POLICY FORUM: SEISMOLOGY

# Monitoring Nuclear Tests

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In May 1998, India and Pakistan announced that they had performed 11 underground nuclear tests (Table 1). These events were the focus of worldwide attention in part because the Comprehensive Nuclear Test Ban Treaty (CTBT) has now been signed by 149 nations, although not by India and Pakistan. As the world considers ratification and implementation of the CTBT, the Indian and Pakistani tests have raised important questions about the systems that have been deployed to support monitoring of a global ban on nuclear explosions. Here we evaluate how the growing international CTBT monitoring system performed, what has been learned about its capabilities for detecting and identifying future tests that may not be announced, and how the results of seismological monitoring compare with the announcements by the Indian and Pakistani governments.

When the CTBT enters into force, international verification will be provided by an International Data Center (IDC) analyzing real-time data collected from a global International Monitoring System (IMS) of 321 geophysical stations (*1*). To prepare for CTBT implementation and to advance the U.S. ability to monitor foreign nuclear tests, the U.S. Department of Defense (DOD) has supported a prototype of the IDC (PIDC) to research and develop effective treaty monitoring systems. Over the past 40 months, this system detected and located more than 70,000 seismic events (*2*), and in May 1998 it monitored the Indian and Pakistani nuclear tests.

### Prototype System Performance

On 11, 28, and 30 May 1998, the PIDC automatically detected and located the announced tests within 1 hour of their origin time. Over the next 12 hours after each event, estimates of locations and source parameters were refined based on automatic processing of auxiliary seismic data and the review of expert analysts. The final results were published within 83 to 121 hours after each event (Table 2) (*3*).

The PIDC separates or screens out natural events, such as earthquakes, using measurements of source parameters, depth, and location (*4*). Events that are screened out are consistent with natural phenomena at a high level of confidence. On the basis of these techniques, none of the tests on 11, 28, or 30 May were screened out by the PIDC. Specifically, the source parameters for the 11 and 28 May events were consistent with values from historical explosions. The compressional and shear wave energies of the 11 May event were comparable to those of Chinese nuclear explosions. Finally, the 30 May event was not screened out because of the high background noise from a large earthquake in Afghanistan that occurred 30 min earlier.

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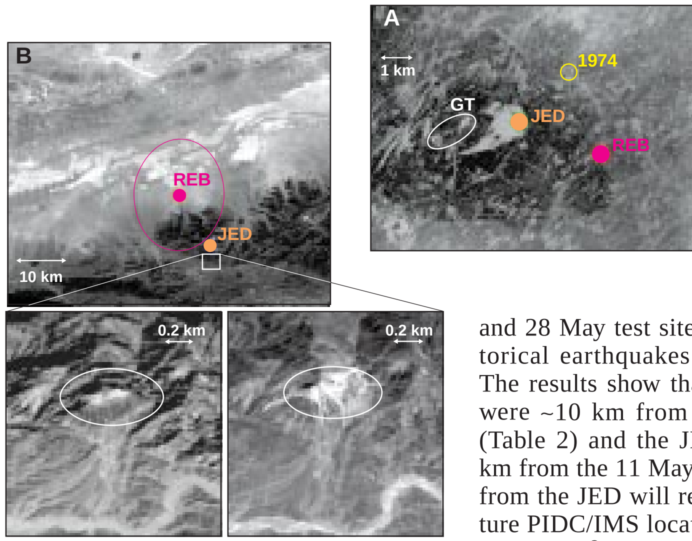


**View from above.** Commercial overhead imagery of the 11 and 28 May tests. (**A**) SPOT image of the India test site showing the location of the 1974 nuclear test, the REB and the JED location, and the actual location of the two explosions (GT). (**B**) SPOT image showing the REB location of the 28 May test and the fixed point of the test site for the JED analysis. The insets are pre- and post-test images, revealing a large disturbed area. The post-shot image was obtained from a commercial Indian satellite with a resolution of 5 m.

### Calibrated Event Locations

The PIDC located the events using the globally averaged IASPEI-91 seismic velocity model (*5*). However, there are unknown systematic errors in these locations because of variations in the geology and thus the velocity structure along different propagation paths. Improvements can be obtained from a Joint Epicentral Determination (JED) using calibrated source locations and historical seismograms (see the figure). For this analysis, we obtained ground-truth locations from commercial imagery of the 11 and 28 May test sites and records of historical earthquakes and explosions (*6*). The results show that the REB locations were ~10 km from the actual test sites (Table 2) and the JED location was 1.9 km from the 11 May test. The corrections from the JED will reduce the error of future PIDC/IMS locations to approximately 100 km$^2$ for events of similar magnitude in this region.

