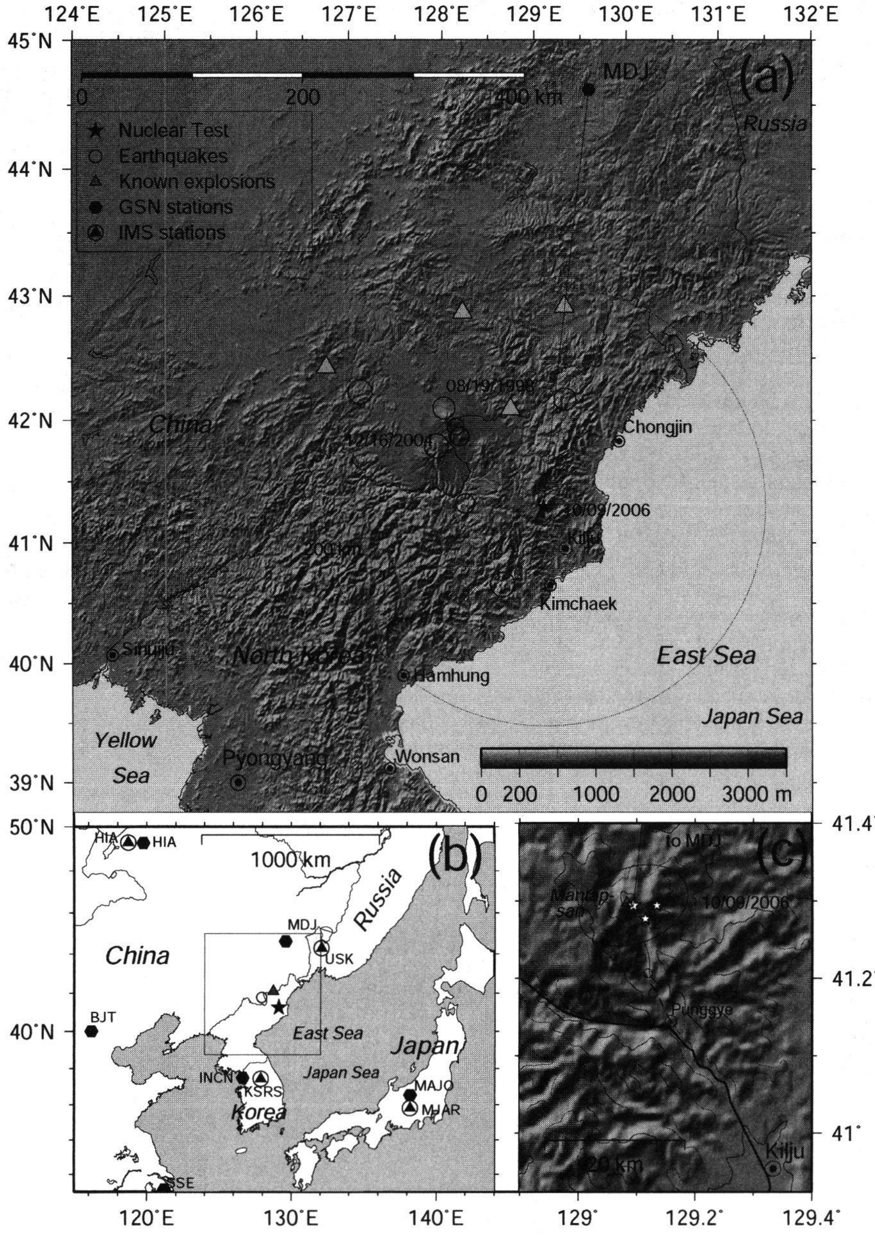

Fig. 1. (a) Locations of recent earthquakes (circles), chemical explosions (triangles), nuclear test on 9 October 2006 (star), and seismographic station MDJ (hexagon) in the North Korea/China region. (b) Map showing the North Korean nuclear test (star), seismographic stations of the Global Seismograph Network (hexagons), and the International Monitoring System (IMS) of the Comprehensive Test Ban Treaty organization (encircled triangles). (c) Seismic locations of the nuclear test (stars), tunnel entrance detected by surveillance satellites (solid square), suspected buildings for test (open square) around the Mantap-san (2205 meters) site, and villages (circles). Punggye is a large village with a railway station at the mouth of the valley, and Kilju is a major city. Locations denoted by 1 and 2 are preliminary locations given by the National Earthquake Information Center and are within 2–3 kilometers of the final solution. Error ellipse indicates 90% confidence interval for the final seismic location uncertainty. Original color image appears at the back of this volume.

