Final Technical Report for Award #G18AP00079

Project Title: Capturing the Onset of Induced Seismicity: Field Experiment at High Rate Disposal Wells, Denver-Julesburg Basin, Colorado

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Dates covered by this award:

August 1, 2018 – December 31, 2019

Acknowledgement of Support and Disclaimer: This material is based upon work supported by the U.S. Geological Survey under Grant No. G18AP00079. The views and conclusions obtained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Geological Survey.

Abstract

This project involved seismological data collection and analysis at actively mitigated high rate wastewater disposal wells in northeast Colorado associated with induced earthquakes as well as at new high rate injection wells in the broader NE Colorado region. This work provides data that is of utility for testing the efficacy of mitigation as well as to explore the temporal variation in earthquake statistics, anisotropy, and interstation Green's functions in response to subsurface fluid effects. Our work has included completion of a uniform seismic catalog for the period 2014-2019 in a region with abundant seismicity and initially a single and then one additional high rate Class II wastewater disposal well, also in the region of tightly clustered seismicity. With this new earthquake catalog we can evaluate the development of seismicity with time, its link with injection parameters, and search for seismic signals associated with pore pressure changes. We did not record any earthquakes at the new high rate wells, they remained seismically quiescent, giving us an important baseline of background seismicity and conditions. The seismicity has remained concentrated in the same region just east of Greeley, Colorado. Seismograms from our seismic stations were all telemetered and the data was immediately made open and available through the IRIS DMC.

1. Introduction

The town of Greeley, Colorado, situated in a previously aseismic segment of the Rocky Mountain Front Range (Figure 1), has experienced low-magnitude earthquakes since 2014. These events have been linked to the injection of oil and gas-derived waste water into the basal sandstone units of the Denver Basin (Yeck et al., 2016; Brown et al., 2017.) In response to the initial widely felt M 3.2 earthquake in 2014, the University of Colorado Boulder rapidly installed seismometers in the region that remained in place through 2019. Abundant seismicity was found in this study, tightly clustered in a region with radius of about 3 km, centered near a Class II wastewater well. An additional Class II injection well less than a kilometer away began operation in April 2015. In June 2016, the combined injection rates of these two wells exceeded 500 K barrels/month, and several felt earthquakes occurred in August 2016.

One of the goals of this grant was to test the hypothesis that deep high rate injection wells are most likely to be associated with induced earthquakes. Seismometers were deployed in northeast Colorado in close vicinity to high rate wastewater disposal wells. However, earthquakes did not occur at the new high rate injection wells that we deployed seismometers near, so our analysis was adjusted to focus on the region that does have earthquakes. We collected data in the vicinity of ten high rate injection wells, in an attempt to capture the onset of induced seismicity. We have found seismicity in only one location, where two wastewater wells are in close proximity. We did observe an increase in seismicity when the second well became operational. The quiescence at the remaining high rate disposal wells is intriguing, as is the locus of seismicity at only one location.

Our work during this grant period included construction of a multi-year (2014-2019) earthquake catalog near two actively mitigated wastewater disposal wells, baseline measurements documenting the absence of seismicity at eight additional wells, and studies of temporal variations including the seismicity distributions, anisotropy, and velocity.

