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Global- and Local-Scale High-Resolution Event Catalogs for Algorithm Testing

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ABSTRACT

During the development of new seismic data processing methods, the verification of potential events and associated signals can present a nontrivial obstacle to the assessment of algorithm performance, especially as detection thresholds are lowered, resulting in the inclusion of significantly more anthropogenic signals. Here, we present two 14 day seismic event catalogs, a local-scale catalog developed using data from the University of Utah Seismograph Stations network, and a global-scale catalog developed using data from the International Monitoring System. Each catalog was built manually to comprehensively identify events from all sources that were locatable using phase arrival timing and directional information from seismic network stations, resulting in significant increases compared to existing catalogs. The new catalogs additionally contain challenging event sequences (prolific aftershocks and small events at the detection and location threshold) and novel event types and sources (e.g., infrasound only events and long-wall mining events) that make them useful for algorithm testing and development, as well as valuable for the unique tectonic and anthropogenic event sequences they contain.

Supplemental Content: Tables listing data quality issues for International Monitoring System (IMS) stations, unconstrained global event bulletin (UGEB) event clusters, UU station quality, unconstrained Utah event bulletin (UUEB) infrasound-only events, and UUEB event clusters.

INTRODUCTION

Within the seismic monitoring community, objectives can vary substantially from earthquake risk mitigation on nearby infrastructure to international nuclear explosion monitoring for treaty verification. Despite the substantial variation in mission, however, the main goals of seismic monitoring are the same: to detect and categorize seismic events. Decreasing instrumentation cost and increasing capacity in data storage and computational resources have vastly increased the scope of analysis that is possible in the seismic domain, yet several obstacles continue to limit what monitoring operations are able to accomplish. For example, researchers within the monitoring community continue to seek solutions to detect discrete events during aftershock sequences (Molchan and Dimitrieva, 1992; Harris and Dodge, 2011; Draelos *et al.*, 2015) and in high-noise environments (Joswig, 1990; Withers *et al.*, 1998; Shelly *et al.*, 2007; Li *et al.*, 2018). In addition to these persistent challenges, operations that monitor smaller event magnitudes often experience compounded difficulty because surface and other noise sources increasingly dominate potential event triggers (Given, 1990). Limiting the number of false positives that are returned from automated processing is one of the main limitations networks face in recovering very small events because for high-quality catalogs, each potential event must be reviewed and verified manually.

One solution to the burden of verification of data processing results from new algorithms is to evaluate and report performance using high-quality shared datasets. In other research fields, benchmark datasets are widely relied on to mark credible advancements in processing architectures and facilitate comparisons between new and standard methods (LeCun *et al.*, 2010; Krizhevsky *et al.*, 2014). The seismic monitoring community has by comparison remained slow to adopt standard datasets for performance and tuning in the past, partly because optimal solutions are typically unique for each seismic network and monitoring objective. However, we believe that although optimization may be unique, evaluation and reporting on shared datasets can strengthen performance reporting for new methods by removing test data differences.

In this article, we introduce two high-resolution seismic event catalogs for global and local regions. The catalogs presented here were developed by exhaustive manual inspection of continuous network data. Although a variety of catalog-enhancing strategies are in use in the seismic community, waveform correlation being among the most common, monitoring agencies typically rely on human analysts for authoritative decisions about each cataloged event because verification is a fundamental tenet of seismic monitoring. Typically, new methods rely on existing catalogs (and their inherent limitations) to benchmark performance increases for new methods. We provide such a catalog for two datasets with the same basic

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Table 1
Local-Scale (UUEB) and Global-Scale (UGEB) Event Catalog Times, Durations, and Catalog Event Count Increase Compared with Events in Existing Catalogs

Catalog Name	Start Time	Duration	Region	Catalog Events	New Events
UGEB	15 May 2010	14 days	Global	LEB: 1494	9884
UUEB	1 January 2011	14 days	Utah	UUSS: 147	7742

