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Applying Waveform Correlation and Waveform Template Metadata to Mining Blasts to Reduce Analyst Workload

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ABSTRACT

Organizations that monitor for underground nuclear explosive tests are interested in techniques that automatically characterize mining blasts to reduce the human analyst effort required to produce high-quality event bulletins. Waveform correlation is effective in finding similar waveforms from repeating seismic events, including mining blasts. In this study we use waveform template event metadata to seek corroborating detections from multiple stations in the International Monitoring System of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization. We build upon events detected in a prior waveform correlation study of mining blasts in two geographic regions, Wyoming and Scandinavia. Using a set of expert analyst-reviewed waveform correlation events that were declared to be true positive detections, we explore criteria for choosing the waveform correlation detections that are most likely to lead to bulletin-worthy events and reduction of analyst effort.

ACKNOWLEDGEMENTS

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ARID	Arrival Identifier
CTBT	Comprehensive Nuclear-Test-Ban Treaty
CTBTO PrepCom	Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization
FAR	False Alarm Rate
IDC	International Data Centre
IMS	International Monitoring System
LEB	Late Event Bulletin
LTA	Long-Term Average
NDEF	Number of Defining Phases. In the Center for Seismic Studies standard, NDEF is defined as the number of locating phases.
ORID	Origin Identifier
PTS	Provisional Technical Secretariat of the CTBTO PrepCom
REB	Reviewed Event Bulletin
SEL	Standard Event List
SNR	Signal-to-Noise Ratio
STA	Short-Term Average
STA/LTA	Ratio of Short-Term Average over Long-Term Average

1. INTRODUCTION

Mining blasts increase the number of seismic events that are detected on global networks such as the International Monitoring System (IMS) and thereby increase analyst workload to produce a bulletin. For that reason, monitoring organizations have shown interest in adopting techniques such as waveform correlation to quickly identify recurring mining blast events to reduce the amount of effort required by analysts to produce a high-quality event bulletin. In 2020, members of the Provisional Technical Secretariat (PTS) of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO PrepCom) invited several experts familiar with waveform correlation methods to participate in a study of mining regions that are particularly problematic for the International Data Centre (IDC). The goal of that research study [1][2] was to reduce analyst workload in monitoring system pipelines due to mining blasts. This report describes a subsequent research study that builds on the prior results and includes additional steps after the waveform correlation detection of a mining blast. This study uses metadata information associated with the template event (i.e. the list of detecting stations and the phases they detected) to develop a set of hypothesized arrivals that can be corroborating evidence for the detection. The purpose of the additional processing steps is to select the waveform correlation detections that are most likely to result in bulletin-worthy events and simultaneously gather the evidence of corroborating arrivals that are consistent with the detection of repeating events, thus reducing workload on the analysts.

The authors used SeisCorr, a software system developed at Sandia National Laboratories for waveform correlation event detection that has previously been used for studies of aftershock sequences [3][4][5] and general regional seismicity, including mining activities [1][2][6]. Using expert analyst-reviewed true event detections as a starting point, we created waveform templates for the set of stations that would be likely to detect a repeating event, which is known from the template event metadata. We apply waveform correlation using the set of corroborating templates to determine if there is evidence of a repeating event shown by the consistency of relative detection times. We present examples of repeating events that were detected using this method.

We analyze the results to develop a set of criteria to select the waveform correlation detections that are most likely to lead to bulletin-worthy events by using template event metadata to search for corroborating arrivals in the two mining regions. Using our recommended criteria for mining regions may accelerate the adoption of waveform correlation for global monitoring by selecting the most useful detections to bring to the attention of seismic analysts.

2. EXPERIMENTAL METHODS

Mining blasts are particularly well suited to detection by waveform correlation because the events are repeated over a small geographic area and the same set of stations will be likely to record the signals. Moreover, the repeating events will fall within a narrower range of magnitudes than natural earthquakes; so, carefully curated waveform templates will detect a larger percentage of the mining blasts. Our method explores empirical results from an iterative search for corroborating arrivals based on template event metadata.

This study applies additional analysis to events that were detected in a prior waveform correlation study of mining blasts [1]. The prior study applied waveform correlation to two mining regions that are problematic for the IDC, one in Wyoming, USA and one in Scandinavia. The two mining regions and the 1-week study periods per region are listed in Table 2-1. The geographical extent of the mining region specifies the location of events that may be used to create historical waveform templates. The geographical extents for both the Wyoming, USA and Scandinavia regions are given as a box bounded by latitude/longitude minimum and maximum values. The temporal span is one week.

Table 2-1. Mining blast geographical and temporal extents.

Region	Temporal Span (UTC)	Temporal span (JDATE)	Geographical Extent (Lat, Lon)
Wyoming, USA	2018-APR-04 to 2018-APR-10	2018094 to 2018100	40°-- 46°N, 110°--100°W
Scandinavia	2018-FEB-12 to 2018-FEB-18	2018043 to 2018049	62°--72°N, 16°--37°E

Table 2-2 shows the three array stations that were chosen for each region to make template waveforms for detection. The arrays are IMS primary seismic stations. Template waveforms from arrays will have waveforms for every element of the array; in other words, an array with 10 stations will have a template with 10 waveforms. Correlation is performed for all elements of the array, and the correlation score across all the waveforms is averaged to determine the correlation score of the template.

Table 2-2. Stations chosen for each study region.

Region	Station Name	Array Name	IMS Treaty Code
Wyoming	Lajitas, TX, USA	TXAR	PS46
	Mina, NV, USA	NVAR	PS47
	Pinedale, WY, USA	PDAR	PS48
Scandinavia	Lahti, Finland	FINES	PS17
	Hamar, Norway	NOA	PS27
	Karasjok, Norway	ARCESS	PS28

The focus of this subsequent research project is to explore using template event metadata to find corroborating detections after an initial waveform correlation detection to assess the credibility and usefulness of the initial detection. Monitoring organizations have been slow to adopt traditional waveform correlation due to the sensitivity of the method, which can result in substantially more marginal quality arrivals for the seismic analysts to review. This study proposes an approach that selects the subset of high quality waveform correlation event detections that correspond to signals that analysts are likely to accept, while avoiding the marginal quality detections that analysts are likely to reject. We call these high quality waveform correlation event detections "bulletin-worthy events", and the efficient, automatic detection of such events can reduce the workload on analysts for mining regions when the repeating event detections are seen at the same group of stations.

The study was conducted using the Sandia-developed SeisCorr software for waveform correlation [3][4][6]. SeisCorr supports three major activities for waveform correlation research: 1) template preparation; 2) correlation of template waveforms with continuous waveform data to detect possible events; and 3) candidate event creation from multistation validation.

For this study, the basic SeisCorr detections were followed by an algorithm to use template event metadata to discover corroborating template waveforms (i.e. template waveforms for other station/phase combinations that were detected for the template event) that we can in turn use to find additional correlation detections to strengthen the evidence for the SeisCorr detected event. The following is an overview of the approach:

- Waveform cross correlation uses template waveforms from historical seismic events to detect recurring events from a similar seismic source.
- Effective waveform cross correlation requires templates with broad frequency content to produce reliable single-station detections over a broad area, but because high-frequency information attenuates strongly over distance, such high-quality templates with broad frequency content only exist for stations at local to near-regional distances from the target seismic sources.
- Our research seeks to improve the effectiveness of waveform cross correlation detections for sparse global networks through use of template event metadata and network analysis of corroborating stations.
- A network-focused perspective of recurring events improves the credibility of detections, since the number of stations that detected the template event originally, in combination with the relative amplitude of recurring detections, enables estimation of how many stations are likely to detect the subsequent event.

The steps of the method are shown in Figure 2-1. Step 1 starts with a detection based on a high-quality template at a station at local to near-regional distances to the target seismic sources. In our prior study of the same mining regions, only 5% of the waveform templates had detections of repeating events over the week-long period while 95% of the waveform templates, created from up to 10 years of historical catalog events, detected no repeating events during this week. From this observation we suggest that it may be possible to curate a small but highly effective template library for mining blasts in the cases where a single high-quality array is located near the target seismic sources.

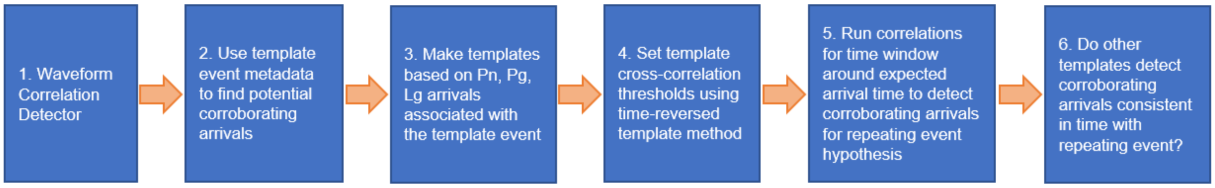


Figure 2-1. Steps of the method to improve effectiveness of waveform cross correlation detections through the use of template event metadata and corroborating arrivals.

