Earthquake Database for Utah Geological Survey Map 277: Utah Earthquakes (1850–2016) and Quaternary Faults

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INTRODUCTION

The earthquake database described here consists of catalogs (chronological lists of origin time, location, and size), along with explanatory information, for the earthquake epicenters shown on Utah Geological Survey (UGS) Map 277, *Utah Earthquakes (1850–2016) and Quaternary Faults* (hereafter, "the map"; Bowman and Arabasz [2017], https://ugspub.nr.utah.gov/publications/maps/m-277.pdf). The seismic events depicted on the map include both tectonic earthquakes and mining-induced seismicity (MIS) associated with underground coal mining in east-central Utah.

The tectonic earthquake data are primarily from a Uniform Moment Magnitude Earthquake Catalog developed for Utah and its surrounding region by Arabasz and others (2016) for the time period 1850 through September 2012. For the map, we extended the catalog through December 2016 and expanded it to include earthquakes smaller than magnitude 2.9. MIS was excluded from the compilation of Arabasz and others (2016) but has been added to the map to show its significance in east-central Utah.

EARTHQUAKE DATABASE

Separation of Database into Two Parts

Data for the seismic events plotted on the map are listed in two separate catalogs, each in the form of a Microsoft Excel workbook and an ArcGIS feature class within a file geodatabase. The catalog files are available at https://ugspub.nr.utah.gov/publications/open_file_reports/ofr-667/ofr-667.zip. The primary catalog used for the map, termed the **Earthquake Catalog (EQ Catalog)**, comprises tectonic earthquakes located within the "Utah Region" (lat. 36.75° to 42.50° N, long. 108.75° to 114.25° W) from 1850 through 2016. This region is the standard region used by the University of Utah Seismograph Stations (UUSS) for the compilation and reporting of earthquakes within and surrounding Utah. Note that the map covers most, but not all, of the Utah Region.

The map delineates two areas in east-central Utah that are characterized by predominantly (more than 90%) MIS. All seismic events (including both MIS and tectonic earthquakes) located in these two areas are listed in a separate catalog, termed the **Coal-Mining-Region Catalog (CMR Catalog)**, which extends from 1928 (the year of the first located event) through 2016. The EQ and CMR catalogs are mutually exclusive. The EQ Catalog does not include tectonic earthquakes located within the two delineated areas of predominantly MIS.

Earthquake (EQ) Catalog

Filename:	Utah_EQcat_1850-2016
Catalog Region:	Utah Region: 36.7500° to 42.5000° N, 108.7500° to 114.2500° W
Catalog Period:	1850–December 31, 2016
Number of Events:	31,909 ($\mathbf{M} \leq 6.63$, no declustering)
UUSS Catalog Version:	January 31, 2017

Coal-Mining-Region (CMR) Catalog

Filename:	Utah_CMRcat_1928-2016
Catalog Region:	Polygonal Wasatch Plateau (WP)-Book Cliffs (BC) mining region, plus rectangular Southern Utah Fuel Company (SUFCO) mining area (table 1)
Catalog Period:	1928–December 31, 2016
Number of Events:	24,493 ($\mathbf{M} \leq 4.16$, no declustering)
UUSS Catalog Version:	January 31, 2017

Table 1. *Map coordinates of vertices defining the bounds of the WP-BC mining region and the SUFCO mining area.*

WP-BC polygon	Lat. (°N)	Long. (°W)	SUFCO rectangle	Lat. (°N)	Long. (°W)
	39.1667	111.3000		38.9033	111.4833
	39.5833	111.3000		39.0333	111.4833
	39.6333	111.3667		39.0333	111.2667
	39.7500	111.3667		38.9033	111.2667
	39.8333	111.2333		38.9033	111.4833
	39.8333	110.5000			
	39.6333	110.2333			
	39.3667	110.1667			
	39.3667	110.5167			
	39.5167	110.5500			
	39.5833	110.6500			
	39.5833	110.9500			
	39.1667	110.9500			
	39.1667	111.3000			

Moment Magnitude

The use of moment magnitude to depict the size of seismic events on the map is significant. Moment magnitude, **M** (sometimes denoted as M_W), is a modern seismological measure of the physical properties of the earthquake source. The definition of **M** follows Hanks and Kanamori (1979): $\mathbf{M} = 2/3 \log M_0 - 10.7$, where M_0 is the earthquake's scalar seismic moment in dyne-cm, generally determined from inversion of either long-period waveforms or surface-wave spectra. **M** is the best indicator of an earthquake's true relative size and has become the preferred size measure for seismic hazard and earthquake engineering applications. Other size measures, such as Richter local magnitude, M_L, do not fully serve these purposes. For all earthquakes of $\mathbf{M} \geq 2.9$ in the EQ and CMR catalogs, the assigned value of **M** is either from direct measurement or from empirical conversion relationships, following the methodology of Arabasz and others (2016), who term the resulting value of **M** a "best-estimate" moment magnitude (BEM).