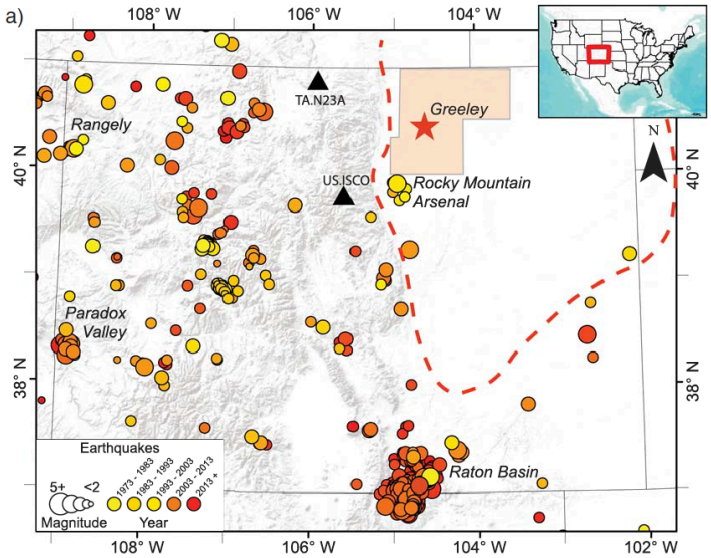

Figure 1. Pre-2014 seismicity of Colorado (circles) as compared to the location of the Weld County 1June2014 earthquake (red star). The approximate boundaries of the Denver-Julesburg Basin (red dashed line) and Weld County (orange shaded region) are shown. The nearest coeval stations to the 1June earthquake, US.ISCO and TA.N23A, are show as black triangles. Other notable regions of documented induced seismicity in Colorado are labeled, including Rocky Mountain Arsenal, Rangely, Paradox Valley, and Raton Basin. Seismicity are from USGS ANSS catalog.

2. Seismometer Deployment in Northeast Colorado

Our seismic data collection in the NE Colorado (Greeley) area started with six seismograph stations centered on the epicenter of the June 1, 2014 Greeley magnitude 3.2 earthquake (Figure 2). Equipment was from the IRIS PASSCAL Rapid Array Mobilization Program (RAMP). Six seismic stations (network code XU 2014-2015) were deployed, the first of which the University of Colorado deployed on June 04, 2014, three days after the Greeley M_w 3.2 earthquake. The initial station deployments all had short period 3-component L22 sensors, one had an Episensor 3-component strong motion accelerometer, and two of the stations were telemetered to the USGS and then to IRIS. All stations had Reftek data loggers.

In 2016 the network was expanded to include a larger part of the Denver Basin, for a total of 16 stations (Figure 3). The seismometers were deployed in close proximity to wastewater injection wells in order to characterize background seismicity and potentially capture the onset induced seismicity. The seismometers at several stations were upgraded from short period to intermediate period (Guralp CMG40T) or broadband (Guralp CMG3) in 2016 and 2017 (Table 1). Telemetry was added to all stations in 2016. The new stations were cited near high rate disposal wells or groups of wells that had not yet experienced seismicity. All data were sent in real-time by cell phone modem to the University of Colorado Boulder, and from there transmitted to the USGS in Golden and the Incorporated Research Institutions for Seismology (IRIS) data management center in Seattle. The continuous waveform data were telemetered to the University of Colorado Boulder and stored on Continuous Waveform Buffer and from there directly transmitted to IRIS for archiving. All data were made immediately open and unrestricted. In December 2019 the telemetry modems became obsolete, and telemetry halted at all stations. In February 2020 a new modem was installed at station GRWE and telemetry resumed at that station only.

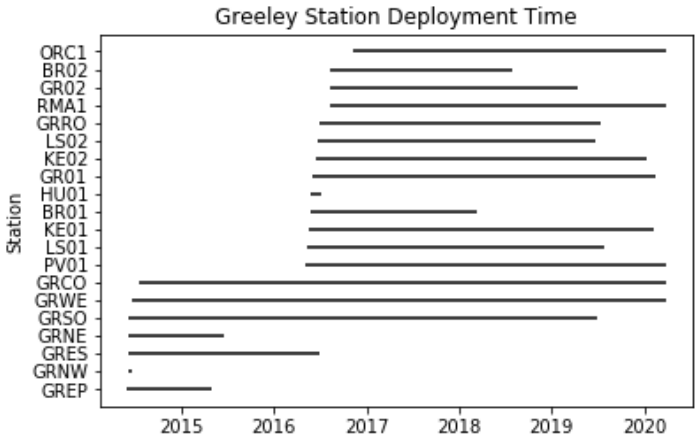

Figure 2. Timeline of northeast Colorado ('Greeley') seismic station deployment. Initial deployment was immediately after the June 1, 2014 M 3.2 Greeley earthquake. Additional stations were deployed throughout NE Colorado in summer 2016, with many in close proximity to high rate wastewater disposal wells.