New events are typically the result of less stringent criteria for detection or catalog inclusion (e.g., quarry blasts, infrasound events, and small mining induced event [MIE]). For example, the UUSS operations during this same time period processed at least 100 additional quarry blast events that were not included in the final 147 event earthquake catalog because they are not pertinent to the earthquake monitoring mission of the UUSS. Similarly, new UGEB events are typically smaller, near-station events that were not included because of the burden analysts would face in real-time monitoring should algorithms be tuned to the sensitivity levels achieved by manual review. LEB, late event bulletin; UGEB, unconstrained global event bulletin; UUEB, unconstrained Utah event bulletin; UUSS, University of Utah seismograph stations.

guarantees of previously published event catalogs, that is, each and every event has been reviewed, located, and verified by a human analyst. However, because our catalogs are not limited by the same constraints as monitoring organizations (e.g., how much time analysts can spend manually building events missed by automated processing or which sources to include based on monitoring objectives), the differences between previously published catalogs and our unconstrained event catalogs are significant. Outlining the differences between existing catalogs and the unconstrained catalogs we provide constitutes a major part of the following discussion. We make our catalogs and the ancillary pick and association tables openly available in the hopes that they will facilitate objective comparisons by the seismic monitoring research community of new methods and optimization techniques that lead to advances in the capacity to detect, locate, and categorize seismic sources. Although the main use envisioned for the catalogs provided here is for algorithms tasked with event building (detection or phase association), a range of other uses are possible depending on user interests. To this end, we also highlight source-type variety and geographic clusters that may be of interest beyond algorithm testing.

UNCONSTRAINED GLOBAL EVENT BULLETIN (UGEB)

International Monitoring System Networks and IDC Event Bulletins

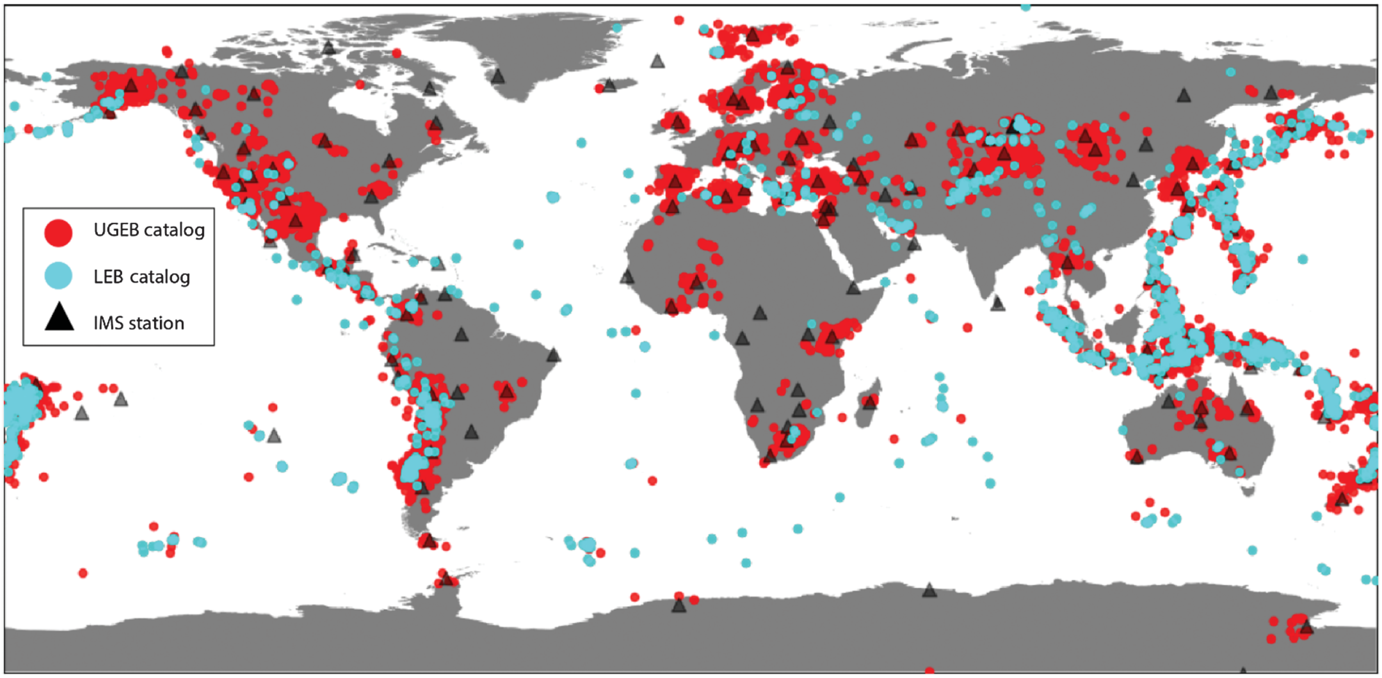
Our global catalog was built using data from the International Monitoring System's (IMS) primary and auxiliary seismic networks for a 14 day period in 15–28 May 2010. The IMS is a global monitoring network operated to verify international compliance with the Comprehensive Nuclear Test-Ban Treaty (CTBT). In support of this directive, 50 globally distributed seismic stations (including 30 arrays) make up the primary network and provide continuous seismic data for subsurface event monitoring. In addition, the IMS uses data from 120 additional stations (including seven arrays) from an auxiliary network to augment data from the primary network after an event has been detected (Bondár *et al.*, 1999; Bahavar and North, 2002). The International Data Centre (IDC) acts as the data repository for IMS data and performs automatic processing and manual analysis to produce event catalogs. IMS seismic data collection and IDC processing together provide verification of international compliance to the CTBT for underground explosions.