The steps are illustrated with an example based on an initial waveform correlation detection by station PDAR (Figure 2-2), which represents step 1. The waveform template is based on a Pn arrival at array PDAR and includes waveforms from all the array elements in addition to the PD01 element shown.

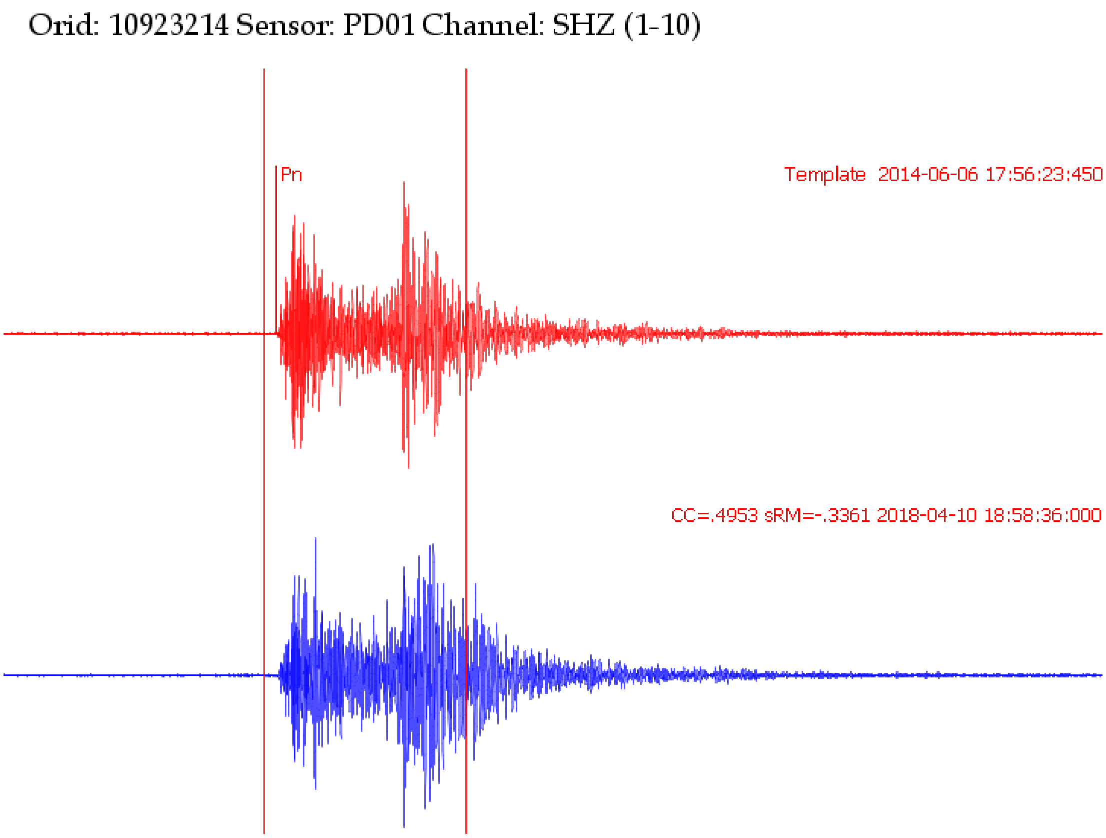


Figure 2-2. Waveform template (red) and detection (blue) for a Pn template from station PDAR for event origin 10923214. The red vertical lines indicate the window of the 80 s template, which begins 5 s before the LEB-picked Pn arrival and contains more than one seismic phase. The figure shows only one array element, PD01, but the template includes waveforms from all 10 elements of the PDAR array.

Step 2 uses the metadata of associated arrivals for the template event origin 10923214 to compile the list of expected arrivals from a potential repeating event that would be recorded at other stations of the network. The list of arrivals from the template event is shown in Table 2-3, and this list provides the group of potential corroborating template waveforms. For this study, we used only the regional Pn, Pg, and Lg arrivals to ensure a high time-bandwidth template. Templates that include multiple phases can be especially effective because the repeating event distance from the station is constrained by the differential arrival time between the phases, thus improving the credibility of the detection (e.g., the example template and detection in Figure 2-2 has multiple phases).

Waveform correlation detections from teleseismic P arrivals are less reliable as single-station detections because the frequency range of the waveform is too narrow to guarantee the detection is from a repeating event at the same location. For this study we choose not to use templates based on teleseismic P.

Table 2-3. Template event origin 10923214 LEB metadata for associated arrivals showing detecting station, associated seismic phase and arrival time.

STA	PHASE[1]	Arrival Time (UTC)
PDAR	Pn	06-JUN-14 18.00.38
PDAR	Pg	06-JUN-14 18.00.43
ELK	Pn	06-JUN-14 18.01.43
ULM	Pn	06-JUN-14 18.01.55
ULM	Lg	06-JUN-14 18.04.26
NVAR	Pn	06-JUN-14 18.02.27
TXAR	Pn*	06-JUN-14 18.03.18
YKA	P*	06-JUN-14 18.04.10
TXAR	Pg*	06-JUN-14 18.04.12
ARCES	P*	06-JUN-14 18.10.00
FINES	P*	06-JUN-14 18.10.43
GERES	P*	06-JUN-14 18.11.18
AKASG	P*	06-JUN-14 18.11.43
ZALV	P*	06-JUN-14 18.12.06
SONM	P*	06-JUN-14 18.12.18
MKAR	P*	06-JUN-14 18.12.42
[1] Phases marked with * were not used as templates.		

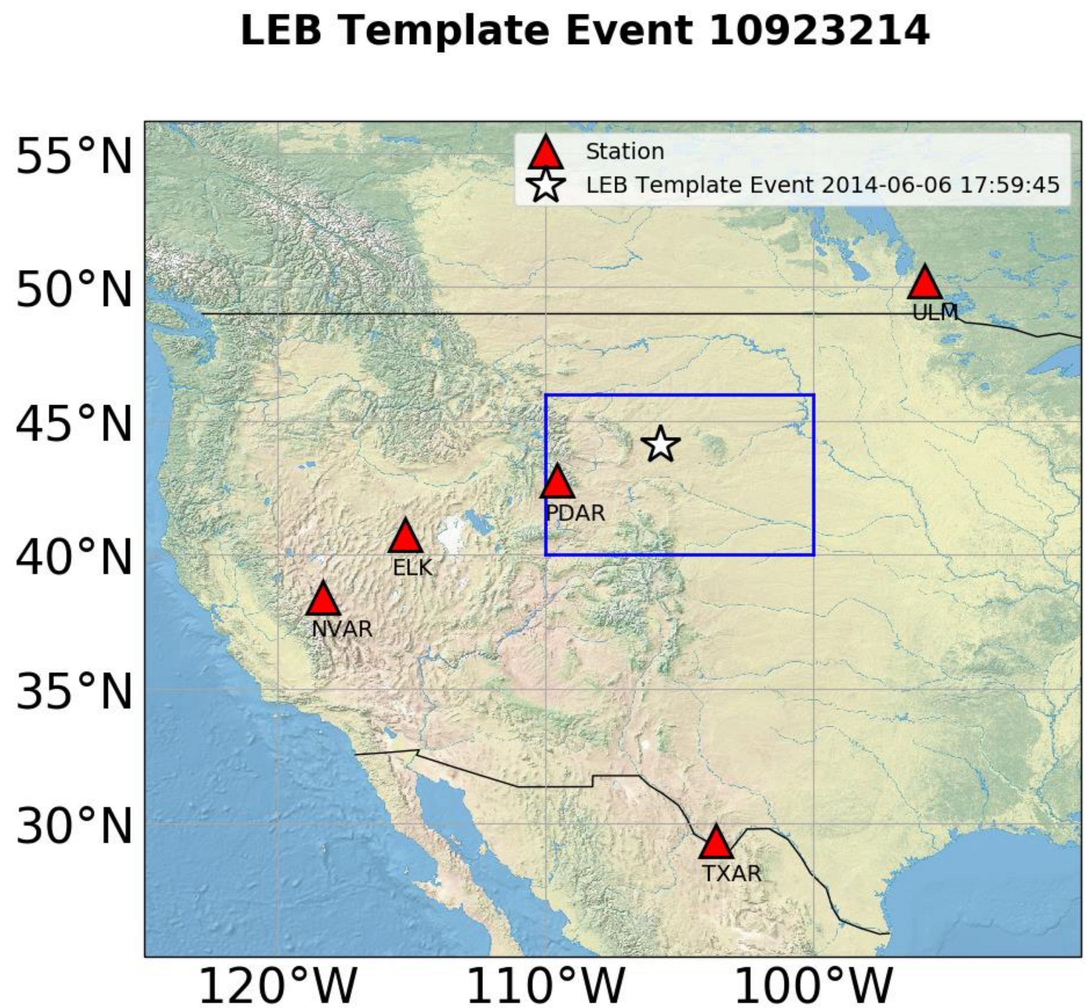


Figure 2-3. Location of LEB template event 10923214, shown by a white star and with the event time in the legend. The five detecting station locations are shown by red triangles with the name of the station. The study area is shown by a blue rectangle.