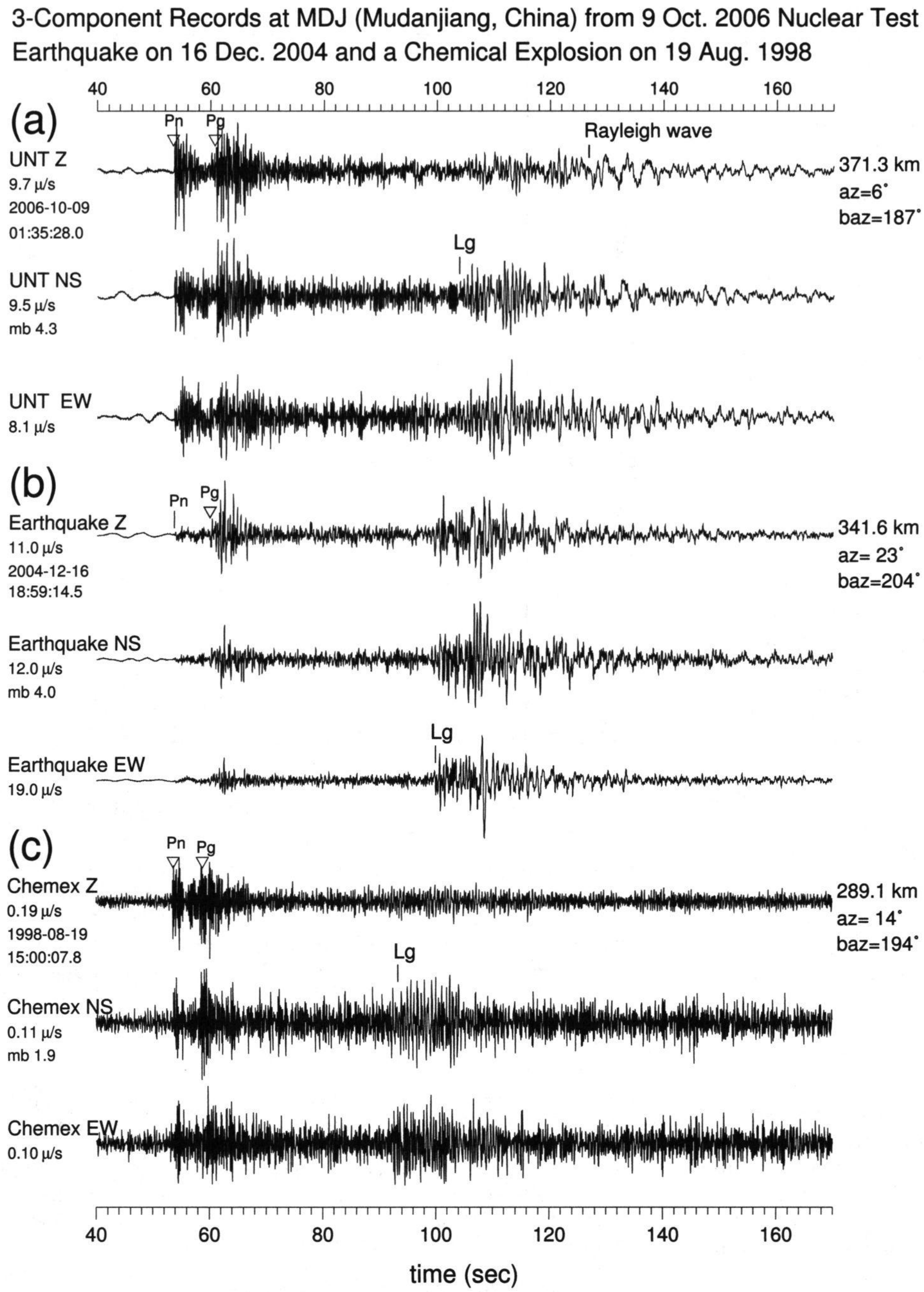

Fig. 2. Three-component seismic records (Z, vertical; NS, north-south; and EW, east-west) at MDJ. (a) The nuclear test on 9 October 2006, (b) an earthquake on 16 December 2004, and (c) a chemical explosion on 19 August 1998. Traces are aligned on P arrivals. The event ID (UNT, underground nuclear test, and chemex, chemical explosion), component, peak amplitude of trace in micrometers per second, origin time, and magnitude are indicated.