More than half (60%) of the IMS primary network stations are seismic arrays, with considerable variation in aperture and geometry for each array (1–60 km: Kværna and Ringdal, 2013). IMS data are automatically processed to produce an event bulletin, the standard event list, which is then reviewed and corrected by analysts to produce the late event bulletin (LEB). The LEB is then automatically screened to remove events that do not meet a minimum criterion (*P*-type phases with accompanying *S*-type phases on at least two seismic arrays or a *P*- and *S*-type phase on one station with at least two other *P*-type phases observed on other stations) to produce the reviewed event bulletin (REB), which is the catalog officially released to states parties. LEB is the most complete catalog available from the IDC, and it contains 1494 events for the 2 week period of 15–28 May 2010, with a daily average of 106 events per day (Table 1; Fig. 1, cyan circles). LEB events are predominantly tectonic earthquakes but also include nontectonic events for limited cases in which large mining operations produce observable signals on more than one IMS station.

High-Resolution Catalog Production

Our unconstrained global event bulletin (UGEB) was built by starting with the LEB and supplementing it with events built by manual review of continuous data from IMS primary and auxiliary network stations by an analyst (Ronald Brogan) with >30 yr of seismic analysis experience and familiarity with IMS network stations, noise characteristics, and known sources.

The manual review process involved scrolling through waveforms from stations in geographic proximity to one another using the analyst review station (ARS) and Geotool (National Data Center [NDC]-in-a-box; Bache *et al.*, 1990) seismic analysis software packages. After a suitable number of signals were identified to establish a credible event, a preliminary location was computed using the Location Slowness Azimuth Time (LocSAT) program (Bratt and Bache, 1988) and the ak135



▲ **Figure 1.** International Monitoring System (IMS) primary stations and cataloged events (late event bulletin [LEB] and unconstrained global event bulletin [UGEB]) from 15–28 May 2010. As in most global seismic catalogs, LEB events (cyan circles) follow plate boundaries. UGEB events (red circles) generally follow LEB event locations but also occur in seismicity clusters where seismically active areas coincide with IMS station locations (black triangles).