A map of the station locations relative to the template event 10923214 is shown in Figure 2-3. Only the stations used for waveform templates are shown on the map.

Step 3 is shown in Figure 2-4, where the associated arrivals for the template event are made into corroborating template waveforms from the same event that was detected by the first station. For this example, templates were made for two additional three-component stations, ELK and ULM, and for two additional arrays, NVAR and TXAR. Two simplifications were made in template preparation by choosing the same filter bands that were chosen for the PDAR template, 1-5 Hz, and the same template window size, 80 s, for all the corroborating templates. For arrays, the templates include a waveform for every array element. For three-component stations, the template contains three waveforms representing the north, east, and vertical components. No short-term-average / long-term-average (STA/LTA) thresholds were applied to assure that a signal was present or that the corroborating template waveform met a minimum signal-to-noise (SNR) criterion.

Waveform correlation performs well with a high time-bandwidth product; thus, a broad frequency band filter was chosen to retain individual characteristics of the signal at the expense of a template that exhibits more background noise. It may be possible to apply denoising techniques [9] to improve the SNR of the signal while retaining an even higher time-bandwidth template, but this remains for future work. In this study the broad range of frequencies likely to produce a credible correlation match was prioritized higher than maximizing the SNR of the signal.

The approach for making corroborating templates worked well for this example despite the simplifying assumptions applied to window length and filter bands. For three-component station ULM, waveform templates were windowed based on both the LEB Pn and Lg picks, so this station had two potential corroborating templates. For array TXAR, the Pn and Pg picks were buried in noise and made poor templates; however, there was an Lg pick with a large amplitude that was chosen as a preferred template for corroboration.

STA	PHASE	Arrival Time (UTC)
PDAR	Pn	06-JUN-14 06.00.38 PM
PDAR	Pg	06-JUN-14 06.00.43 PM
ELK	Pn	06-JUN-14 06.01.43 PM
ULM	Pn	06-JUN-14 06.01.55 PM
ULM	Lg	06-JUN-14 06.04.26 PM
NVAR	Pn	06-JUN-14 06.02.27 PM
TXAR	Pn	06-JUN-14 06.03.18 PM
TXAR	Pg	06-JUN-14 06.04.12 PM
TXAR	Lg	06-JUN-14 06.08.06 PM

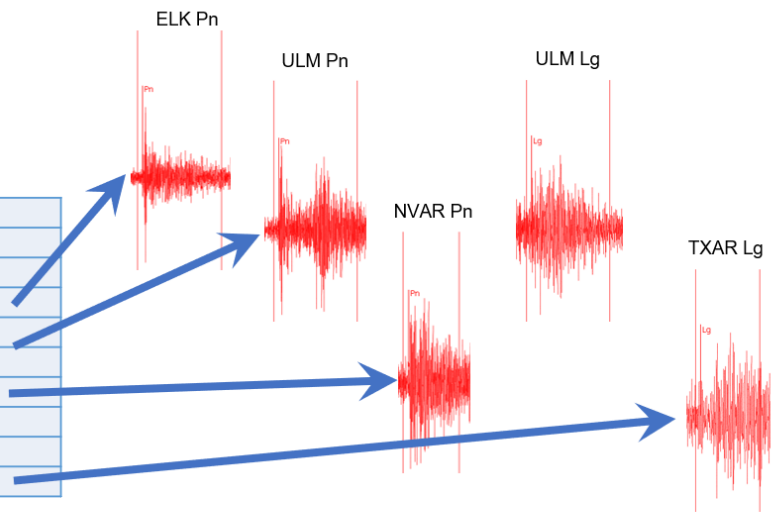


Figure 2-4. Templates created from the template event arrival waveforms can be used to corroborate a repeating event. The table shows the LEB picked arrivals that lead to the template waveforms on the right side of the figure.

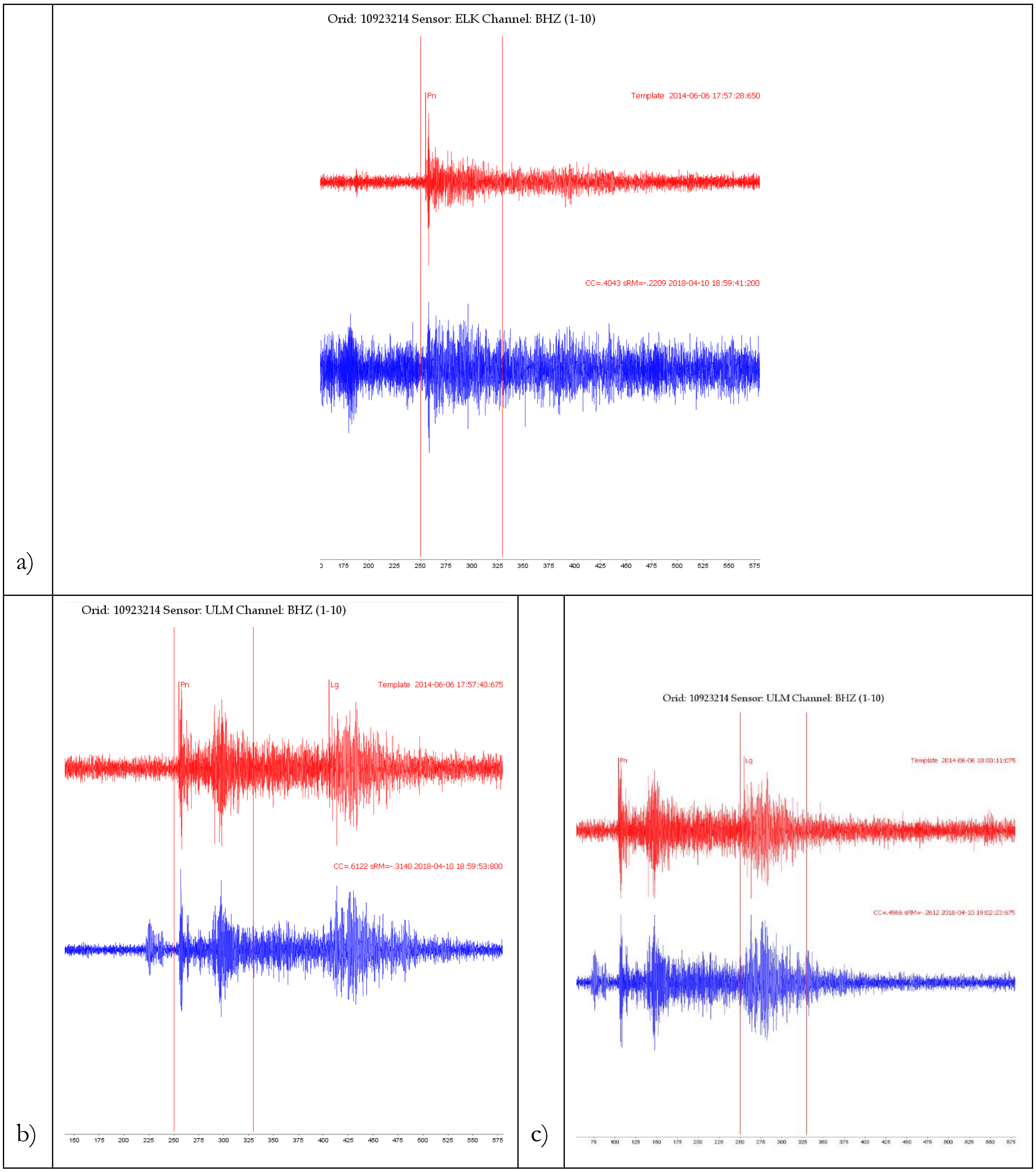
Step 4 sets the cross-correlation threshold for the newly created templates. We used the time-reverse method [6] to set the thresholds, with a desired false alarm rate (FAR) of 1 FA/year. The reversed templates were correlated against a 24-hour period that corresponds to the time of the desired corroborating detection, to set a threshold adequate to exclude noise detections.