We applied linear discriminant function (LDF) analysis of *Pg/Lg* spectral ratios at frequencies of 5–15 hertz to assess their discrimination power in the sample data set. The LDF obtained for the band of 7–15 hertz performed best. We find that all events in the sample data are classified correctly and the total misclassification probability is only 2%. Although data from only one station, MDJ, at distances of 200–400 kilometers were analyzed, similar results could be obtained from several other stations in the region, suggesting that three-component *Pg/Lg* spectral ratios provide an efficient method for classifying earthquakes and explosions in northeastern North Korea and China down to only a few tons TNT equivalent.

Testing the Nuclear Test Ban Treaty

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 that began operations in early 2000 in Vienna, Austria. The fact that a seismogram archive of both earthquakes and small explosions was available for the best station in the region enabled identification of the 9 October event as an explosion of some kind with very high confidence based upon three-component *P/S* spectral ratios. Identification of explosions in this region can be done even down to a very small fraction of a kiloton provided seismic data of the type available in October 2006 are available.

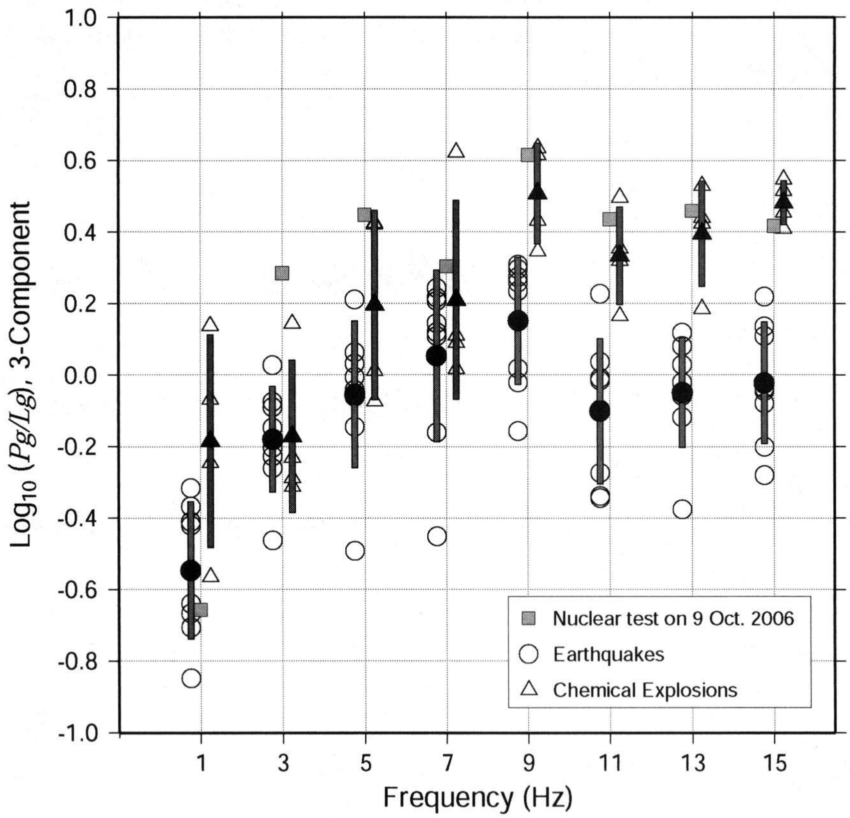

Fig. 3. Three-component Pg/Lg spectral ratios at eight discrete frequency points used in discrimination analysis are plotted for earthquakes, chemical explosions, and the nuclear test. A mean value at each discrete frequency point is plotted for earthquakes (solid circles) and explosions (solid triangles), with their shaded arms representing the scatter (standard deviation). The explosions have higher P/S ratios than the earthquakes, and the separation of the two populations is better achieved at high frequencies. The event of 9 October 2006 (squares) falls in the explosion population. Original color image appears at the back of this volume.

Acknowledgments

We thank F. Wu at the State University of New York at Binghamton and R. Herrmann at St. Louis University for providing information on chemical explosions and earthquakes in northeastern China. This is contribution 7022 from the Lamont-Doherty Earth Observatory.