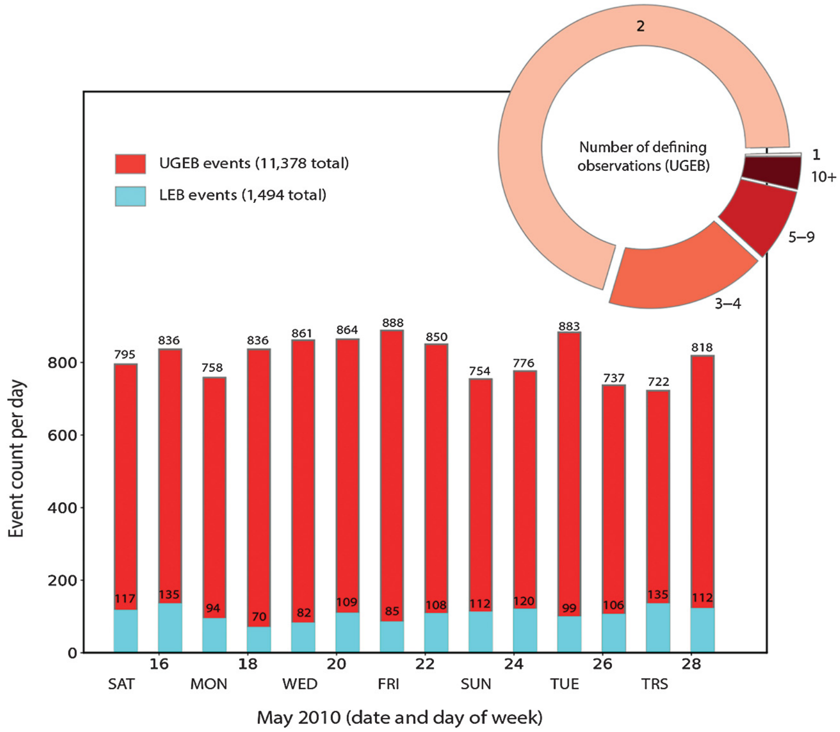
velocity model (Kennett *et al.*, 1995). Subsequently, any identifiable phase arrivals on additional stations were picked and associated. Multiple station-specific filter bands were applied during review to enhance signal visibility (see Ⓔ Table S1, available in the supplemental content to this article, for station-specific data quality issues). Analysis relied on a standard suite of processing methods such as beamforming, azimuth and slowness from frequency–wavenumber (f-k) analysis, and three-component polarization analysis for nonarray stations. On average, the analysis time to real-time ratio was 3/1, that is, 8 hr of data took 24 hr to analyze. After review, the final comprehensive UGEB catalog contained 11,378 events, increasing the daily event average to 813 events per day (a 662% increase compared to LEB events; Fig. 2). Similar to the LEB catalog, the UGEB contains events of both tectonic and anthropogenic origin.

We emphasize that the primary objective for the catalogs provided here is to establish that an event occurred and identify and associate visible phases on all available stations; therefore, minimal effort was put into any further event parameter estimation. The locations we provide are not meant to offer high-resolution solutions for location techniques and have a range of accuracies depending on a number of factors, including the characteristics of the constraining stations and observations. Associated phases that are used for event location always have time as a defining attribute but may also include back azimuth or slowness when the number of associated phases is limited. Location error estimates including full error covariance for each event are included in the origerr table available in the supplemental content to this article. Depths for events from single-station observations were always constrained to the surface. Similarly, we do not compute magnitudes for the new events in the UGEB but rely on the number of location-defining signal detections as a proxy for magnitude (Fig. 2).

UGEB Event Characteristics and Discussion

The identification of sources in the LEB over long time scales is known to be biased by station location (Kværna and Ringdal, 2013). Similarly, exaggerated seismicity near IMS station locations over the relatively short-duration UGEB is apparent in Figure 1. Apparent seismicity increases near IMS stations are the result of relaxed detection criteria compared with LEB event criteria, which require that signal amplitudes persist across interstation distances, a requirement typically not achieved by small sources because of geometric spreading and attenuation.