For earthquakes of $\mathbf{M} < 2.9$, the assigned value of magnitude in the catalogs is not uniformly a BEM value. The decision to plot events smaller than **M** 2.9 on the map required reliance on the UUSS earthquake catalog, in which magnitudes in this size range are listed as either M_L or coda magnitude, M_C, an empirical estimate of M_L (see Pechmann and others, 2006). However, magnitudes below about M_L or M_C 2.5 cannot be reliably converted to **M** using the methodology of Arabasz and others (2016). Therefore, we have simply retained the UUSS magnitudes of these smaller events and listed them in the EQ and CMR catalogs as M_L UU (if available) or M_C UU, where UU ascribes the magnitude to the UUSS. The estimated moment magnitudes of all such events are smaller than **M** 2.9 and their epicenters are plotted in this size class on the map.

Explanation of Fields in the Earthquake (EQ) and Coal-Mining-Region (CMR) Catalogs

For each event line in the EQ and CMR catalogs, table 2 gives an explanation of the information provided in successive columns (fields). The first 13 fields (Mag through Mag Type) follow a standard structure commonly used by the USGS and also used in the earthquake catalog of Arabasz and others (2016). Supplementary information is provided in the subsequent 15 fields for instrumentally located earthquakes—primarily for events on and after July 1, 1962. For all earthquake locations extracted from what we term the UUSS Instrumental Earthquake Catalog (see appendix for an explanation and overview), this systematically includes quality grading of epicentral and focal-depth precision and parametric data for the hypocentral solution—the coordinates in three-dimensional space of the earthquake's origin point, variously termed the focus or hypocenter. (An epicenter is the vertical projection of an earthquake's hypocenter on the earth's surface.) In a following section on *Data Quality*, we elaborate on our assessment of the quality of epicentral locations and focal-depth determinations. Table 3 explains the source codes used for the magnitude type $\mathbf{M}^{\sim}$|[source], and table 4 provides miscellaneous notes for three event lines in the EQ Catalog.

Table 2. *Explanation of data fields in the EQ and CMR catalogs.*

Data Field	**Explanation**
Mag	Magnitude (type specified in the Mag Type field). "-9.99" indicates a very small earthquake for which a magnitude could not be determined.
Long, Lat	Longitude and latitude (in degrees) of the earthquake's location using the WGS84 geographic coordinate system. Epicenters with a UUS source (i.e., instrumental locations by the University of Utah Seismograph Stations beginning July 1, 1962) have coordinates specified to four decimal places; all others, to three decimal places.
Depth	Earthquake focal depth, in kilometers.
Year, Mo, Day, Hr, Min, Sec	Earthquake origin date and time expressed in Coordinated Universal Time (UTC), or equivalently in Greenwich Mean Time (GMT) prior to 1960. In converting local standard time to UTC (or GMT), we accounted for advances in standard time that took place prior to the institution of Daylight Saving Time in 1967. These advances occurred during World War I (between March 31 and October 27, 1918, and between March 30 and October 26, 1919) and during World War II (between February 9, 1942, and September 30, 1945). These adjustments explain time differences of 1 hour with some origin times in USGS source catalogs.
sigM	Standard deviation of normally distributed errors for the best-estimate moment magnitude, when listed.
Round	Rounding error for the best-estimate moment magnitude, when listed.
Mag Type	All magnitudes, except M_L UU and M_C UU, are best-estimate moment magnitudes for which the following descriptors indicate the basis (see Arabasz and others, 2016, for full details): **M**obs = observed moment magnitude from a direct instrumental measurement of seismic moment. $\mathbf{M}^{\sim}$|[source] = a magnitude type assumed to be equivalent to **M** (source indicates the origin of the reported magnitude, explained in table 3). **M**pred|I_0 = predicted moment magnitude, $\mathbf{M}_{\text{pred}}$, from converting maximum Modified Mercalli Intensity, I_0, to **M**. **M**pred|Xi = $\mathbf{M}_{\text{pred}}$ from converting a single instrumental size measure, X_i, to **M**. **M**pred|Xvar = $\mathbf{M}_{\text{pred}}$ from inverse-variance weighting of $\mathbf{M}_{\text{pred}}$ values from two or more instrumental size measures. **M**pred|Xnon = $\mathbf{M}_{\text{pred}}$ from inverse-variance weighting of $\mathbf{M}_{\text{pred}}$ values from two or more non-instrumental size measures. **M**pred|Xmix = $\mathbf{M}_{\text{pred}}$ from inverse-variance weighting of $\mathbf{M}_{\text{pred}}$ values from a mix of instrumental and non-instrumental size measures. M_L UU = Richter local magnitude determined by UUSS. M_C UU = coda magnitude determined by UUSS.
Epicenter Quality	Quality code for instrumental epicentral locations (see *Data Quality* for basis): A = excellent, B = good, C = fair, D = poor, U = undetermined
Depth Quality	Quality or characterization code for instrumental focal depths: 1 = well-constrained focal depth from UUSS Instrumental Earthquake Catalog (see *Data Quality* for basis). 2 = for Mag Type **M**obs, focal depth is from a moment-tensor solution or (prior to 1989) another type of special waveform analysis; generally of comparable reliability to UUSS well-constrained focal depths. An available Depth Quality of 1 supersedes 2. 3 = focal depth not from UUSS Instrumental Earthquake Catalog, reliability uncertain but probably not well-constrained. 4 = focal depth from UUSS Instrumental Earthquake Catalog, not well-constrained (see *Data Quality* for basis). *Note: For event lines before 1981 from the UUSS Instrumental Earthquake Catalog, focal depths of 7.0 km are nearly all "restricted," i.e., the hypocentral solution was held fixed at the trial focal depth of 7.0 km due to poor depth resolution.*
Depth Change	An entry in this column signifies that the instrumentally determined focal depth has been adjusted. UUSS focal depths for Utah Region earthquakes computed prior to October 1, 2012, are relative to a datum 1.5 km above sea level; since that date, they have been computed relative to sea level. For uniformity, a value of 1.5 km has been added to all UUSS focal depths on and after October 1, 2012, except where the focal depth comes from a moment-tensor solution (Depth Quality = 2).
EQ Flag	Event lines in the CMR Catalog with an EQ Flag indicate that the event has been determined to be a tectonic earthquake: EQ-1 = tectonic earthquake documented by Arabasz and others (2016). EQ-2 = event identified by Stein (2016) as a tectonic earthquake, based on multiple criteria. EQ-2* = event identified by Stein (2016) as a tectonic earthquake, based on multiple criteria, and possibly related to fluid injection.

