ASSESSING EVENT LOCATION CAPABILITY WITH GROUND TRUTH EVENTS AT THE DEGELEN MOUNTAIN TEST SITE, KAZAKHSTAN

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ABSTRACT

We are investigating seismic event location capability in Kazakhstan using first-P arrivals from nuclear explosions with relatively precise or exact ground truth information. We use a waveform cross-correlation (WCC) method to determine high-precision relative arrival times. We then use the improved arrival times to examine several issues regarding location accuracy and precision. Since the true explosion locations are known precisely, we can evaluate both relative (joint hypocenter determination, JHD) and absolute (single-event) location capability. Aspects we are currently investigating include relative and absolute location accuracy, in particular using sparse regional-distance observations, the spatial variability of derived source-specific station corrections (that is, path corrections), and the influence of global heterogeneity on absolute location accuracy.

We have combined information from several sources in order to establish adequate ground truth information for Degelen Mountain. Locations and origin times for 68 Degelen explosions were published by Bocharov et al. (1989). Tunnel portal coordinates for all Degelen explosions were released as part of a tunnel closure project (Leith, 1998). In addition, we obtained sections of a map showing all of the Degelen tunnels, albeit with some apparent distortions and no coordinates (W. Leith, pers. comm.). By combining the true portal coordinates with the tunnel maps, we were able to determine approximately the complete location and geometry of all the tunnels. Using the Bocharov et al. (1989) ground truth information, we then verified our estimated tunnel geometry for those events, and determined that the explosions all took place at essentially the tunnel ends. We then adopted the other tunnel ends as our best estimates of the locations for the remaining Degelen explosions.

We were able to obtain sufficient digital data for 19 Degelen explosions to carry out our WCC-JHD analysis. Each event had between 4 and 17 observations. Using all the digital data and fixing one event location at ground truth, we can locate the other 18 with a mean mislocation of only 2 km. If we restrict the data to stations within 40°, resulting in only 7 usable events with between 3 and 8 observations, fixing one location and solving for the other 6 yields an average mislocation of about 7 km. We have also carried out single-event locations using our WCC data. If no station corrections are applied, the mean mislocation is about 12 km, with a significant southward location bias. Using the station corrections derived from our JHD analysis, the mean mislocation decreases to about 2 km.

For location using path corrections to be accurate and effective in practice, the rate at which the corrections change with changing source location must be relatively modest. Otherwise, the standard interpolation and extrapolation approach will yield erroneous results. We compared the sets of JHD path corrections we derived for events at Degelen with our previous results for Balapan. The corrections are very highly correlated (r = 0.98) with a linear least-squares fit slope of 0.97 and an intercept of 0.3 s. This might suggest that the corrections should be readily transportable between the two nearby regions. However, we find that using the Balapan corrections to locate Degelen events results in a mean mislocation of about 5 km, with a general bias to the northeast. Examining the path correction differences more closely, we find that they have a strong azimuthal pattern. This effect could possibly be due to either local or global heterogeneity.

We are also investigating the contributions of global 3-D structure to mislocation. We present the preliminary results of an analysis of single-event location accuracy using a high-resolution global 3-D model. The resulting location accuracy using the 3-D model does not approach that obtained using JHD-derived path corrections.

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OBJECTIVE

We are carrying out investigations of seismic event location capability using events that have ground truth information to allow a direct assessment of actual location errors and computed precision estimates. The objectives are to determine the most effective approaches for precise and accurate event location for CTBT monitoring purposes. Waveform cross-correlation methods have been applied to determine more accurate relative arrival times for available digital seismic data from nuclear explosions at Degelen Mountain, Kazakhstan. These arrival times, along with the original bulletin times, are used for a comparison of two strategies for improving absolute location accuracy and reducing estimated location uncertainty, one "calibration-based" and the other "model-based." The calibration-based approach involves joint hypocenter determination (JHD), including the estimation of path corrections. The model-based approach involves the use of a global three-dimensional (3D) velocity model to provide improved travel time estimates.