### Announced Indian Tests on 13 May

The Indian government announced that two subkiloton tests were conducted on 13 May at 06:51 Greenwich mean time. These events were undetected at the regional auxiliary station NIL (*7*) and the non-IMS Kyrgyz Network (KNET) (*8*). Because the 11 May explosion was well recorded at both sites (signal/noise ratios were >1000 at NIL), we conclude that the existing seismic network was capable of detecting a very small test, if it was successful. To quantify this capability, we used filtering and cross-correlation techniques to search the regional data from NIL for as much as 6 hours before and after the announced time. No signal consistent with a test was found, although there were several small signals from earthquakes in the Hindu Kush region. Based on this analysis and the noise levels over a wide range of frequencies, we place an up-

**TABLE 1. ANNOUNCED TESTS**

| Date | Country | No. | Yield (kt) |
|---|---|---|---|
| 5/11/98 | India | 3 | 55 |
| 5/13/98 | India | 2 | 0.8 |
| 5/28/98 | Pakistan | 5 | 30–35 |
| 5/30/98 | Pakistan | 1 | NA* |

*NA, not available

**TABLE 2. PIDC-REVIEWED EVENT BULLETIN (REB) AND JOINT EPICENTER DETERMINATION (JED) AND IMAGERY LOCATIONS**

| | PIDC REB | | | | | | JED | | | Imagery | | | ΔREB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Origin Time (GMT) | Lat. (°N) | Long. (°E) | Unc. 90%(km²) | $m_b$ | $M_s$ | Lat. (°N) | Long. (°E) | Unc. (km²) | Lat. (°N) | Long. (°E) | Unc. (km) | Imagery§ (km) |
| 11 May 98* | 10:13:44.2† | 27.072 | 71.761 | 250 | 5.0 | 3.2 | 27.081 | 71.738 | 113 | 27.078 | 71.719 | <0.5 | 4.2 |
| 28 May 98‡ | 10:16:17.0 | 28.903 | 64.893 | 274 | 4.9 | 3.6 | – | – | FP | 28.830 | 64.950 | <1 | 9.8 |
| 30 May 98 | 06:54:06.6 | 28.495 | 63.781 | 336 | 4.3 | <4.96 | 28.433 | 63.860 | 80 | NA | NA | NA | NA |

*Fixed point (FP) for this analysis was the 18 May 74 nuclear test. Imagery shows it to be at 27.095°N, 71.752°E (uncertainty <0.1 km). The origin time is 02:34:59.3 GMT. †The JED origin time is 10:13:45.3 GMT. ‡Fixed point used for 30 May 98 analysis. §Distance between REB and imagery locations. Unc., uncertainty; NA, not available.

per bound of $m_b < 2.5$ on the size of a test, indicating that the seismic magnitude of the 13 May event was at least 500 times smaller than that of the 11 May event.

## Yield Estimation

We estimated the explosive yields of the tests using calibrated magnitude-yield relations for a wide variety of nuclear test sites (*9*), together with modeling of the corresponding network-averaged, teleseismic, *P* wave spectra (*10*). Because the magnitude-yield relations are calibrated only for limited parts of the world, they can only be applied to geologically similar regions and test conditions. The differences among scaling relations for different sites are large, varying by more than a factor of 4 for a given magnitude and emplacement geometry [for example, 10 to 45 kilotons (kt) for the 11 May explosions].

We refined these estimates by analyzing the network-averaged, teleseismic, compressional wave spectra to characterize the geophysical environment of the tests and identify the appropriate magnitude-yield relation. The scaling from the former Soviet Shagan River test site was most consistent, and the spectra can be modeled with the following mean estimates for the yields of the seismic sources: 12 kt (11 May), 9 kt (28 May), and 4 kt (30 May). The 95% confidence intervals, based only on the fit to the model, are 9 to 16 kt (11 May), 6 to 13 kt (28 May), and 2 to 8 kt (30 May). If we account for errors associated with emplacement conditions and near source effects, the total uncertainty in the yield estimates is 50%. Scaling this analysis to the background noise at NIL suggests that the upper bound of the yield of the announced 13 May test is 30 tons, if it was performed under similar conditions as the 11 May explosion (*11*).