Table 2. *Continued.*

Source of Epicenter	Source of listed epicentral coordinates: CGS = U.S. Coast and Geodetic Survey annual publication, *United States Earthquakes*. DOS = Doser (1989). PDE = USGS Preliminary Determination or Epicenters. PEC = Pechmann and others (1992). SRA = USGS "SRA" catalog (after Stover and others, 1986; see Arabasz and others, 2016, p. E-8). STO = Stover and Coffman (1993). UUH = UUSS historical earthquake catalog of Arabasz and McKee (1979). UUS = UUSS Instrumental Earthquake Catalog beginning July 1, 1962 (see appendix), v. January 31, 2017. UUX[1] = UUSS *Utah Earthquake Catalog, July 1962–June 1978*, in Arabasz and others (1979, p. 145–241). WES = Westaway and Smith (1989). WMM = USGS "Western Moment Magnitude" catalog (v. June 6, 2011; see Arabasz and others, 2016, p. E-8). ——— [1] The code UUX identifies 14 earthquakes during 1962 to 1976 that have locations based on four phases (NPH = 4). These events appeared in the published listing of Arabasz and others (1979, p. 145–241) but were later removed from the UUSS Instrumental Earthquake Catalog because they did not meet the requirement that NPH be 5 or greater. Because these events are of significant size ($2.83 \leq \mathbf{M} \leq 3.46$), Arabasz and others (2016) included them in their catalog, and we likewise include them in the present EQ Catalog.
Note: The following additional fields provide supplementary information for event lines listing UUS as the indicated Source of Epicenter.	
MAG UU	Preferred magnitude listed in the UUSS earthquake source catalog.
MAG UU Flag	Indicator of the magnitude type for the listed MAG UU (if none, type = Mc UU): W = Richter local magnitude, M_L, based on original or synthetic Wood-Anderson seismograms. M = Moment magnitude, **M**.
ML UU	Value of Richter local magnitude determined by UUSS.
Mc UU	Value of coda magnitude determined by UUSS.
NPH	Number of *P*- and *S*-wave arrival times (phases) used in the earthquake location.
GAP	Maximum angular gap in degrees between azimuthally adjacent stations.
DMIN	Epicentral distance in kilometers to the closest recording station.
RMS	Weighted root-mean-square of the travel-time residuals in seconds.
ERH	Standard horizontal location error in kilometers.
ERZ	Standard vertical location error in kilometers.

Table 3. *Explanation of source codes for Mag Type* **M**~|*[source].*

Source Code	**Description**
MLBRK	M_L attributed to the University of California, Berkeley.
MLERD	M_L attributed to the Department of Energy in Idaho Falls, Idaho.
MLPAS	M_L attributed to the California Institute of Technology, Pasadena.
MLREN	M_L attributed to the Nevada Seismological Lab in Reno, Nevada.
MsGR	Gutenberg-Richter surface-wave magnitude.
MxJON, MxSJG	Wiechert magnitude at Reno, Nevada (Jones, 1975).
UknPAS	Unknown magnitude type attributed to the California Institute of Technology, Pasadena.
UknUU	Unknown magnitude type attributed to the University of Utah.