Beyond algorithm testing and development, the UGEB catalog contains several compelling tectonic event sequences that may be useful. A few examples include the 222-event sequence centered near Baicheng in central Asia (ID 7 in Ⓔ Table S2), which may provide waveform templates to link ongoing seismicity that predates the UGEB by five or more years. A second sequence includes a set of events under the Warramunga array in Australia (ID 8 in Ⓔ Table S2). The Warramunga events are likely ongoing aftershocks of the 1988 M_w 6.6 Tennant Creek earthquake, the largest earthquake in Australia's recording history (Bowman, 1992). Additional sequences and seismicity clusters of potential interest in the UGEB catalog can be found in Ⓔ Table S2.



▲ **Figure 2.** Bar chart of events per day for the UGEB (red) and the LEB (cyan). Event rates for both the UGEB and the LEB are consistent throughout the duration of the catalog, potentially indicating that a majority of events within each catalog are tectonic earthquakes. Inset, donut chart shows the number of location-defining observations per event as a proxy for event magnitude for UGEB events and shows that a majority of events were small with just two defining observations. Defining observations used for event locations include associated phases that have one or more defining attributes (e.g., arrival time, back azimuth, or slowness).

UNCONSTRAINED UTAH EVENT BULLETIN

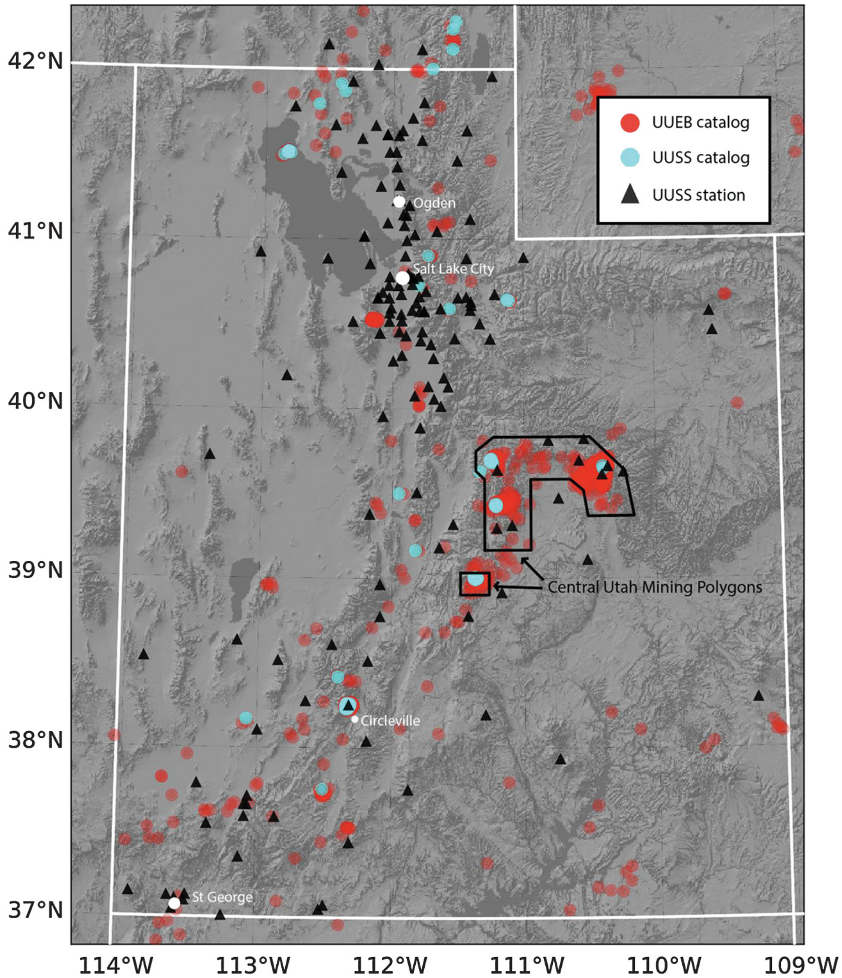
University of Utah Seismograph Stations Network and Event Catalog