References

Broad, W., D. Jehl, D. Sanger, and T. Shanker (2005), North Korea nuclear goals: Case of mixed signals, *N. Y. Times*, 25 July.

Kim, W.-Y., V. Aharonian, A. L. Lerner-Lam, and P. G. Richards (1997), Discrimination of earthquakes and explosions in southern Russia using regional high-frequency three-component data from the IRIS/JSP Caucasus network, *Bull. Seismol. Soc. Am., 87*, 569–588.

Murphy, J. R. (1996), Type of seismic events and their source descriptions, in *Monitoring a Comprehensive Test Ban Treaty*, edited by E. Husebye and A. M. Dainty, pp. 247–293, Springer, New York.

Office of the Director of National Intelligence (2006), Statement by the Office of the Director of National Intelligence on the North Korea nuclear test, *ODNI News Release 19-06*, Washington, D. C., 16 Oct.

Richards, P. G., and W.-Y. Kim (2007), Seismic signature, commentary, *Nature Phys., 3*, 4–6.

Walter, W., K. Mayeda, and H. Patton (1995), Phase and spectral ratio discrimination between NTS earthquakes and explosions: Part 1. Empirical observations, *Bull. Seismol. Soc. Am., 85*, 1050–1067.

Author Information

Won-Young Kim and Paul G. Richards, Lamont-Doherty Earth Observatory of Columbia University, Palisades, N. Y.; E-mail: wykim@ldeo.columbia.edu

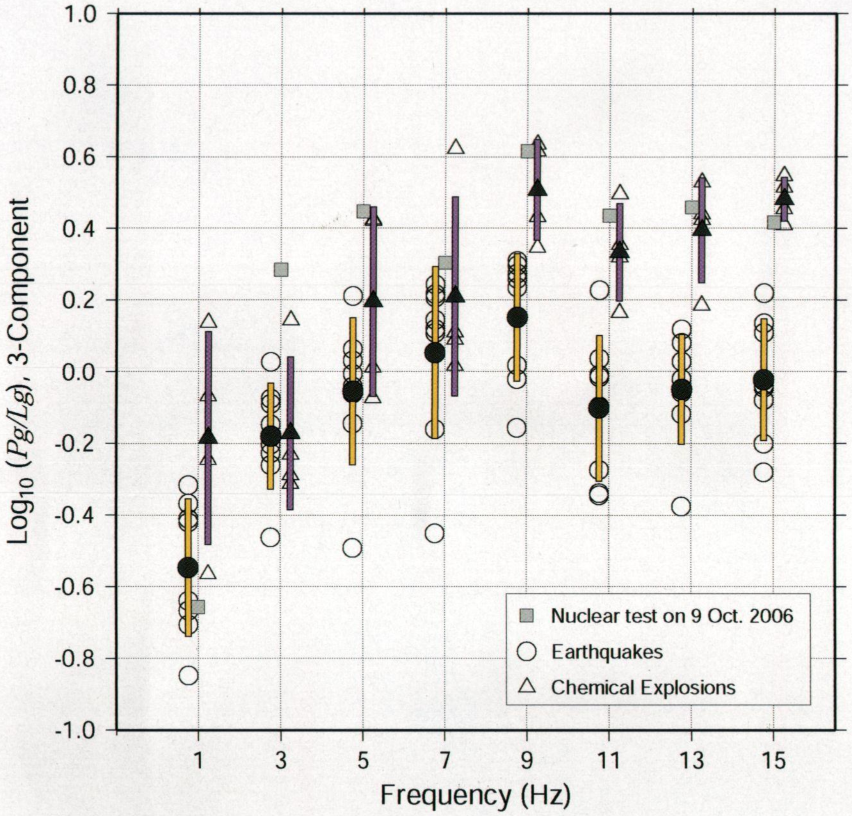

Fig. 3. Three-component Pg/Lg spectral ratios at eight discrete frequency points used in discrimination analysis are plotted for earthquakes, chemical explosions, and the nuclear test. A mean value at each discrete frequency point is plotted for earthquakes (solid circles) and explosions (solid triangles), with their colored arms representing the scatter (standard deviation). The explosions have higher P/S ratios than the earthquakes, and the separation of the two populations is better achieved at high frequencies. The event of 9 October 2006 (squares) falls in the explosion population.