Table 4. *Miscellaneous notes regarding individual event lines in the EQ Catalog.*

Event (year/mo/day hr:min)	**Note**
1975/03/28 02:31	Focal depth is from Bache and others (1980).
1988/08/14 20:03	Epicenter, focal depth, and hypocentral solution parameters are all from Pechmann and others (1992).
1989/01/30 04:06	Epicenter and hypocentral solution parameters for a focal depth of 24.7 km are from Pechmann and others (1992). The assigned focal depth of 24.0 km is from Dziewonski and others (1990).

Data Quality

The information here is to guide evaluations of the map locations (epicenters) and focal depths of earthquakes in the EQ and CMR catalogs. Users are cautioned to be mindful of limitations of the data, particularly in attempting to spatially associate events in the database with geologic structures or other features.

Historical Events Prior to July 1, 1962

The EQ Catalog contains 395 earthquakes predating July 1, 1962. Their listed epicenters have undetermined location errors with likely uncertainties of the order of tens of kilometers. Focal-depth information is sparse and poorly constrained where reported. The vast majority (357) of these 395 events in the EQ Catalog have non-instrumental locations based on felt effects. The source for each non-instrumental location is documented in Arabasz and others (2016). Most come from the historical earthquake catalog of Arabasz and McKee (1979), who assigned coordinates corresponding to the location of a town or city where felt effects were strongest. Only 38 of the 395 events in the pre-July 1962 part of the EQ Catalog have instrumentally determined earthquake locations, indicated by an entry in the field for Source of Epicenter. For 36 of these 38 events (with the source STO or SRA), the earthquake locations are hypocenters determined by the U.S. Coast and Geodetic Survey during the period 1934–1962 and are based on widely spaced seismographs in the western United States. Location uncertainty for these epicenters is estimated to be, at best, ± 10–20 km after about 1950 and sometimes ± 0.5 degree of latitude and longitude during earlier times.

The CMR Catalog contains four earthquakes predating July 1, 1962. The locations for two of these events are non-instrumental, taken from the UUSS historical earthquake compilation of Arabasz and McKee (1979). The locations for the other two are from the U.S. Coast and Geodetic Survey. Location and focal-depth uncertainties for these four earthquakes are large, as described in the preceding paragraph.

Instrumentally Located Events, July 1962–December 2016

The following discussion applies to instrumentally located events in both the EQ and CMR catalogs extracted from the UUSS Instrumental Earthquake Catalog. The location errors of the hypocenter of a seismic source include ERH, the standard horizontal error (in kilometers), and ERZ, the standard vertical error (in kilometers). ERH and ERZ are simplified errors from a three-dimensional ellipsoid (Klein, 1978). We use parameters from each hypocentral solution to assess separate quality ratings for the computed epicenter and for the computed focal depth. A quality rating of A (excellent), B (good), C (fair), or D (poor) was assigned to each epicenter with a UUS source by using the average rating from the two schemes outlined in table 5. The lower rating was used when the two ratings were one level apart, and epicenters with a D rating in either scheme were assigned a D. The estimated 95% confidence interval on horizontal location, using ± 2.2 ERH as an approximation, is ≤ ± 2.2 km for quality A epicenters, ≤ ± 5.5 km for quality B epicenters, ≤ ± 11.0 km for quality C epicenters, and > ± 11.0 km for quality D.

Table 5. *Basis for assessing and rating Epicenter Quality.*

Rating	**Station Geometry Scheme**		**Statistical-Measure Scheme**	
	NPH*	**GAP***	**RMS* (sec)**	**ERH* (km)**
A	≥ 6 AND	≤ 90°	< 0.15 AND	≤ 1.0
B	≥ 6 AND	≤ 135°	< 0.30 AND	≤ 2.5
C	≥ 6 AND	≤ 180°	< 0.50 AND	≤ 5.0
D	Worse than above	Worse than above	Worse than above	Worse than above

* Defined in table 2.

For each earthquake having an epicenter with a UUS source, we evaluated the quality of the computed focal depth in the following way. For a "well-constrained" focal depth (Depth Quality = 1), we required DMIN, the map distance (in kilometers) from the epicenter to the nearest recording station, to be less than or equal to the computed focal depth, H, or 5.0 km and ERZ ≤ 2.0 km (Arabasz and others, 1992). A 95% confidence interval on focal depth is estimated by ± 2.0 ERZ. All UUS-sourced focal depths that did not meet the rigorous requirement for being well-constrained were assigned a Depth Quality of 4 ("not well constrained"). Our assignment of a Depth Quality of 2 or 3 is explained in table 2.