Our normal use of the time-reverse method adds a small increment of 0.05 to the resulting template threshold to raise the threshold above the background noise level. This slight adjustment has been useful for studies when templates are correlated across years of continuous data. For the corroborating templates there was no adjustment to the template threshold resulting from the time-reverse method because the corroborating detectors should be as sensitive as possible, and they will be used only for a short time window to verify the initial detection.

Step 5 correlates the corroborating template waveforms for each station, using a 2-hour window centered on the initial detection to seek evidence for the repeating event hypothesis. The results are shown in Figure 2-5. This example was successful at demonstrating the method because five independent detections at four additional stations were found during the expected time window.

Moreover, the evidence provided by the double detection at station ULM (b and c) matching three seismic phase waveforms is strong evidence for a repeating event.

Some of the corroborating templates in this example are poor signals with high noise levels. Independently these templates would not make good waveforms for continuous data stream cross-correlation. The individual detections are likewise poor signals and could be missed as a coherent set of detections. Yet in combination with the initial PDAR detection and the combined detections from other corroborating templates, the evidence for a repeating event is convincing.



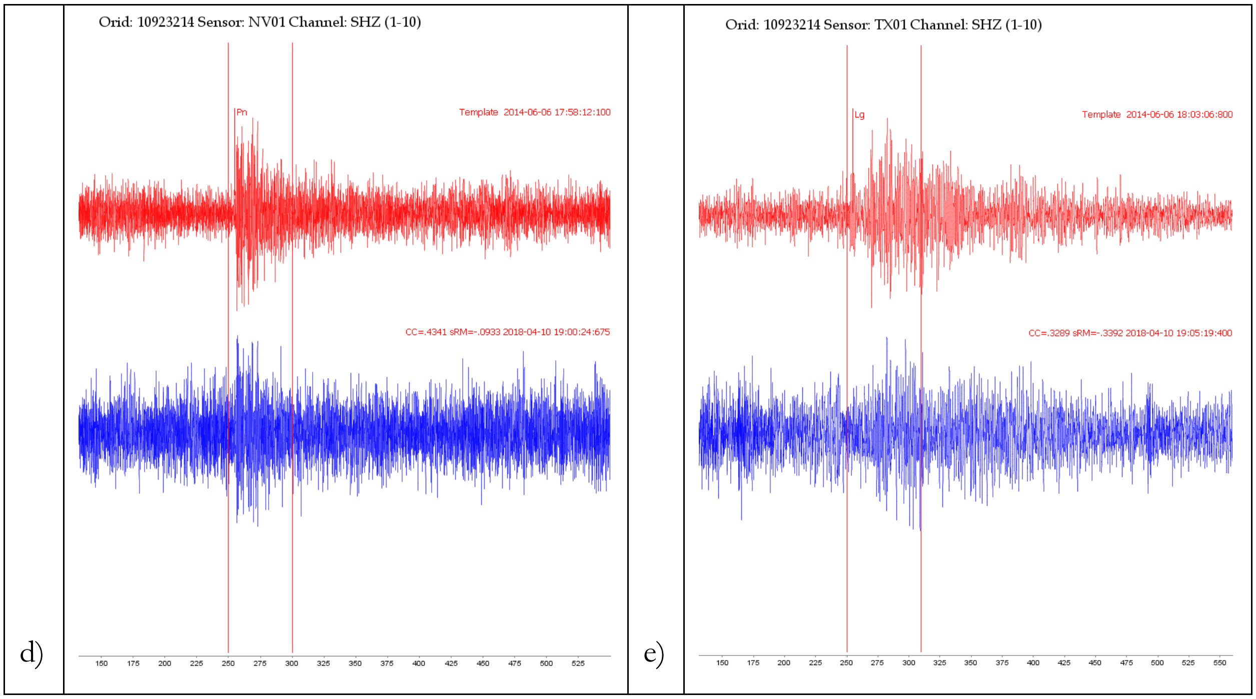


Figure 2-5. Templates (red) and corresponding correlation detections (blue) for 2-hour time window based upon initial PDAR detection to detect corroborating arrivals for repeating event hypothesis. Template windows are indicated by vertical red lines. For three-component stations ELK and ULM, only the vertical component is shown. For arrays NVAR and TXAR, only the vertical component of the first array element is shown. a) Pn at ELK. b) Pn at ULM. Note that the template includes multiple phases, Pn and Pg. The Lg phase is not part of the template window. c) Lg at ULM. The Pn and Pg phases are not part of the template window. d) Pn at NVAR. e) Lg at TXAR.

Step 6 calculates time differences relative to the initial template times and initial detection times to look for consistency in arrival time differences between stations that would be expected for a repeating event (Table 2-4). For simplicity, the template time and detection time are used for this calculation; the template starts 5 s prior to the picked arrival in all templates, so the template time precedes the arrival time. The last two columns in the table show the time differences relative to the station PDAR, with excellent agreement for almost all time differences. Any discrepancies are likely due to a slight difference in location between the two events. This approach has a further advantage in that a relative location for the detected event can be calculated if there are enough corroborating detections.

Table 2-4. Table of delta time calculations for corroborating templates from LEB ORID 10923214 and detections from correlation during the study period in Wyoming.

LEB ORID 10923214					
Station	Phase	Template date/time (UTC)	Detection date/time (UTC)	Difference in Template Times Relative to PDAR (s)	Difference in Detection Timings Relative to PDAR (s)
PDAR	Pn	6/6/14 17:56:23	4/10/18 18:58:36	0	0
ELK	Pn	6/6/14 17:57:28	4/10/18 18:59:41	65	65
ULM	Pn	6/6/14 17:57:40	4/10/18 18:59:43	77	77
ULM	Lg	6/6/14 18:00:11	4/10/18 19:02:23	228	227
NVAR	Pn	6/6/14 17:58:12	4/10/18 19:00:24	109	108
TXAR	Lg	6/6/14 18:03:06	4/10/18 19:05:19	403	403

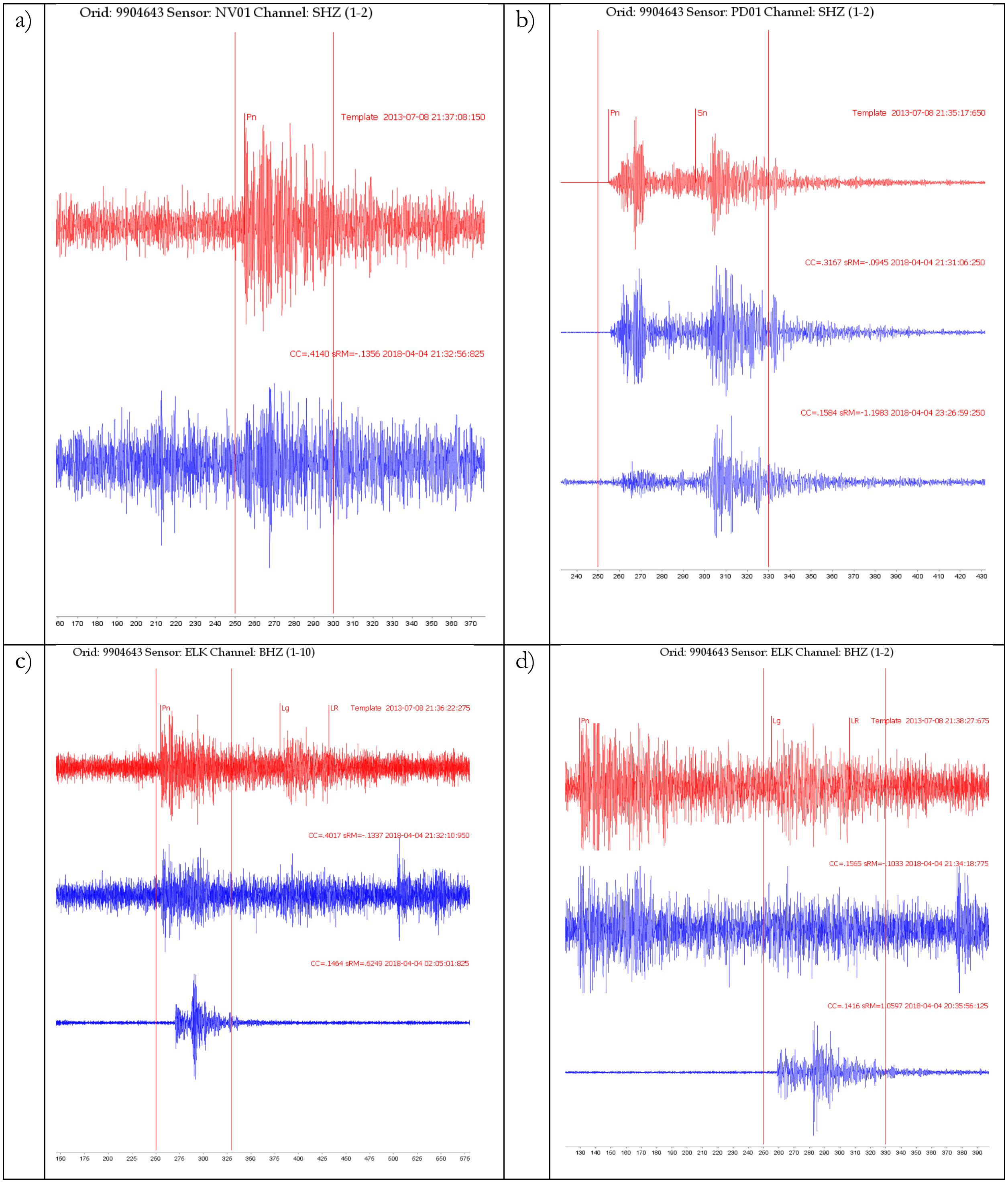
Using waveform correlation only as a signal detector does not guarantee a reduction in analyst workload if marginal events that do not meet bulletin-inclusion criteria are detected. Our research targets the selection of waveform correlation detections that will lead to bulletin-worthy events. The chosen example shows that a credible repeating event can be detected by dynamically creating additional templates from arrivals that were associated to the template event. The individual waveform correlation detections may not be convincing, yet the combined group of corroborating arrivals are consistent in time with a repeating event. A simple calculation of time differences can establish the credibility of the repeating event and can lead to a relative location.