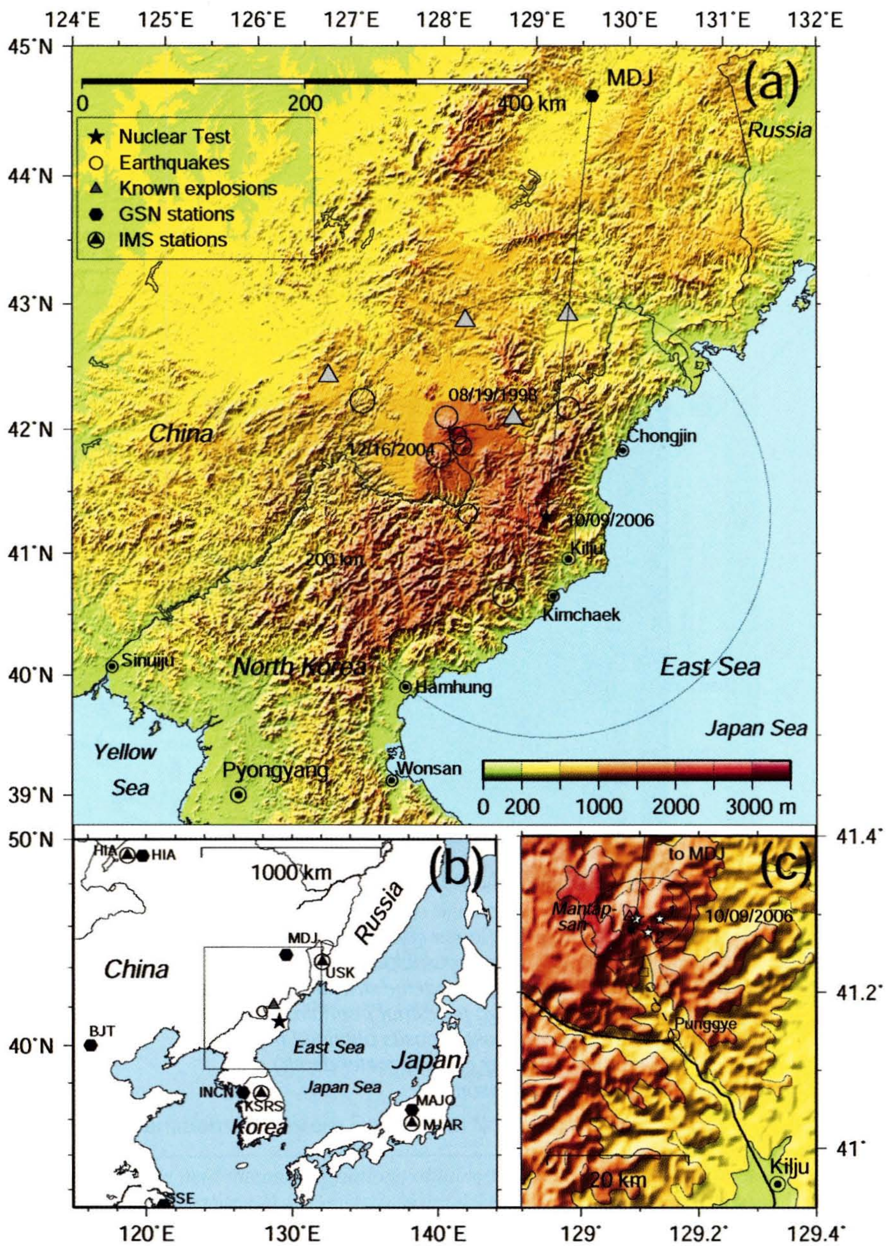

Fig. 1. (a) Locations of recent earthquakes (circles), chemical explosions (triangles), nuclear test on 9 October 2006 (star), and seismographic station MDJ (hexagon) in the North Korea/China region. (b) Map showing the North Korean nuclear test (star), seismographic stations of the Global Seismograph Network (hexagons), and the International Monitoring System (IMS) of the Comprehensive Test Ban Treaty organization (encircled triangles). (c) Seismic locations of the nuclear test (stars), tunnel entrance detected by surveillance satellites (solid square), suspected buildings for test (open square) around the Mantap-san (2205 meters) site, and villages (circles). Punggye is a large village with a railway station at the mouth of the valley, and Kilju is a major city. Locations denoted by 1 and 2 are preliminary locations given by the National Earthquake Information Center and are within 2–3 kilometers of the final solution. Error ellipse indicates 90% confidence interval for the final seismic location uncertainty.