Our second catalog, the unconstrained Utah event bulletin (UUEB), was built using data from the regional monitoring network in the state of Utah. The University of Utah seismograph stations (UUSS) network has been monitoring regional and local seismicity in and around Utah for more than 50 yr (Arabasz, 1979) concurrently with a network of broadband and short-period seismometers, accelerometers, and other geophysical sensors (Koper and Pankow, 2015). The fundamental mission of the UUSS in Utah is to mitigate and reduce risk from local earthquakes. Therefore, UUSS station density is highest where earthquakes pose a higher risk for local inhabitants, generally following the Intermountain Seismic Belt along the transition between the dominant tectonic regimes in Utah, the Basin and Range province on the west, and the Colorado Plateau and middle Rocky Mountains provinces on the east (Smith and Sbar, 1974; Arabasz and Smith, 1981). UUSS analysts produce a bulletin for events in Utah and bordering regions that are available to the public (production catalogs: see Data and Resources). Waveform data from UUSS stations and nearby networks are made publicly available in near-real-time through the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC).

Our Utah catalog covers a 14 day period between 1 and 14 January 2011. This interval was selected to include a mainshock (M_w 4.5)–aftershock sequence near Circleville, Utah, that began on 3 January. The catalog produced by UUSS analysts during the 2 week period included 147 tectonic and mining-related earthquakes (within the catalog region outlined in Fig. 3). Minimum trigger counts (detections on a specific station) of between four and five were required for event detection. An acceptable location computed from at least five *P*- and/or *S*-wave arrival times was required for inclusion in the UUSS catalog. In the central Utah mining areas (see polygons in Fig. 3) where many mining-related events occur every day, detection sensitivity is lowered to reduce analyst workload for events not pertinent to the UUSS's primary earthquake monitoring objectives.

To produce the UUEB, we used various methods to augment the existing UUSS catalog before manual review. An additional 362 events were identified using the waveform correlation and event detection system (Arrowsmith *et al.*, 2016). The UUSS (via Kristine L. Pankow) also provided 37 previously uncataloged events related to the Circleville sequence that were identified using subspace detection methods (Gibbons and Ringdal, 2006). Because the UUSS catalog does not generally include mine blasts yet (blasting occurs regularly in Utah), UUSS analysts provided 100 quarry blasts for reference that were detected and classified as part of routine UUSS data processing but not included in the UUSS earthquake catalog. Finally, we identified 6439 events in the central Utah underground mining polygons using templates that were established on the first day of manual processing and the SeisCorr waveform correlation software (Slinkard *et al.*, 2016; Fig. 3; near latitude 39.62° N, longitude 110.40° W). Of the SeisCorr events, 5995 met a three-station minimum criterion and were retained. All events produced by these various methods were verified by our analyst.

The baseline catalog augmentation described earlier was followed by comprehensive manual review of continuous waveform data. To conduct the manual review of this 2 week dataset, the waveform and metadata for the UU (short period, broadband, and accelerometer) and YJ (infrasound) networks were acquired from the IRIS-DMC and loaded into a CSS3.0 relational database schema. We then performed waveform review using the ARS software and methods consistent with those described for the UGEB catalog (see Ⓔ Table S3 for station-specific data quality issues). Ak135 travel-time tables (Kennett *et al.*, 1995) were used for locations for body-wave phases, and the IASP91 travel-time table was used for *Rg*



▲ **Figure 3.** University of Utah Seismograph Stations (UUSS) (accelerometers, short-period, and broadband sensors) and catalog events (UUSS and unconstrained Utah event bulletin [UUEB]) between 1 and 14 January 2011. The defining boundary for the UUEB event catalog (red circles) follows the UUSS (cyan circles) authoritative review boundary for Utah (36.75°–42.50° N, 108.75°–114.25° W). UUSS stations (Incorporated Research Institutions for Seismology [IRIS] network code UU) are represented by black triangles. A total of 86% of the UUEB events occur within the mining polygons in central Utah (outlined in black).

phases (Kennett and Engdahl, 1991). We highlight that there were six temporary infrasound stations operating in Utah in 2011 and that these data are also available from the IRIS-DMC. We include eight infrasound events (identified without seismic data) but do not expect our catalog to be exhaustive for these sources because this was not a priority for our analysis (see Ⓔ Table S4). The IDC's I-phase travel-time table was used for infrasound phases.