RESEARCH ACCOMPLISHED

All of the Degelen Mountain nuclear tests were conducted in tunnels that had been bored roughly horizontal into the mountain. Excellent sources of Degelen Mountain ground truth information exist for tunnel entrances, or portals (Leith, 1998), but few sources exist for coordinates of the explosions aside from Bocharov et al. (1989). Bocharov et al. (1989) only reports ground truth for events between 1961 and 1972. Unfortunately, the events for which sufficient waveform data for cross-correlation are available occurred between 1977 and 1988. In order to bridge this gap and establish adequate ground truth for many of the later explosions, we obtained two maps of the Degelen Mountain tunnel complex (W. Leith, pers. comm.). One map is larger and composed of four different map sections, the other is smaller and a single sheet. We were informed that the smaller map should be considered less accurate, therefore we used the larger sectioned map for the ground truth estimate. The large map illustrates many of the reported Degelen Mountain tunnels, albeit with some apparent distortions and no coordinates. An absolute framework for the large map is determined by overlaying GPS-estimated tunnel portal locations of Leith (1998). The approximate locations and orientations of all tunnels on the map sections are then determined by digitizing the tunnel portals and ends. Our estimate for the locations of all tunnels on the map sections is shown in Figure 1. Tunnel labels used in the figure correspond to those listed from the KNNC Tunnel Data Volumes in Leith (1998). Even though very good locations are known for the tunnel portals, this process was deemed necessary because most explosions probably occurred at, or much closer to, the tunnel ends as opposed to tunnel portals.

In order to test our ground truth estimates, our tunnel portal estimates are compared to the GPS-determined portals of Leith (1998). The 142 portals corresponding to Leith (1998) compared well, with a median difference of 77 meters. For this comparison there were 6 notably large differences (larger than 900 meters) between the map-based estimate and the locations in Leith (1998). The tunnels in question are those labeled 104, 151, 152, 200M-bis, 806, and E-2 in Figure 1. All 6 of the discrepant portals appear in the same general location, relative to the other tunnels, on both the large and small maps. Additionally, one of them (tunnel E-2) has a tunnel end, based on our estimate, that corresponds to one of the Bocharov et al. (1989) reported explosion locations (event 680929). Because of this, we believe the map-based estimate to be generally closer to the true portal location for these 6 tunnels. The source of the discrepancy is currently under investigation.

To further test our ground truth estimates, our tunnel locations are compared to explosion locations reported by Bocharov et al. (1989). Bocharov et al. (1989) reported locations of 53 events that occurred in 46 different tunnels on our maps. All of these events located very close to our estimates of their corresponding tunnels with the majority at the ends of the estimated tunnels. Based on the close proximity of Bocharov et al. (1989) reported events to the ends of our estimated tunnels and the assumption that tests could not be conducted farther into a tunnel than the previous test was conducted, it follows that the first detonation in a tunnel was usually at the tunnel end. These initial tunnel explosions, determined by the chronological order of tests in a given tunnel, had a median distance of 80 meters from their corresponding tunnel end. In the case where multiple explosions occurred in a single tunnel, each event location was equally close to their corresponding tunnels. Approximately 75% of the events listed in Leith (1998) occurred in unique tunnels. Unfortunately, given current information, we cannot determine where multiple detonations in a single tunnel occurred. Since most tunnels only had one explosion that was most likely at the tunnel end, and the mean tunnel length was only 685 meters, the tunnel ends are adopted as our ground truth estimate for events that were not reported by Bocharov et al. (1989).

Origin times for the 84 Degelen Mountain events in the ISC catalog not reported by Bocharov et al. (1989) are refined using published ground truth locations and our map-based ground truth location estimates, origin times reported by Bocharov et al. (1989), and ISC catalog arrival times. The objective is to restrain a portion of the origin times in order to sufficiently constrain the remaining origin times to give very good absolute estimates. This procedure involves applying JHD with epicenters restrained to ground truth estimates and only the origin times reported by Bocharov et al. (1989) restrained. The JHD technique then solves solely for path corrections and the remaining unrestrained origin times relative to our reference velocity model ak135.

To evaluate this procedure, a data set is constructed from only the 68 Degelen Mountain events reported by Bocharov et al. (1989). With the event epicenters restrained to their absolute locations, the origin times are restrained in different ratios to test the accuracy with which the unrestrained origin times can be recovered. With 23 of 68 origin times restrained, all of the remaining origin times are recovered within 0.4 seconds with an RMS error of 0.13 seconds. The same recovery is observed when 46 of 68 origin times are restrained. Based on this exercise, the origin times estimated in this manner are assumed to be within 0.4 seconds of their true values. The resulting origin times for each event are listed in Table 1 along with 95% confidence limits and our map-based location estimates.