Remarks on the Earthquake (EQ) Catalog

As noted at the outset, data for the period 1850 through September 2012 are primarily from a Uniform Moment Magnitude Earthquake Catalog developed by Arabasz and others (2016), hereafter referred to as "the 1850–2012 catalog." We point the reader to that publication for a more complete description of the present EQ Catalog, beyond explanations provided here.

The 1850–2012 catalog unified earlier catalogs compiled or produced directly by the two primary agents of seismic monitoring of the region: the UUSS and the U.S. Geological Survey (USGS). The unified catalog was designed to cover the "Extended Utah Region" (lat. 36.00° to 43.50° N, long. 108.00° to 115.00° W), an area larger than the standard UUSS Utah Region. Authoritative source catalogs used to produce the unified catalog included (1) compilations of historical earthquakes since 1850 documented by USGS and UUSS researchers and (2) catalogs of instrumentally recorded earthquakes resulting from regional seismic monitoring by the UUSS since mid-1962 and from national-scale seismic monitoring by the USGS since 1973 (or in earlier decades by the U.S. Coast and Geodetic Survey).

Extending the 1850–2012 Catalog to Create the EQ Catalog

The EQ Catalog temporally extends the 1850–2012 catalog from September 30, 2012, through December 31, 2016. Spatially, it is restricted to the area of the Utah Region, as defined above. In terms of magnitude threshold, the EQ Catalog lowers the threshold magnitude of **M** ~2.5 for the 1850–2012 catalog to include all earthquakes instrumentally located by the UUSS since July 1, 1962. Epicenters for earthquakes before and after this date are shown in different colors on the map to differentiate instrumentally located earthquakes from earlier historical earthquakes, for which 90% of the locations are based on felt effects.

When we compiled the 1850–2012 catalog, we incorporated only those earthquakes from the UUSS Instrumental Earthquake Catalog having a preferred magnitude of 2.45 or larger, whether M_L UU or M_C UU. For the EQ Catalog, we effectively imported the *entirety* of the UUSS Instrumental Earthquake Catalog for the Utah Region in two steps. First, for the period October 1, 2012, to December 31, 2016, we imported all events having a preferred magnitude (M_L UU or M_C UU) of 2.45 or larger and then used the same methodology as Arabasz and others (2016) to determine a best-estimate value of **M** for each event. Second, for the period July 1, 1962, to December 31, 2016, we imported all events with a preferred magnitude (M_L UU or M_C UU) of 2.44 or smaller. We did not attempt to convert magnitudes for these smaller events to **M** (see section on Moment Magnitude, above).

EQ Catalog Supersedes the 1850–2012 Catalog

Digital earthquake catalogs are commonly timestamped, recognizing that changes may occur with time. We advise users that the present EQ Catalog supersedes the 1850–2012 catalog of Arabasz and others (2016). In compiling the EQ Catalog, we made changes to some original event lines in the 1850–2012 catalog. A few data-entry errors were corrected. Also, 11 events, previously unrecognized as probable blasts, were removed from the catalog. These include (1) three events in the vicinity of the Bridger coal mine complex (lat. 41.78° N, long. 109.50° W) in southwestern Wyoming, (2) two events in the vicinity of a phosphate mine (lat. 40.62° N, long. 108.75° W) near Vernal, Utah, and (3) six events in the vicinity of a quarry (lat. 37.12° N, long. 113.36° W) at Sand Hollow State Park in southeastern Utah. When we compiled the EQ Catalog we also removed some probable blasts among events imported from the UUSS Instrumental Earthquake Catalog with a preferred magnitude (M_L UU or M_C UU) of 2.44 or smaller in two areas: (1) the Sand Hollow State Park quarry and (2) the vicinity of a quarry site (lat. 38.48° N, long. 113.06° W) near Milford, Utah.

Non-Tectonic Seismic Events and Human-Triggered Earthquakes

Arabasz and others (2016, p. E-9) discuss non-tectonic seismic events and human-triggered earthquakes in the Utah Region. Non-tectonic seismic events consist primarily of (1) surface blasts associated with quarrying and surface mining and (2) seismicity associated with underground mining. Systematic attempts are routinely made to remove confirmed and suspected blasts from the UUSS Instrumental Earthquake Catalog, and similar attempts have been made for the present EQ Catalog. The problem is a challenging one. Despite diligent screening efforts, some unrecognized blasts may remain in the catalog.

MIS in the Utah Region is prominently associated with underground coal mining in east-central Utah, which we address below in our discussion of the CMR Catalog, and also with underground mining of trona (a sodium evaporite mineral) in southwestern Wyoming. Although outside the map area, a total of 31 seismic events (representing all located events in the rectangular area lat. 36.75° to 42.50° N and long. 108.75° to 114.25° W) were removed from the EQ Catalog as trona-mining seismicity (see Arabasz and others, 2016, p. E-11).