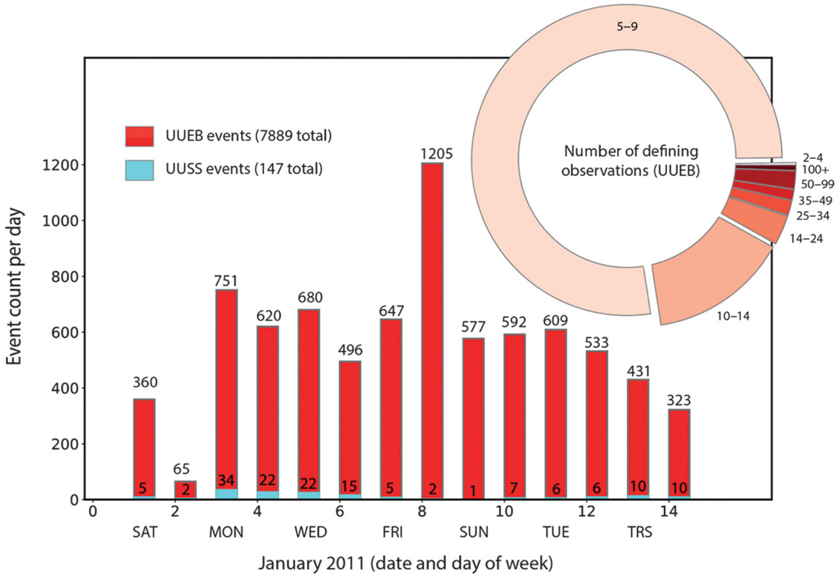
As with the UGEB, the focus of the UUEB was on detecting seismic events and identifying all associated arrivals, with limited analysis of source characteristics. Figure 4 shows that the UUEB contains events mostly including between five and nine observations. Figure 4 also shows that the daily event counts vary between 65 and 1205 events over the catalog duration. The UUEB catalog includes event origin times and locations, as well as location error estimates (average length of the semimajor axis is 5.2 ± 9.0 km), associated phase picks, and amplitude measurements. The vast majority (95%; 7889/8270) of UUEB events are located near or within Utah (Fig. 3, boundary: 36.75°–42.5° N latitude, 108.75°–114.25°W longitude). The remaining events are distributed regionally and globally. These non-Utah event solutions are included in the local Utah catalog to help subsequent user's link observations on UU data to nonlocal sources. No magnitudes are provided for the UUEB events.

UUEB Event Characteristics and Discussion

The primary difference between the UUEB and UUSS catalogs in January 2011 is that the former includes many more events from the coal mining districts in central Utah. Within the UUEB catalog, 86% of the total events are considered potentially mining induced events (MIEs) based on location. Although the UUSS catalog includes events within the underground mining region (37 events), they represent a smaller fraction (25%) of overall seismicity in the 147 event UUSS catalog (event counts are from the mining polygons in Fig. 3). The inclusion of MIE in the UUEB catalog underscores the nonlinear increase in events that nonbiased detection methods may experience when detection thresholds are lowered to include surface and near-surface anthropogenic sources.

The other region with abundant representation in the UUEB catalog is the region near the M_L 4.6 (M_w 4.5) earthquake near Circleville, Utah (Fig. 3). Signal detection algorithm performance typically decreases during aftershock sequences because detectors experience difficulty when amplitude excursions related to discrete events overlap in time. UUSS routine processing identified 85 events in the Circleville region (38.2° N–38.3° N, 112.2° W–112.4° W), and an additional 37 events were identified by Kristine L. Pankow of the UUSS using subspace detection based on templates from routine processing. The UUEB catalog for the same region contains 852 events, a 598% increase from subspace detection and a 902% increase from routine catalog processing. The increase in known events within the Circleville source region makes the UUEB catalog valuable for testing algorithm capability under aftershock conditions (i.e., a high quantity of events with limited to no temporal separation), in addition to being useful for understanding the spatiotemporal evolution of aftershocks in the Circleville region.