3. ADDITIONAL EXAMPLES

This empirical study explores a method for a set of repeating mining blasts, yet unexpected difficulties often appear when an algorithm processes real data. The examples in this section illustrate some of the issues that were discovered and form the basis for later discussion and conclusions.

The example based on Template Event ORID 10923214 (Table 2-4) illustrates how well this method can work to find repeating events. The template event had 18 associated arrivals with Number of Defining Phases (NDEF) 16 and a magnitude m_b of 3.95. The template event in Wyoming was large enough for IMS arrays in Europe and Asia to record teleseismic P arrivals. Waveform correlation detected the repeating event with a relative magnitude of 0.461 and calculated magnitude m_b 3.8. The size of the initial event, number of detecting IMS stations, and relative magnitude of the detection may predict when an initial waveform correlation will lead to credible corroborating templates; in other words, the relative magnitude of the repeated event is important for estimating whether the event is bulletin-worthy, and an important criteria for inclusion in a bulletin is the number of detecting stations. One of the goals of this study is to use this small mining blast dataset to explore whether the approach to corroborating arrivals is worth pursuing on a larger scale for sparse networks.

Figure 3-1 shows another example that is based upon an initial detection by array NVAR, which is not the closest station to the event. We use the template event ORID 9904643 metadata to create potential corroborating templates for stations (phases): PDAR (Pn), ELK (Pn and Lg), and ULM (Pn and Lg). Consider only the first detection for all the corroborating templates where there is more than one detection shown (upper blue waveform in each panel). The evidence for a repeating event based on the first set of detections is contained in the table of time difference calculations (Table 3-1). As can be seen from the close agreement of relative arrival times from PDAR, this example suggests a repeating event with six independent detections at four stations. Moreover, the independent Pn and Lg templates detect the same event as can be seen by viewing the waveforms for ELK (c, d) and ULM (e, f). This example shows that the method can be applied even if the initial detection was not made by the closest station to the source.


a)
Orid: 9904643 Sensor: NV01 Channel: SHZ (1-2)
Pn
Template 2013-07-08 21:37:08:150
CC=.4140 sRM=-.1356 2018-04-04 21:32:56:825
b)
Orid: 9904643 Sensor: PD01 Channel: SHZ (1-2)
Pn
Sn
Template 2013-07-08 21:35:17:650
CC=.3167 sRM=-.0945 2018-04-04 21:31:06:250
CC=.1584 sRM=-1.1983 2018-04-04 23:26:59:250
c)
Orid: 9904643 Sensor: ELK Channel: BHZ (1-10)
Pn
Lg
LR
Template 2013-07-08 21:36:22:275
CC=.4017 sRM=-.1337 2018-04-04 21:32:10:950
CC=.1464 sRM=.6249 2018-04-04 02:05:01:825
d)
Orid: 9904643 Sensor: ELK Channel: BHZ (1-2)
Pn
Lg
LR
Template 2013-07-08 21:38:27:675
CC=.1565 sRM=-.1033 2018-04-04 21:34:18:775
CC=.1416 sRM=1.0597 2018-04-04 20:35:56:125

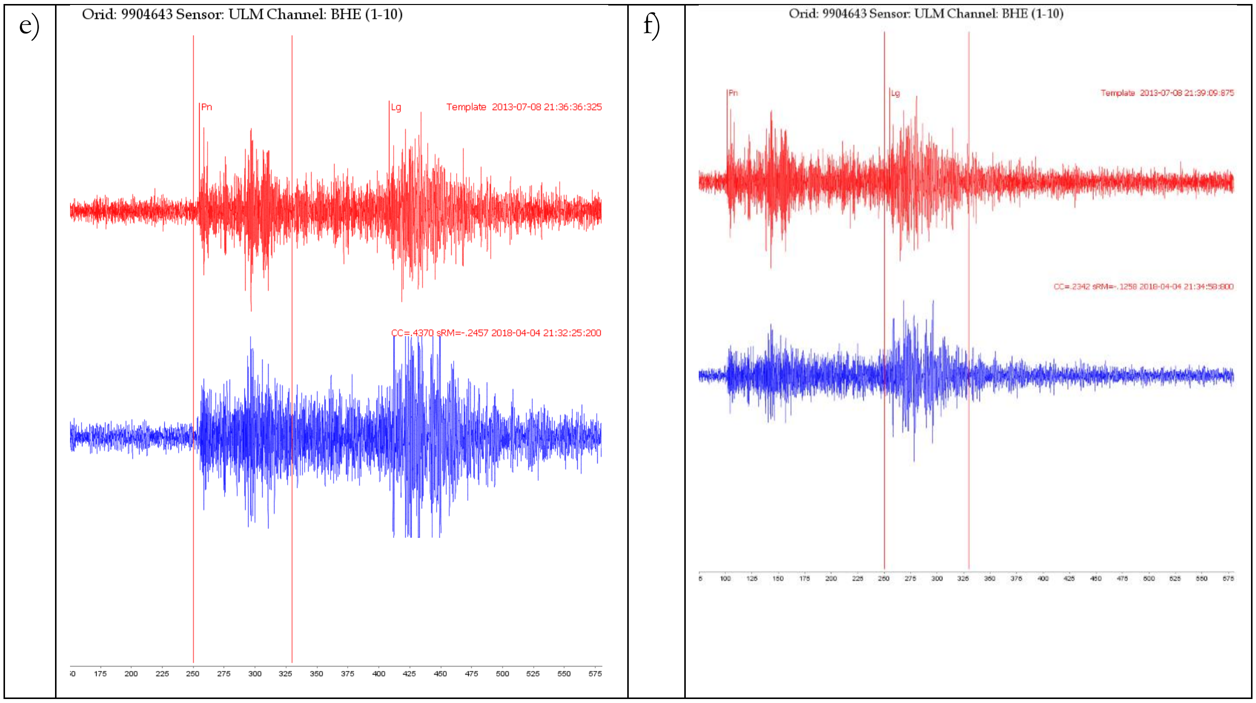


Figure 3-1. Templates (red) and correlation detections (blue) based upon initial NVAR detection to detect corroborating arrivals for repeating event hypothesis. Template windows are indicated by vertical red lines. For three-component stations ELK and ULM, only the vertical component is shown. For arrays NVAR and PDAR, only the vertical component of the first array element is shown. a) Pn at NVAR with one detection. b) Pn at PDAR where the template also includes the Sn phase, and there are two detections. c) Pn at ELK, with two detections. d) Lg at ELK, with two detections. e) Pn at ULM with one detection. f) Lg at ULM with one detection.

Table 3-1. Table of relative time calculations for corroborating templates from LEB ORID 9904643 and first set of correlation detections shown in Figure 3-1.