JHD is applied to relocate the events using 144 cross-correlation (C-C) derived teleseismic and regional arrival times from 19 nuclear explosions at Degelen Mountain. The initial locations for these events are set to the ground truth estimate described above. Each event had between 4 and 17 observations. For all of the Degelen Mountain relocation analyses, event 870717 is restrained as the master event. This event was chosen because it had a relatively large number of observations (12) and the largest magnitude (6.4 mb) of the group as reported in the pIDC's Nuclear Explosion Database (NEDB). Most events relocated to within 3 km of our ground truth estimate, and all relocated to within 4.5 km, with a mean mislocation of 2.0 km (Figure 2). All 95% confidence ellipses covered less than 16.5 km^2, with most being less than 8 km^2, and a mean coverage of 6.6 km^2. Only 5 of the 18 relocated events had confidence ellipses that covered their ground truth location estimate. This underestimation of location uncertainties is expected given the very small number of observations (Evernden, 1969) and is a well-known problem in such location scenarios. No correlation exists between azimuthal gap and mislocation for our locations using waveform cross-correlation picks, despite having a large average azimuthal gap of 146°. This is contrary to the trend observed by Thurber and Engdahl (2000) wherein mislocation increases with increasing azimuthal gap using worldwide ground truth events and ISC data. We attribute this difference to the accuracy of our arrival times.

In a more realistic CTBT-like monitoring situation, far fewer events would normally be available for JHD and the event magnitudes would most likely be small, resulting in observations being made only out to regional distances or slightly beyond. This scenario is especially challenging for seismic location due to the fact that regional seismic phases pass through significant portions of the Earth's crust and uppermost mantle, which have a laterally heterogeneous velocity structure that is poorly represented by our 1-D reference velocity model. In order to investigate location capability in such a situation, the full C-C Degelen Mountain data set is limited to phases arriving from less than 40° epicentral distance. Imposing this limitation eliminates 12 events because they have less than 3 observations, and reduces the number of observations to between 3 and 8 for the 7 remaining events. Again, 870717 is chosen as the master event. As expected, both mislocations and uncertainties increase substantially for the unrestrained 6 events (Figure 3). The mean mislocation is 7.43 km with the largest being 15.4 km. Four of the events have associated 95% confidence ellipses covering less than 570 km^2, well within the CTBT 1000 km^2 goal. The other two events have ellipses covering 1730 and 8869 km^2, which is not surprising as each event had only three observations. The average azimuthal gap for this "regional" data set is 165°.

We also use the software package LocSAT of the International Data Centre to locate the explosions in the 1-D reference earth model ak135 both without and with station corrections. The station corrections were obtained from our JHD of explosions at Degelen Mountain and Balapan. We test to what extent these two sets of station corrections are transportable; can we use them to locate events that occurred in the general vicinity of the two sites? To be able to compare the locations estimated using both sets of corrections, we only include stations for which both corrections are available, that is, stations that recorded at least three Balapan and three Degelen Mountain explosions. Using only the resulting set of twenty stations, the number of observations per event ranges from 4 to 16, and is 8 on average. The azimuthal gap ranges from 90° to 240°, with an average gap of 190°.

Figure 4 shows the ground truth locations (solid dots) and our estimated locations (open squares) of Degelen Mountain explosions without and with station corrections. On the top (Figure 4a) we show our estimates without using any station corrections. A systematic bias of the estimated locations is evident; the median mislocation distance is 14.4 km. When we apply the source region specific station corrections for Degelen (middle, Figure 4b) we obtain much improved locations, with the median mislocation distance reduced to 2.7 km. Note that if we do not restrict the data set to stations that have observations of both Balapan and Degelen Mountain explosions, the median mislocation distances are11.8 km without and 1.7 km with station corrections, respectively.

There is a strong linear correlation between the Degelen Mountain and Balapan station corrections, suggesting that the station corrections might be transportable. Degelen Mountain corrections are systematically 0.3 s larger than the Balapan corrections. This offset could be due to a difference in structure beneath the two sites, for example a different crustal structure, however, it could also be due to a difference in the origin time estimates used in the JHD procedure. The estimated origin times are assumed accurate to within 0.4 seconds, so we cannot resolve whether the offset is due to structure or not. However, when we plot the difference between the two station corrections as a function of azimuth to the station, a smoothly varying pattern, resembling a sinusoid, becomes apparent. Indeed, if we locate Degelen Mountain events using the Balapan corrections, the estimated locations are slightly displaced towards Balapan (Figure 4c). We interpret these systematic mislocations as due to a difference in structure between Degelen Mountain and Balapan. However, the median mislocation distance is only 4.7 km, still a significant improvement compared to just locating in ak135 with no station corrections (Figure 4a).