Earthquakes induced by the injection of fluids into underground rock formations are known to occur in the Utah Region, most notably along the Colorado-Utah border (see Arabasz and others, 2016, p. E-11 to E-13). Injection-induced earthquakes commonly release stored tectonic stress on pre-existing faults and can contribute to seismic hazard (see Ellsworth, 2013). Following Arabasz and others (2016), we have not removed injection-induced earthquakes from either the EQ or CMR catalogs.

Comment on Largest Earthquake Mainshocks on UGS Map M-277

At the bottom of the map, a table lists the 18 largest mainshocks (**M** 4.9–6.6) located within the boundaries of the map. By definition, a mainshock is the largest event in an earthquake sequence (a spatial and temporal clustering of earthquakes) that may include foreshocks, aftershocks, or similar-size events in an earthquake swarm. Each of the 18 mainshocks is discussed by Arabasz and others (2016, p. E-40), including the basis of the assigned best-estimate moment magnitude, **M**. Magnitude values of some of the historical events differ significantly from earlier magnitude assignments made using other scales. Arabasz and others (2016, p. E-40) also discuss another historical mainshock in the Utah Region, an earthquake of **M** 5.6 on November 10, 1884, near Paris, Idaho, located in the Bear Lake Valley just beyond the northern limit of the map.

In viewing the epicenters of larger earthquakes on the map, there is a notable grouping of four earthquakes in the magnitude 5 range in the Nevada-Utah border region (lower left part of map). These earthquakes were part of a vigorous earthquake swarm sequence that occurred from August 1966 into early 1967. The largest event of the sequence, labeled Mainshock No. 13, was a shock of **M** 5.2 that occurred at the start of the sequence on August 16, 1966 (Arabasz and others, 2016, p. E-45).

Remarks on the Coal-Mining-Region (CMR) Catalog

We use the term mining-induced seismicity (MIS), introduced earlier, to encompass all seismic events induced by underground mining, generally involving the sudden failure of material at mining openings or in the surrounding rockmass. MIS is considered to release predominantly non-tectonic stress. MIS associated with underground coal mining in east-central Utah is a well-recognized phenomenon that has been studied since the 1960s (see Arabasz and others, 2016). The maximum depth of mining is ~1 km below the ground surface. The region's largest mining-related seismic event to date (**M** 4.2; Whidden and Pankow, 2012) was the August 6, 2007, Crandall Canyon mine collapse (Pechmann and others, 2008).

Predominance of MIS in the CMR Catalog

The abundant seismicity located within the delineated source areas of the CMR Catalog predominantly represents MIS, based on its close space-time correlation with active underground coal mining (e.g., Arabasz and others, 1997, 2005; Arabasz and Pechmann, 2001; Boltz and others, 2014). Of the 24,493 events in the CMR Catalog, tectonic earthquakes make up a very small fraction—likely less than five percent and conservatively less than ten percent, as we proceed to explain.

Only 135 (< 1%) of the events in the CMR Catalog have a flag (see EQ Flag column) identifying the event as a tectonic earthquake. However, due to spatial and temporal shortcomings in seismographic coverage of the coal-mining region, we cannot claim to have reliably discriminated every tectonic earthquake among the thousands of events in the catalog. This limitation applies especially to microearthquakes (magnitude < 3). To assess the relative number of tectonic earthquakes, we rely on results of special investigations that have involved representative sampling of seismicity in the region of the CMR Catalog.

Attempts to discriminate tectonic earthquakes and MIS in the coal-mining region have variously utilized well-constrained focal depths and P-wave first motions (e.g., Arabasz and Pechmann, 2001; Arabasz and others, 2005); moment-tensor inversion (Whidden and Pankow, 2012); cross correlation and spectral content of recorded waveforms in combination with other event features (Stein, 2016); and differences between M_L and M_C for individual events, which can be diagnostic of shallow focal depth (Koper and others, 2016).

Arabasz and Pechmann (2001) examined all seismic events of M_L 3.0 or larger in the WP-BC polygon from January 1978 through June 2000. Of 18 candidate events, only one (a shock of **M** 3.2 in 1996) could be shown to be a tectonic earthquake at a normal seismogenic depth. Systematic moment-tensor inversions of seismic events in Utah of M_L ~3.5 and larger since 1998 (Whidden and Pankow, 2012, and subsequent unpublished analyses) have identified only two tectonic earthquakes in the coal-mining region: one of **M** 3.2 in 2008, and another of **M** 4.0 in 2011. The other two seismic events in this region with moment-tensor solutions are both mining-related: the 2000 **M** 3.9 Willow Creek mine event (Arabasz and Pechmann, 2001) and the 2007 **M** 4.2 Crandall Canyon mine collapse mentioned earlier.