LEB ORID 9904643					
Station	Phase	Template date/time (UTC)	Detection date/time (UTC)	Difference in Template Times Relative to PDAR (s)	Difference in Detection Times Relative to PDAR (s)
PDAR	Pn	7/8/13 21:35:17	4/4/18 21:31:06	0	0
ELK	Pn	7/8/13 21:36:22	4/4/18 21:32:10	65	64
ELK	Lg	7/8/13 21:38:27	4/4/18 21:34:18	190	192
ULM	Pn	7/8/13 21:36:36	4/4/18 21:32:25	79	79
ULM	Lg	7/8/13 21:39:09	4/4/18 21:34:58	232	232
NVAR	Lg	7/8/13 21:37:08	4/4/18 21:32:56	111	110

We chose the example in Figure 3-1 because there are additional waveform correlation detections by some of the templates and we can also examine those event hypotheses for corroborating detections. The templates from stations NVAR (a) and ULM (e, f) did not record any corroborating detections. The second set of detections are the lower blue waveforms in panels (b), (c), and (d). The delta time calculations for the second set of detections by PDAR (b) and ELK (c, d) are shown in Table 3-2. The waveforms appear to represent real events rather than noise, but the detections are not consistent with a repeating event hypothesis like LEB ORID 9904643 because there is no arrival time consistency between array PDAR and station ELK. For example, the template Pn delta time for station ELK in Table 3-2 is only 65 seconds but the Pn detection delta time is -76918 seconds. The large inconsistency between Pn delta times shows that the ELK detection is not from an event colocated with LEB ORID 9904643. Moreover, the inconsistent time deltas of the Lg detection at station ELK with both the Lg template delta time and the Pn detection time provide additional evidence that the ELK detections are false waveform correlation detections. This example shows that seeking corroborating detections can minimize the impact of marginal waveform correlation detections in addition to improving the credibility of true positive waveform correlation detections.

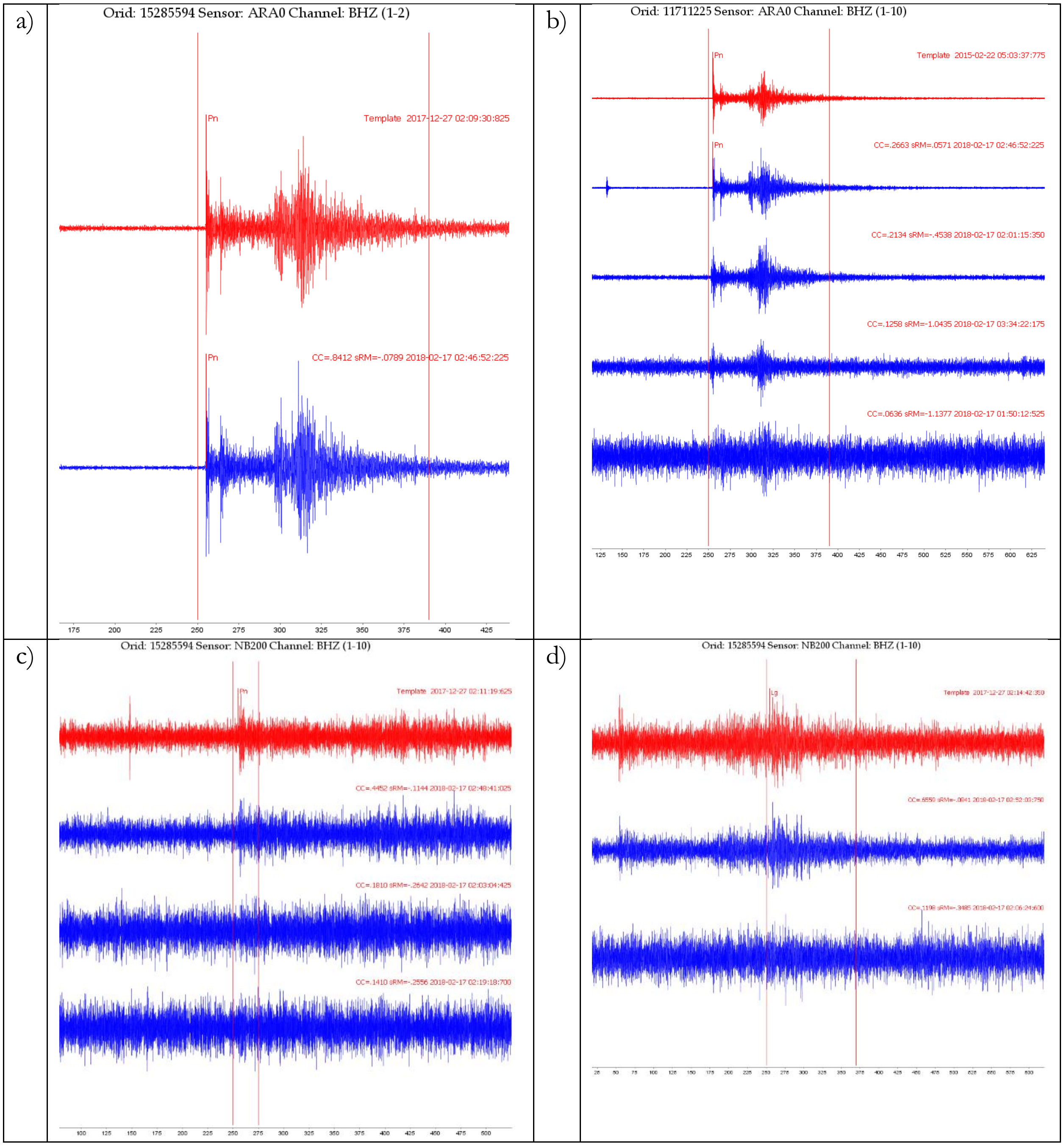
Table 3-2. Table of relative time calculations for corroborating templates from LEB ORID 9904643 and the second set of correlation detections shown in Figure 3-1.

LEB ORID 9904643					
Station	Phase	Template date/time (UTC)	Detection date/time (UTC)	Difference in Template Times Relative to PDAR (s)	Difference in Detection Times Relative to PDAR (s)
PDAR	Pn	7/8/13 21:35:17	4/4/18 23:26:59	0	0
ELK	Pn	7/8/13 21:36:22	4/4/18 02:05:01	65	-76918
ELK	Lg	7/8/13 21:38:27	4/4/18 20:35:56	190	-10263

An example from the Scandinavia region (Figure 3-2) shows that multiple detections may be corroborated by the same set of templates. This situation exists where there are numerous repetitions of a mining blast event that have a similar source, location, and magnitude. This example is interesting because there are two ARCES templates that detected the same event. The ARCES template from LEB ORID 15285594 (a) detected the event, while the ARCES template from LEB ORID 11711225 (b) detected the same event (top blue waveform) but also an additional second, third and fourth detections, listed in order of correlation score. The subsequent detections in (b) are events of lower magnitudes. Smaller events are less likely to be corroborated by other stations, and that is exemplified by the set of detections in (b).

The first set of possible corroboration correlation detections, based on the template event LEB ORID 15285594, are shown by the upper blue waveforms in Figure 3-2. This set of detections identify a repeating event as shown in the table of delta time calculations (

Table 3-3). The close agreement of relative arrival times from ARCES indicates a repeating event with five independent detections at four stations, ARCES (a), NOA (c, d), FINES (e), and SPITS (f).