## Evidence for Multiple Tests

India and Pakistan announced that their tests on 11 and 28 May consisted of multiple explosions (Table 1). In principle, it would be straightforward to confirm these statements using seismic data collected at close regional distances and high frequencies (*12*). However, we cannot make definitive conclusions using only the available far-field waveforms. For example, spectral analysis of the 11 May NIL record is consistent with a single seismic source, and the teleseismic records are almost identical to the records of India's single test performed in 1974. By comparison, Indian news reports and open-source imagery indicate that the 11 May explosions were performed at two sites separated by approximately 1 km. This result indicates that the detonations were nearly simultaneous or that one of the near-simultaneous tests was much larger than the other.

Seismograms of the 28 May event are generally more complex than those of the 30 or 11 May tests. Body wave magnitudes and lengths of the compressional wave coda varied azimuthally. Possible explanations include multiple explosions, triggered release of tectonic stresses after the explosion, or scattering of seismic waves from geologic structures near the source. Efforts to fit models of these sources to the observed seismograms are not definitive. Future progress in this area will depend on the availability of additional regional seismic data (*13*).

## Implications for the CTBT

The prototype CTBT network and data center provided effective and timely monitoring of the tests on 11, 28, and 30 May. We provided additional information through analyses of other open-source data. Yield estimates for the tests are below the values announced by the Indian and Pakistani governments. Future monitoring capability in this region will be greatly improved by the calibration value of the data from these nuclear tests and by the deployment and upgrade of the IMS seismic system as the CTBT is implemented. Whereas the tests were detected by only one IMS station at regional distance, there would have been at least eight additional regional detections from the full IMS (*14*). Indeed, the monitoring and analysis of the May 1998 events were remarkably successful given the limited development of the current network. Generalizing these results, we conclude that effective global monitoring of the CTBT is largely contingent on the full development of the IMS, supported by research and development to fully exploit this advanced monitoring system. Using data from the entire network, there are sufficient scientific and technical capabilities to perform global treaty monitoring to very low thresholds. In future policy discussions about CTBT ratification, the experience of monitoring the Indian and Pakistani nuclear tests should convey high confidence in the evolving systems of treaty verification.

### References and Notes


1. The text of the CTBT specifies the locations and characteristics of the IMS stations. It includes a primary network of 50 seismic stations and an auxiliary network of 120 stations, 80 radionuclide detectors, 11 hydroacoustic stations, and 60 infrasound stations.
2. Thirty-six primary and 58 auxiliary seismic stations are now operational. In its current state, the network relies on voluntary efforts and contributions of national governments and organizations. In the future, six of the primary stations will be upgraded from single three-component sensors to multistation arrays. All stations will be linked by satellite directly to the IDC.
3. Details of the results can be found at the PIDC Web page (http://www.pidc.org/dataprodbox/prod.html).
4. Historically, the most reliable screen has been the difference between long-period surface ($M_s$) and short-period body ($m_b$) wave magnitudes. For explosions, $m_b$ is typically greater than ($1.76 + 0.8\ M_s$). Spectral ratios of regional *P* and *S* waves tend to separate earthquake and explosion populations because of differences in the compressional and shear wave energy emitted by explosive and earthquake sources.
5. The PIDC uses IASPEI-91 for all seismic locations except in the Baltic shield, where a specially calibrated model has been implemented.
6. H. Israelsson *et al.*, in preparation.
7. For the past 8 years, the NIL station has been constructed and operated through funding from the University of California, San Diego; DOD; and the National Science Foundation.
8. It is expected that data from high-quality non-IMS stations will enhance the analysis of "special" events detected under CTBT monitoring.
9. J. R. Murphy, in *Monitoring a Comprehensive Test Ban Treaty*, E. S. Husebye and A. M. Dainty, Eds. (Kluwer Academic, Dordrecht, 1996), pp. 225–245.
10. J. R. Murphy, *Bull. Seismol. Soc. Am.* **79**, 156 (1989); *Geophys. J. Int.* **113**, 535 (1993).
11. Media reports indicate that the 13 May test was performed in a sand dune region about 10 km from the 11 May test site. Under such conditions, the upper bound of the 13 May test could be as large as 300 tons.
12. For multiple explosions of similar size, the Fourier transform of such data would show peaks at frequencies corresponding to the delay in the arrival time of the different explosions.
13. Data from the NIL station would be especially valuable for this purpose but are not available because Pakistan discontinued communication to the station during its tests. Such actions should not be of concern when the full IMS is deployed, because of the large redundancy in the system.
14. Planned stations are located in Iran (2), Pakistan (2), Turkmenistan (1), Bangladesh (1), Armenia (1), Saudi Arabia (1), Kyrgystan (1), Nepal (1), and Oman (1). The NIL station will be upgraded to a more sensitive multistation array. There could be both a primary array and an auxiliary three-component station located in India if it signs and ratifies the CTBT.