Among the thousands of microearthquakes, the simplest tool for screening tectonic earthquakes is to seek well-constrained focal depths below the depth of mining. But this screening is generally handicapped by inadequate seismograph spacing (see Koper and others, 2016). Only 17% of the events in the CMR Catalog have a well-constrained focal depth. Stein (2016) used a combination of several discrimination methods to identify the source type of ~6400 events, primarily microearthquakes, in the Wasatch Plateau region. His study area includes the western half of the WP-BC polygon (west of long. 110.95° W) and the SUFCO rectangle. Within these regions of the CMR Catalog, Stein analyzed 6222 events from mid-1998 through 2011, and he identified 5226 (84%) as MIS events and 131 (2%) as tectonic earthquakes. The remaining 865 events (14%) could not be classified unambiguously, but nearly all have epicenters within mine permit boundaries suggesting a high probability that they are MIS events. It is reasonable to argue that MIS accounts for more than 90% of the total 6222 events.

Based on all available data and evidence, we are persuaded that MIS predominates in the CMR Catalog, conservatively accounting for more than 90 percent—and likely more than 95 percent—of the 24,493 events in the catalog. This judgment is supported by our direct involvement in seismic monitoring of the coal-mining region for decades as well as by our familiarity with space-time variations in the observed seismicity that correlate with changes in the location, procedures, and site geology of mining activities. We are aware of a different view about the causation of seismicity within the WP-BC polygon recently offered by Brown and Liu (2016), which we address next.

Injection-Induced Earthquakes in the CMR Catalog

Tectonic earthquakes in the CMR Catalog include naturally occurring earthquakes and probably some earthquakes induced by the injection of fluids into underground rock formations. Stein (2016) identified 25 tectonic earthquakes ($1.1 \leq M_L \leq 2.4$) that were possibly induced by fluid injection in wastewater wells along the eastern side of the Wasatch Plateau. All 25 are included in the CMR Catalog and are specifically designated (see EQ Flag column).

Brown and Liu (2016) describe the practice of wastewater injection in oil and gas wells in Carbon and Emery Counties and examine its correlation with seismicity. These authors claim that since ~1998 there has been a significant increase in seismicity within our delineated WP-BC polygon, where MIS is acknowledged to occur, and that wastewater injection has been a major cause of the increased seismicity. Some of the fundamental assumptions and analyses in Brown and Liu (2016) are demonstrably wrong, most notably their invalid analysis of seismicity rate changes, which properly requires that earthquakes below a threshold magnitude of complete reporting not be counted. Despite assessing a minimum magnitude of completeness, they ignore it in comparing time histories of total-catalog earthquake rates, coal production, and wastewater injection—leading to unsupportable conclusions.

Two MIS Events with Epicenters Outside the Delineated Mining Regions

The map shows two epicenters located just *outside* the boundaries of the defined coal-mining regions that have gray-colored symbols specific to events *within* the "Areas of Predominantly Mining-Induced Seismicity." One epicenter lies outside the western boundary of the SUFCO rectangle and the other lies outside the eastern boundary of the WP-BC polygon. Despite their epicentral locations, these two events (listed below) were judged by Arabasz and others (2016) to be mining-related, and we intentionally include them in the CMR Catalog.

M	Longitude	Latitude	Depth (km)	Year	Mo	Day	Hr	Min	Sec
4.05	-110.200	39.600	0	1961	5	6	16	12	20.70
3.90	-111.4970	39.0068	1	2012	7	31	10	27	28.39

The 1961 event was instrumentally located (with low precision) by the U.S. Coast and Geodetic Survey. Its best-estimate moment magnitude is based on a Modified Mercalli Intensity of V, with strongest felt effects at Columbia, Utah, within about 4 miles of the Geneva coal mine; the Sunnyside coal mines are also nearby. Arabasz and others (2016) judged that the event was likely an MIS event, based on the paucity of tectonic events in the area, together with the known association of MIS with the Geneva and Sunnyside mines.

The 2012 event was located by the UUSS close to, but just outside, the western permit boundary of the SUFCO mine. Its moment magnitude and depth are from a UUSS moment tensor solution. The shock's shear-slip (normal-faulting) moment tensor permits the interpretation that it was tectonic, but its very shallow focus and proximity to the SUFCO mine suggest that it was caused by mining-induced stresses in the rockmass surrounding the mine.

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APPENDIX

UUSS INSTRUMENTAL EARTHQUAKE CATALOG

General Background

The earthquake record in Utah and the surrounding Intermountain Region relied initially on reports and newspaper accounts of felt earthquakes and later on seismographic recordings made during several stages of evolving instrumental coverage (e.g., Smith and Arabasz, 1991; Arabasz and others 1992). The UUSS Instrumental Earthquake Catalog refers to the compilation of the locations and magnitudes of instrumentally recorded earthquakes in Utah and its surrounding region resulting from systematic analysis and data processing by seismologists and staff of the University of Utah Seismograph Stations (UUSS). The instrumental catalog extends continuously from July 1962 to the present and is available online at http://quake.utah.edu/earthquake-center/earthquake-catalogs (where "Utah Catalogs" are for the standard Utah Region, as we have defined it in the main report).