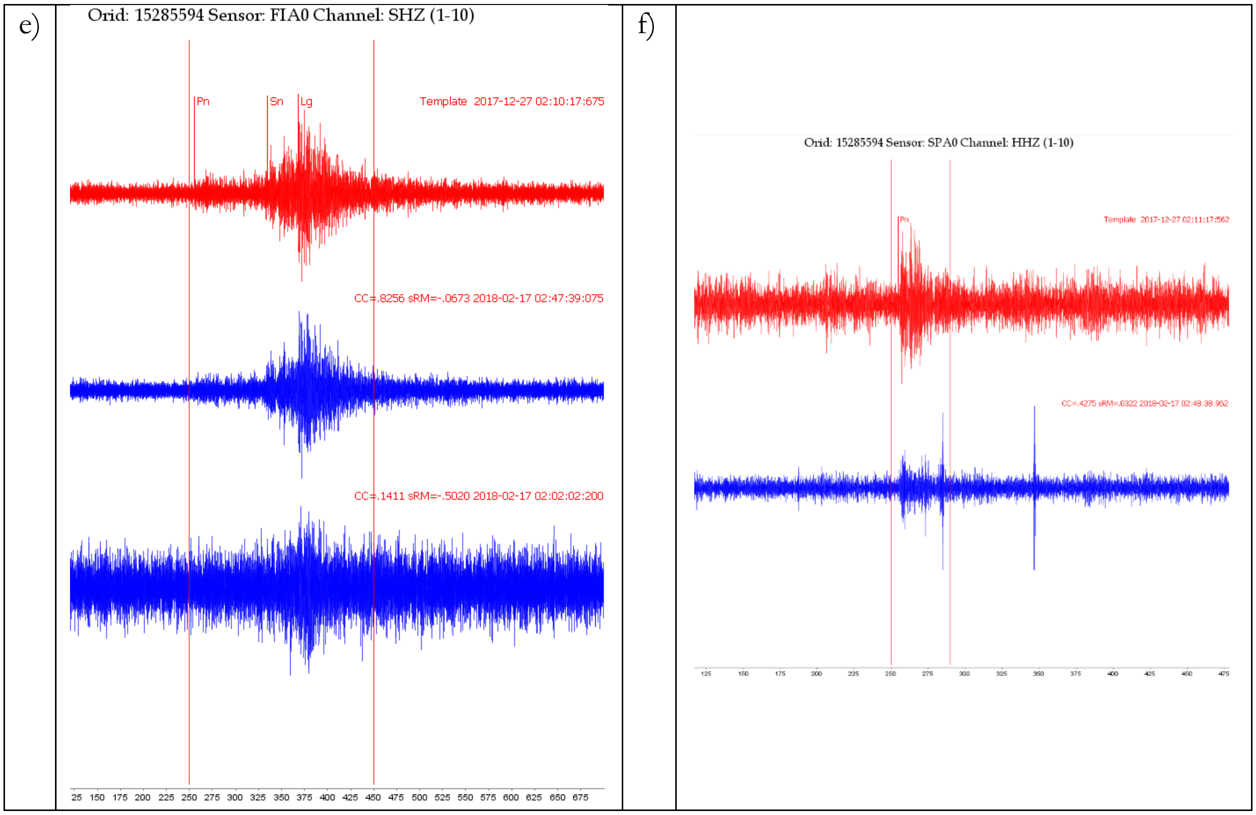


Figure 3-2. Templates (red) and correlation detections (blue) based upon initial ARCES detection to detect corroborating arrivals for repeating event hypothesis. Template windows are indicated by vertical red lines. For arrays ARCES, FINES, NOA, and SPITS only the vertical component of the first array element is shown. a) Pn at ARCES for template ORID 15285594 with one detection. The template includes the entire waveform. b) Pn at ARCES for template ORID 11711225 with four detections. c) Pn at NOA, with three detections. d) Lg at NOA, with two detections. e) Pn at FINES where the template also includes the Sn and Lg phases, and there are two detections. f) Pn at SPITS with one detection.

Table 3-3. Table of relative time calculations for corroborating templates from LEB ORID 15285594 and first set of correlation detections shown in Figure 3-2.

LEB ORID 15285594					
Station	Phase	Template date/time (UTC)	Detection date/time (UTC)	Difference in Template Times Relative to ARCES (s)	Difference in Detection Times Relative to ARCES (s)
ARCES	Pn	12/27/17 02:09:30	2/17/18 02:46:52	0	0
NOA	Pn	12/27/17 02:11:19	2/17/18 02:48:41	109	109
NOA	Lg	12/27/17 02:14:42	2/17/18 02:52:03	312	311
FINES	Pn	12/27/17 02:10:17	2/17/18 02:47:39	47	47
SPITS	Pn	12/27/17 02:11:17	2/17/18 02:48:38	107	106

The second set of detections (Figure 3-2) by NOA (c, d) and FINES (e) based on the template event LEB ORID 15285594 are shown by the second row of blue waveforms. The ARCES and SPITS templates based on LEB ORID 15285594 only detected one event. We first look for a consistent set of delta arrival times based on the NOA and FINES detections only. Table 3-4 shows that agreement of delta arrival times indicates a repeating event with three independent detections at two stations, NOA (c, d), and FINES (e). The agreement of three independent detections makes this a credible repeating event.

Table 3-4. Table of relative time calculations for corroborating templates from LEB ORID 15285594 and second set of correlation detections shown in Figure 3-2.

LEB ORID 15285594 (NOA, FINES)					
Station	Phase	Template date/time (UTC)	Detection date/time (UTC)	Difference in Template Times Relative to NOA Pn (s)	Difference in Detection Times Relative to NOA Pn (s)
NOA	Pn	12/27/17 02:11:19	2/17/18 02:03:04	0	0
NOA	Lg	12/27/17 02:14:42	2/17/18 02:06:24	203	200
FINES	Pn	12/27/17 02:10:17	2/17/18 02:02:02	-62	-62

We explored a potential extension to the method of seeking corroborating detections. We augment the corroborating detections based on a single template event by substituting duplicated detections from the same station but from a different template event. For example, Figure 3-2 shows waveform templates from station ARCES that detected the same arrival at 2/17/18 02:46:52.225 UTC but were based on different template events (a) LEB ORID 15285594 and (b) LEB ORID 11711225. The template based on LEB ORID 15285594 detected only one event, but the template based on LEB ORID 11711225 duplicated the detection and also detected three additional events. We substituted the detection date/time from the second detection based on LEB ORID 11711225 (Table 3-5, bold font). The augmentation for this example expanded the set of consistent delta times, further improving the credibility of the set of detections. This example shows that the waveform template (a) with the highest cross-correlation score (0.8412) was not the most useful waveform template for detecting repeating mining events (b), possibly because the waveform template has characteristics that are too specific due to local geology. The use of detection time substitution based on duplicate detections should be particularly useful in mining regions where template events are densely located and template libraries can evolve over time to include the most useful template waveforms.

Table 3-5. Table of relative time calculations for corroborating templates from LEB ORID 15285594 and second set of correlation detections shown in Figure 3-2 but including substitution of detection at ARCES based on template event LEB ORID 11711225.

LEB ORID 15285594 (NOA, FINES) and LEB ORID 11711225 (ARCES)					
Station	Phase	Template date/time (UTC)	Detection date/time (UTC)	Difference in Template Times Relative to ARCES (s)	Difference in Detection Times Relative to ARCES (s)
ARCES	Pn	12/27/17 02:09:30	2/17/18 02:01:15	0	0
NOA	Pn	12/27/17 02:11:19	2/17/18 02:03:04	109	109
NOA	Lg	12/27/17 02:14:42	2/17/18 02:06:24	312	309
FINES	Pn	12/27/17 02:10:17	2/17/18 02:02:02	47	47

4. ANALYSIS

This study uses a set of expert analyst-reviewed events that were determined in the previous study [1] to be detections of true events, hereafter referred to as true positives. The true positive events are from a dataset of waveform correlation detections in the mining regions of Wyoming and Scandinavia (Table 2-1) [1]. That study concluded that waveform correlation detects additional true positive events that were missed by the IDC automated pipeline, but also suggests that detecting more mining blasts for the seismic analysts to review does not guarantee a reduction in analyst workload if the events are marginal detections that do not lead to bulletin-worthy events. This study seeks to improve on the results from the prior study by developing a strategy to choose the most useful waveform correlation detections using template metadata to search for corroborating detections; thus, the seismic analysts may be presented with convincing evidence from multiple stations. This section of the paper reviews the true positive template and detection metadata and offers insights for choosing the most useful waveform correlation detections for mining blasts.

The preferred waveform correlation detections meet each of the following criteria:

1. At least four stations recording picked Pn or Pg arrivals in the template event.
2. A cross-correlation score that exceeds the template threshold by 0.1 if the template threshold was chosen by the time-reverse threshold setting method. This criterion excludes marginal detections from the initial collection of preferred detections.
3. An estimated relative magnitude of between 1.1 and 0.4. of the template event magnitude Mining blast events with a larger relative magnitude will be detected by traditional methods, and events with a smaller relative magnitude are unlikely to be large enough to corroborate with multiple stations.

The example in Table 4-1 meets all the criteria recommended. Metadata from template event LEB ORID 9904643 is shown in the four leftmost columns: the arrival ID (ARID) uniquely identifies the seismic waveform; the recording station; the seismic phase; and the picked arrival time. The six rightmost columns contain metadata from template detections: SeisCorr origin ID; waveform template ID; the cross-correlation threshold for the template; the cross-correlation score of the detection; the estimated relative magnitude of the detected event; and the detection time. In this example, a waveform correlation detection by NVAR Pn template 3864752 at 4/4/18 21:37:06 UTC created SeisCorr event 24999297. The NVAR Pn template and detection waveforms may be seen in Figure 3-1 (a), and the corroborating detections by station PDAR Pn (b), ELK Pn (c), and ULM Pn (e) are based on ARIDS 87760874, 87761860, and 87760892, respectively. The Lg arrivals are not included in Table 4-1 because Lg picks are not considered time-defining arrivals even though Lg waveforms are valuable regional waveform correlation detectors. This study chose to start with time-defining arrivals to be consistent with the goal of detecting bulletin-worthy events.