Although manual review methods for the Circleville sequence considerably outperformed waveform correlation methods, we do not expect (nor do we observe) this to be consistent for all known sources. As a counter example, waveform



▲ **Figure 4.** Bar chart of events per day for the UUEB (red) and the UUSS catalog (cyan). Although there is significantly lower activity on weekend days at the beginning of the catalog (the New Year holiday weekend), subsequent weekend days have some of the highest day rates in the UUEB catalog (e.g., 8 January, Saturday). Inset, donut chart shows the number of defining observations as a proxy for magnitude and demonstrates that a majority of events (typically corresponding to events inside the mining induced event [MIE] polygon) are small and detected on nine or fewer (typically five) nearby stations.

correlation methods outperformed our analyst at finding (unverified) events (7% of the MIE events identified through waveform correlation were not included in the manually reviewed catalog). We highlight this fact to reiterate that the catalogs presented here will likely be most valuable for users who are developing algorithms aimed at improving the quality of manually REBs. The catalogs presented here will be less useful for the verification of algorithms intended to find events or signals that an analyst cannot verify. Additional sequences and seismicity clusters of potential interest in the UUEB catalog can be found in Ⓔ Table S5.

CONCLUSION

Algorithms are commonly developed and tested against network catalogs whose completeness and quality are inherently limited by the nature of continuous real-time operations, most notably the amount of time that analysts are given to review content before it is made public. New algorithms typically seek to lower detection thresholds without exponentially increasing the number of false events because for many monitoring agencies, such false events must be manually screened by analysts. However, because most event catalogs that are used to evaluate algorithm performance are incomplete, the amount of work needed for manual discrimination between false positives and legitimate new detections can represent a formidable impediment to algorithm tuning and testing. The main purpose of the UGEB and UUEB catalogs presented here is to provide high-quality event bulletins against which seismic data processing algorithms may benchmark performance metrics. Unlike most catalogs, our analyst was given essentially unlimited time to search for events; hence, completeness was ultimately limited only by the decision of whether or not a verifiable event had occurred.

Each catalog was intended to contain all verifiable seismic events, regardless of their source. Although source-specific data processing methods such as waveform correlation may be able to recover more events than our catalogs contain, we suggest that the catalogs provided here are complete for locatable and human verifiable events present in the IMS and Utah data over the catalog time periods. For some monitoring cases, anthropogenic sources are considered noise and hence are deliberately ignored, whereas the main purpose for other monitoring operations is to identify anthropogenically generated events. Our catalogs include both tectonic and anthropogenic sources, making them useful for the development of strategies for either monitoring objective.

Embedded in the issue of event detection for network data is the problem of associating picks from individual stations within the network to discrete seismic sources. Each of our events includes a comprehensive set of phase picks for all observable phases on all network stations where phase picks were available, making the catalogs useful for multiple aspects of the detection problem.

DATA AND RESOURCES

International Monitoring System (IMS) primary and auxiliary network waveform data as well as International Data Centre (IDC) event catalogs are available by request through a state party's national data center. University of Utah seismograph stations (UUSS) catalogs are publicly available at http://quake.utah.edu/regional-info/earthquake-catalogs (last accessed August 2018). Continuous waveform data from the UUSS (UU and YJ networks) are available from the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC) though public web-based requests. The unconstrained Utah event bulletin (UUEB) and unconstrained global event bulletin (UGEB) catalogs are available as relational database files in the Ⓔ supplemental content to this article. Catalog production used processing software developed at Sandia National Laboratories (Probabilistic Event Detection, Association and Location [PEDAL], see Draelos *et al.*, 2015) and IMS software (analyst review station [ARS] and Geotool [National Data Center {NDC}-in-a-box]) for waveform review (Bache *et al.*, 1990).

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