We also evaluate how well we can locate the Degelen explosions when we use a recent 3D global P wave velocity model, BSE [Bijwaard et al., 1998]. A subset of the events have relatively small mislocations (15 km or less), but the rest have substantially larger mislocations (> 20 km). When we only use teleseismic data, these large mislocations are substantially decreased. Thus, the global model reproduces teleseismic travel times much better than regional travel times, which is not surprising. However, even when only teleseismic data are used, a systematic mislocation to the west-northwest is apparent.

CONCLUSIONS AND RECOMMENDATIONS

Ground truth information is a key to evaluating seismic event location capability. For the Degelen Mountain explosions, where we have developed high-quality ground truth information, the improved arrival times from cross-correlation analysis and appropriate path corrections yield excellent relative (JHD) and absolute (single-event) location results, even from sparse stations at relatively close distances with large azimuthal gaps. In both cases, we obtain location accuracies that are adequate for CTBT monitoring. Path corrections vary modestly from the adjacent Balapan area, but the variations are enough to cause significant location bias if corrections from one site are applied to the other. Preliminary locations using an existing global 3-D model are much less accurate, but the accuracy can be improved substanitally if regional-distance data are excluded. The calibration-based approach yields superior accuracy, but the model-based approach should be more transportable.

Key Words: Location, Ground Truth, Corrections, Calibration, Waveform Cross-Correlation

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Table 1. 152 ISC-reported Degelen Mountain nuclear explosions including our estimated origin times and their uncertainties (+/- value, 95% confidence), ground truth location estimates, and body-wave magnitudes (pIDC). The first 68 events are from Bocharov et al. (1989).