There are 4 stations that recorded picked Pn arrivals. The CC score of 0.41 exceeds the CC threshold of 0.18 by more than 0.1. The estimated relative magnitude of 0.73 is large enough to expect that waveform correlation can detect the corroborating arrivals. Furthermore, for this example there are picked Lg arrivals for stations ELK and ULM that provide additional evidence of the repeating event in Table 3-1.

Other criteria were considered, such as the magnitude of the template event and SNR of the detecting template or the existence of other picked phases such as Lg in the template event metadata. Yet we found that imposing too many criteria on the dataset in this study eliminated the entire set of preferred waveform correlation detections and left no corroborating candidates to study; thus, we suggest a minimal initial set of criteria. In a larger future study with application to a global dataset for a longer period of time, it may be necessary to expand or refine the criteria. Mining blasts are expected to be similar in magnitude for a region, thus are particularly well suited to the application of minimal criteria for selection of preferred waveform correlation detections. Other types of repeating events, such as aftershocks, may require more criteria to match the magnitude of the template event with the estimated magnitude of the detected event to ensure valid waveform correlation detections.

During the one-week period in the Wyoming region the prior study [1] detected 106 true positive mining blast events using waveform correlation; in contrast, the REB contains only 13 bulletin-worthy events for the same timeframe. The current study recommends a set of three criteria to choose preferred waveform correlations to reduce the number of detections added to the analyst workload. For the Wyoming region, the criterion requiring template events with four or more stations that recorded picked Pn and/or Pg arrivals, in combination with the criterion that limits the relative magnitude range of the detection, eliminated most of the 106 waveform correlation detections from the preferred set of detections because the detected events have smaller relative magnitudes than the template event. Applying the combined set of three criteria yields a set of six waveform correlation detections that would qualify for the method of searching for corroborating arrivals, which is a realistic set of detections to add to the analyst workload, especially if the additional detections include corroborating arrivals at multiple stations.

The prior study [1] of the Scandinavia region detected 371 true positive mining blast events using waveform correlation while the REB contains 19 bulletin-worthy events. Applying the same set of three criteria to the Scandinavia region resulted in 28 preferred waveform correlation detections; in contrast, the automated pipeline generated 33 Standard Event List (SEL3) events for the analysts to review so the techniques are generating comparable quantities of events for analyst review. For the Scandinavia region, the criterion limiting the relative magnitude range in combination with the criterion for correlation score was the most restrictive combination. This region had more template events with five or more stations that recorded Pn and Pg arrivals, so fewer waveform correlation detections were eliminated based on the criterion that required at least four or more Pn and/or Pg arrivals.

Table 4-1. Metadata for template event LEB ORID 9904643 and waveform correlation detection by NVAR Pn template 3864752 on 4/4/18 21:37:06 UTC[1]

LEB ORID 9904643 metadata				NVAR Pn template 3864752 metadata for detection on 4/4/2018					
ARID	Station	Phase	Arrival Time 08-JUL-13	SeisCorr Origin	Template	CC Threshold	CC Score	Relative Magnitude	Detection Time
87760874	PDAR	Pn	09.39.32 PM						
87761860	ELK	Pn	09.40.37 PM						
87760892	ULM	Pn	09.40.51 PM						
87760998	NVAR	Pn	09.41.22 PM	24999297	3864752	0.179809725	0.413958	0.731758424	04-APR-18 09.37.06 PM
87760979	ARCES	P	09.48.56 PM						
87760984	FINES	P	09.49.39 PM						
87795349	GERES	P	09.50.13 PM						
87795350	AKASG	P	09.50.38 PM						
87761060	ZALV	P	09.51.01 PM						
87795348	SONM	P	09.51.14 PM						
87761150	MKAR	P	09.51.38 PM						

[1] Arrival and detection times in this table are copied from the bulletin and differ from template start times and waveform correlation detection times in other figures and tables. The template start times precede the picked arrival by 5 seconds.

5. DISCUSSION

Waveform correlation is an established technique for finding repeating events. The technique works extremely well for dense networks and local distances where the template has a high time-bandwidth product for a high SNR waveform, making detection of false events unlikely. This study seeks to stretch the application of the technique to sparse global networks by using additional information beyond the waveform to develop supporting evidence for the repeating event. We have chosen to use the template event metadata to create a set of corroborating templates, some of which may be so marginal that they would not pass SNR threshold or STA/LTA threshold tests. Yet, a group of marginal detections based on the same template event may be convincing when taken in combination with one or more detections of the event from nearby stations also based on the same template event. One of the benefits of this approach is that only template waveforms from stations at local or regional distances must be curated as template libraries because the corroborating templates can be windowed on demand based on metadata of recorded arrival times in the template event. We acknowledge that more complexity is required for this method than for a typical waveform correlation system; to implement this method, a correlation detection will spin off processes to dynamically window waveforms, set thresholds for the corroborating arrivals, and correlate the potentially corroborating templates during the timeframe of the expected arrival from a repeating event. However, this algorithmically-based approach to using template metadata may prove less manually intensive than maintaining template libraries for all the mining regions on a global scale.

The Wyoming example based on template event ORID 10923214 (Figure 2-5) illustrates how well this method can work to find repeating events. The template event had 18 associated arrivals, NDEF 16 and magnitude m_b 3.95. The template event was large enough for IMS arrays in Europe and Asia to record teleseismic P arrivals. Waveform correlation detected the repeating event at array PDAR with a cross-correlation score of 0.4953, relative magnitude of 0.461 and calculated magnitude m_b 3.8. The size of the template event, number of detecting IMS stations, and relative magnitude of the detection meet the criteria proposed to predict if the initial waveform correlation detection will lead to credible corroborating templates and bulletin-worthy repeating events. The detected repeating event is smaller than the template event, yet waveform correlation detects enough similarity with the corroborating templates to register a detection for other stations that detected the template event.

Templates that incorporate the Lg waveforms are valuable detectors due to high time-bandwidth characteristics of that phase [7][8]. Array TXAR in the Wyoming region and array NOA in the Scandinavia region recorded many high-quality Lg arrivals. Lg templates were excluded from the selection criteria in this study because Lg is not a time-defining phase. Future studies could explore including Lg detections within the selection criteria because at regional distances Lg is generally the seismic phase with the largest amplitude.

Success in the application of waveform correlation to any given dataset is almost completely dependent on the choice of waveform templates. Poor templates lead to poor detections, and in previous studies we pointed out the continued need for excellent template curation strategies and better template selection algorithms for global sparse networks. Arrivals that are associated to the wrong events are possible sources of error that can lead to confusing waveform correlation detection results; for example, misassociating arrivals may merge different events, or conversely, split arrivals across multiple events that should be associated into a single event. Templates from misassociated events lead to events being assigned wrong locations. Moreover, corroborating templates made from misassociated arrivals will never detect a legitimate repeating event that is consistent with other arrivals for the same template event. Hence, we propose that negative evidence for a repeating event (i.e., a missing arrival) is not a useful criterion for event detection until the template event has been used successfully and reliably for repeating event detection at various relative magnitudes so that patterns of corroborating detections are known.

We believe that the most successful template events for the approach described in this paper will be larger events with a sufficient number of arrivals in the template event metadata to make it worthwhile to look for corroborating templates. A repeating mining blast event with a much lower magnitude is unlikely to lead to a bulletin-worthy event because attenuation of the waveform as it propagates to more distant stations will make corroborating detections less likely. More study is needed to determine whether our recommended relative magnitude range of 0.4 – 1.1 is applicable to all mining regions or if the values vary by region and local IMS station density. This is especially true for events with lower magnitude than the template event.

A known limit of waveform correlation is the requirement for a useful historical archive to exist. For this reason, waveform correlation cannot be applied to a newly installed station with no recorded waveform archive. New stations must record a suitable number of events before they can be monitored using waveform correlation, and how long this will take depends on how often the repeating events occur. Another possible limitation is that the location and other characteristics of events from a mine may change over time, so templates that are too old cannot match current event data because the area of the mine they represent is no longer in use.

In conclusion, mining blasts are a frequent source of seismic events that must be dealt with on a global scale by monitoring organizations, and waveform correlation performs well as a repeating event detector for geographically colocated events with comparable source characteristics. Using template event metadata to corroborate repeating events is especially suitable to mining blasts and is likely to improve global monitoring pipelines by correctly associating groups of arrivals and reducing the possibility of misassociating mining blast signals, i.e. by addressing automatic processing deficiencies that take appreciable analyst time to correct..

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