Continuous seismic monitoring in Utah effectively began in 1962 with the operation of a skeletal statewide network consisting of up to 10 onsite-recording seismographic stations during the 1960s and early 1970s. For historical perspective, see http://quake.utah.edu/wp-content/uploads/Cook-Display-Handout.pdf. In the mid-to-late 1970s, UUSS seismologists made extensive efforts, combining all available data from UUSS and non-UUSS seismographic stations, to systematically revise the locations and magnitudes of all recorded earthquakes in the Utah Region from July 1962 through September 1974. The results, which were published as part of the special publication *Earthquake Studies in Utah, 1850 to 1978* (Arabasz and others, 1979), constitute the beginning of the UUSS Instrumental Earthquake Catalog.

In 1974, the UUSS began installing and operating a network of high-gain telemetered seismic stations with continuous centralized recording on the University of Utah campus. This network enabled significantly better locations and magnitude determinations than for the pre-1974 period. The number of stations in the network grew from 27 at the end of 1975 to more than 50 by 1980. Digital recording of the network data began in January 1981. Since the early 1990s, there have been several stages of expansion and major modernization of the UUSS regional seismic network. At the end of 2016, the UUSS was operating 245 stations in Utah and neighboring areas (see http://quake.utah.edu/monitoring-research/station-map; see also http://quake.utah.edu/wp-content/uploads/2016Q4.pdf).

Appearance of Event Lines in the UUSS Instrumental Earthquake Catalog

Event lines for individual earthquakes in the UUSS online instrumental catalog are in the UUSS standard "Hypo71" sum file format, having the appearance of the following example:

```
161231 1133 01.12 36 56.54 113 31.26    4.78 W 1.86 16 175 26.0 0.21  0.9  2.4
```

The format is described at http://quake.utah.edu/earthquake-center/earthquake-catalogs/catalog-details. As explained therein, the first three fields list the origin date and time. The next five fields list the latitude, longitude, and depth. The depth is followed by a magnitude flag ("W" in the example), magnitude, and then six parameters indicative of the quality of the hypocentral solution: NO [alternatively labeled NPH in table 2 of the main report], GAP, DMN, RMS, ERH, and ERZ.

Data Analysis

Data analysis procedures used to produce the UUSS Instrumental Earthquake Catalog differ for the periods before and after the beginning of digital network recording on January 1, 1981. For the pre-digital-recording period, details (including velocity models and magnitude estimation procedures) are described by Richins (1979, p. 79–89) for July 1962 through June 1978, and by Richins and others (1981) for July 1978 through December 1980. The computer program HYPOELLIPSE (Lahr, 1979) was used to locate all events from July 1962 through December 1980.

For the time period from January 1981 through September 2012, modified versions of the computer program HYPOINVERSE (Klein, 1978) were used to locate local earthquakes recorded by the UUSS network in order to generate the catalog summary of hypocenters and duration magnitudes M_C. Additionally, beginning in 1994, local magnitude M_L was computed from horizontal-component, synthetic digital Wood-Anderson seismograms in addition to paper Wood-Anderson seismograms from one to three stations (Pechmann and others, 2007; see also http://quake.utah.edu/earthquake-center/earthquake-catalogs/catalog-details/summary-of-uuss-magnitude-determinations-1981-2006). Locations of earthquakes in the Utah Region were determined using a set of three velocity models (see details at http://quake.utah.edu/earthquake-center/earthquake-catalogs/catalog-details/computation-of-uuss-earthquake-locations-1981-present).

On October 1, 2012, UUSS began using the ANSS Quake Monitoring System (AQMS) software package, standardly used for data processing by regional seismic networks participating in the Advanced National Seismic System (ANSS). The primary effect on the earthquake catalog data comes from computing the earthquake locations with a newer version of the computer program HYPOINVERSE (Klein, 2015) and a revised and expanded set of velocity models. As implemented at the UUSS, this new version of the location program selects the velocity model for each travel time calculation based on the locations of both the epicenter and the station instead of just the station, as was done previously. This new version also accounts for station elevation differences more accurately and reports focal depths relative to sea level instead of the elevation datum 1.5 km above sea level used previously. In the future, all of the earthquake locations in the catalog will be recalculated using the current location program and velocity models.

For the entire catalog period from July 1962 through December 2016, located seismic events identifiable as blasts have been routinely deleted from the catalog. Blast identification is accomplished by contacting individual blasting operations and/or correlation with known blasting areas and the time of day of frequent blasting. Some additional details regarding the 1981-to-present catalog are available at http://quake.utah.edu/earthquake-center/earthquake-catalogs/catalog-details/quality-and-completeness-of-uuss-catalog-data-1981-present).

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