YRMODAHRMN	SEC	+/-	LATITUD	LONGITU	MAG
640315 8 0	0.4	0.00	49.8160	78.0752	6.2
640516 6 0	59.8	0.00	49.8077	78.1020	6.2
640719 6 0	0.6	0.00	49.8091	78.0929	6.0
641116 6 0	0.2	0.00	49.8087	78.1334	6.1
650303 614	59.4	0.00	49.8247	78.0527	6.0
650511 640	0.2	0.00	49.7702	77.9943	5.2
650617 345	0.0	0.00	49.8284	78.0669	5.8
650729 3 5	0.2	0.00	49.7797	77.9981	4.5
650917 4 0	0.1	0.00	49.8116	78.1467	5.6
651008 6 0	0.4	0.00	49.8259	78.1114	5.8
651121 458	0.0	0.00	49.8192	78.0636	6.1
651224 5 0	0.2	0.00	49.8045	78.1067	5.2
660213 458	0.1	0.00	49.8089	78.1210	6.5
660320 550	0.3	0.00	49.7616	78.0239	6.2
660421 358	0.1	0.00	49.8097	78.1000	5.4
660507 358	0.2	0.00	49.7429	78.1050	4.8
660629 658	0.5	0.00	49.8344	78.0734	5.6
660721 358	0.0	0.00	49.7367	78.0970	5.9
660805 357	59.6	0.00	49.7643	78.0424	6.1
660819 352	59.9	0.00	49.8271	78.1088	5.1
660907 351	59.7	0.00	49.8288	78.0637	4.8
661019 357	59.9	0.00	49.7471	78.0205	6.3
661203 5 2	0.2	0.00	49.7469	78.0334	4.9
670130 4 1	59.5	0.00	49.7674	77.9914	4.8
670226 357	59.8	0.00	49.7457	78.0823	6.6
670325 558	1.1	0.00	49.7536	78.0630	5.9
670420 4 8	0.0	0.00	49.7416	78.1054	6.3
670528 4 7	59.6	0.00	49.7564	78.0169	6.2
670629 256	59.9	0.00	49.8167	78.0490	5.3
670715 326	59.9	0.00	49.8359	78.1182	6.0
670804 658	0.3	0.00	49.7603	78.0555	5.8
671017 5 4	0.2	0.00	49.7809	78.0038	6.1
671030 6 4	0.0	0.00	49.7944	78.0079	6.0
671208 6 3	59.8	0.00	49.8171	78.1638	5.4
680107 346	59.9	0.00	49.7544	78.0309	5.3
680424 1035	59.7	0.00	49.8452	78.1032	5.0
680611 3 5	59.7	0.00	49.7930	78.1451	5.8
680712 12 8	0.0	0.00	49.7547	78.0899	5.9
680820 4 5	59.6	0.00	49.8226	78.0774	4.8
680905 4 5	59.6	0.00	49.7416	78.0756	6.2
680929 343	0.0	0.00	49.8120	78.1219	6.3
681109 254	0.1	0.00	49.8005	78.1391	4.9
681218 5 1	59.7	0.00	49.7459	78.0920	5.7
690307 826	59.8	0.00	49.8215	78.0627	6.3
690516 4 2	59.7	0.00	49.7594	78.0758	6.0
690704 246	59.6	0.00	49.7460	78.1113	6.0
690723 247	0.2	0.00	49.8156	78.1296	6.1
690911 4 2	0.0	0.00	49.7763	77.9967	5.0
691001 4 2	59.9	0.00	49.7825	78.0983	5.9
691229 4 2	0.0	0.00	49.7337	78.1022	5.1
700129 7 3	0.0	0.00	49.7956	78.1239	5.9
700327 5 2	59.6	0.00	49.7478	77.9990	5.4
700628 158	0.0	0.00	49.8015	78.1068	6.2
700724 357	0.0	0.00	49.8097	78.1284	5.8
700906 4 2	59.9	0.00	49.7597	78.0054	6.0
701217 7 1	0.0	0.00	49.7456	78.0992	6.1
710322 433	0.3	0.00	49.7985	78.1090	6.0
710425 332	59.9	0.00	49.7685	78.0339	6.4
710525 4 3	0.4	0.00	49.8016	78.1388	5.2
711129 6 2	59.9	0.00	49.7434	78.0785	5.5
711215 752	59.8	0.00	49.8264	77.9973	4.9
711230 621	0.2	0.00	49.7600	78.0371	5.8
720310 456	59.8	0.00	49.7453	78.1197	5.8
720328 422	0.1	0.00	49.7331	78.0757	5.6
720607 128	0.0	0.00	49.8267	78.1155	5.7
720706 1 3	0.0	0.00	49.7375	78.1101	4.8
720816 316	59.8	0.00	49.7655	78.0588	5.6
721210 427	0.0	0.00	49.8194	78.0582	6.0
730216 5 3	0.0	0.05	49.8061	78.1034	5.6
730710 127	0.1	0.05	49.7730	78.0451	5.4
731026 427	0.1	0.05	49.7469	78.1320	5.3
740130 457	0.1	0.08	49.8158	78.0401	5.4
740516 3 3	0.1	0.05	49.7459	78.0374	5.3
740710 257	0.0	0.05	49.7791	78.1027	5.3
740913 3 2	59.9	0.06	49.7653	78.0549	5.2
741216 623	0.0	0.07	49.7598	78.0754	5.0
741216 641	0.3	0.07	49.8329	78.0318	4.8
750220 533	0.1	0.04	49.7965	78.0093	5.7
750311 543	0.0	0.05	49.7462	78.1060	5.4
750608 327	0.0	0.05	49.7606	78.0125	5.5
750807 357	0.0	0.05	49.8038	78.1234	5.2
751213 457	0.0	0.06	49.8076	78.1144	5.1
760115 447	0.0	0.06	49.8120	78.1576	5.3
760421 458	0.1	0.06	49.7462	78.1060	5.1
760519 257	0.2	0.08	49.7770	78.0009	5.0
760723 233	0.0	0.06	49.7492	78.0617	5.1
761030 457	0.1	0.10	49.8285	78.0516	4.9
761230 357	0.2	0.06	49.7686	78.0331	5.2
770329 357	0.0	0.05	49.7704	78.0136	5.4
770425 4 7	0.1	0.06	49.8076	78.1144	5.1
770730 157	0.1	0.05	49.7500	78.0399	5.3
770817 426	59.9	0.06	49.8200	78.1400	5.1
771029 3 7	0.0	0.04	49.8265	78.0801	5.6
771226 4 2	59.9	0.07	49.8038	78.1234	4.9
780326 357	0.0	0.04	49.7643	77.9993	5.6
780422 3 7	0.0	0.04	49.7469	78.1251	5.3
780529 456	60.0	0.07	49.7986	78.1022	4.7
780728 246	59.9	0.04	49.7488	78.0893	5.7
780829 236	59.9	0.05	49.8074	78.1091	5.2
780920 5 3	0.1	0.13	49.7934	78.1447	4.3
781015 537	0.1	0.05	49.7395	78.1127	5.2
781031 417	0.1	0.05	49.7875	78.0974	5.2
781129 433	0.0	0.05	49.7826	78.0073	5.3
781214 443	0.1	0.09	49.8061	78.1034	4.8
781220 432	59.9	0.08	49.8169	78.0542	4.7
790506 317	0.1	0.05	49.7643	77.9993	5.2
790531 555	0.0	0.05	49.8265	78.0801	5.3
790718 317	3.3	0.06	49.7791	78.1027	5.2
790927 413	0.2	0.11	49.7500	78.0399	4.5
791018 417	0.1	0.05	49.8200	78.1003	5.2

Table 1 (continued)

YRMODAHRMN	SEC	+/-	LATITUD	LONGITU	MAG
791130 453	0.6	0.09	49.7794	78.0953	4.5
791221 442	0.1	0.09	49.7957	78.1230	4.7
800410 4 7	0.2	0.06	49.7780	78.0547	5.3
800522 357	0.1	0.04	49.7739	78.0287	5.8
800731 333	0.1	0.05	49.7955	78.0907	5.5
800925 621	12.9	0.08	49.7855	78.0805	4.9
810630 157	15.3	0.05	49.7669	78.0744	5.4
810717 237	18.1	0.05	49.8064	78.1352	5.3
810814 227	15.2	0.06	49.7587	78.0565	5.3
811120 457	5.1	0.06	49.7401	78.0965	5.2
811222 431	5.4	0.07	49.8267	78.0757	5.1
820219 356	13.4	0.05	49.8136	78.0319	5.4
820625 2 3	7.0	0.07	49.7749	78.0996	5.0
820823 243	6.7	0.08	49.7473	78.0331	5.0
820921 257	3.1	0.05	49.7839	78.1347	5.5
821225 423	8.4	0.10	49.7763	78.0280	4.9
830330 417	10.1	0.09	49.7810	78.0413	5.0
830412 341	8.2	0.08	49.7910	78.0807	5.0
830530 333	47.1	0.04	49.7439	78.1127	5.5
830624 256	13.8	0.08	49.7459	78.0374	5.0
830911 633	13.1	0.10	49.7854	78.0806	4.9

YRMODAHRMN	SEC	+/-	LATITUD	LONGITU	MAG
831129 219	8.8	0.05	49.7355	78.0994	5.5
831226 429	9.2	0.04	49.7975	78.1036	5.7
840415 317	11.5	0.04	49.7499	78.0824	5.9
840909 259	8.7	0.06	49.8060	78.0997	5.1
841018 457	8.3	0.11	49.7328	78.0987	4.5
841123 355	7.5	0.10	49.8176	78.0551	4.7
850725 311	9.1	0.06	49.8157	78.0096	5.3
870226 458	24.3	0.04	49.8299	78.0835	5.4
870403 117	12.3	0.04	49.7467	78.1162	7.3
870506 4 2	8.0	0.04	49.7742	77.9986	6.1
870606 237	9.2	0.04	49.8327	78.0704	5.4
870717 117	9.1	0.03	49.7664	78.0287	6.4
870918 232	8.9	0.20	49.8060	78.0997	4.4
871016 6 6	7.0	0.15	49.7313	78.0906	4.6
871220 255	9.1	0.07	49.7742	77.9986	5.2
880206 419	8.9	0.10	49.7664	78.0287	4.8
880422 930	9.3	0.07	49.7942	78.1000	5.1
881018 340	9.1	0.07	49.7799	78.0079	5.2
881123 357	9.0	0.04	49.7726	78.0378	5.6
890217 4 1	9.1	0.05	49.8235	78.0680	5.3
891004 1130	0.1	0.09	49.7498	78.0117	5.2

Figure 1. Tunnel portals (triangles) (Leith, 1998) and actual (Bocharov et al., 1989) or estimated (this study) ground-truth explosion locations (circles) for Degelen Mountain.

Figure 2. Degelen Mountain JHD mislocations and 95% confidence ellipses for 19 events using all digital data.

Figure 3. Degelen Mountain JHD mislocations and 95% confidence ellipses for 7 events (one fixed) using stations within 40°.

Figure 4. Estimated (open squares) and ground truth (solid circles) locations of 19 Degelen Mountain explosions, using only stations (20) that recorded at least three Balapan and three Degelen Mountain

explosions. a) Without station corrections, b) with station corrections obtained from Degelen Mountain data, and c) with station corrections obtained from Balapan data.