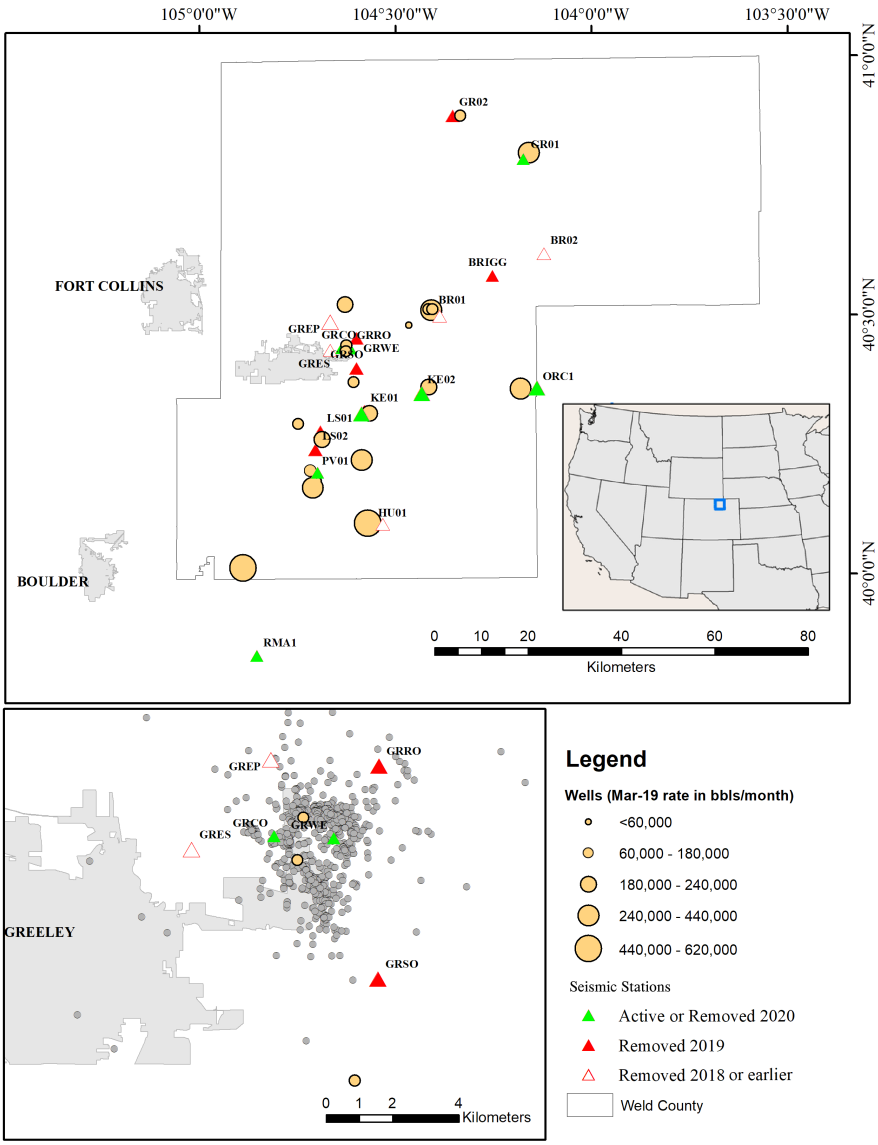

Figure 3. (top) Seismic stations (triangles) and wastewater disposal wells (tan circles, sized by March 2019 monthly volume) in northeast Colorado. Seismic station BRIGG was operated by the Colorado Geological Survey, all other stations were operated by University of Colorado Boulder with install dates from 2014-2016 and removal dates from 2015-2020 (Table 1). Green triangles represent stations currently active or removed in 2020, solid red triangles are stations removed in 2019, and unfilled red triangles are stations removed in 2018 or earlier. Timeline of deployment is in Figure 3 and Table 1. (bottom) Zoom in of seismic stations, wastewater disposal wells, and seismicity east of Greeley, Colorado. Seismicity from June 2014 to May 2019. NGL C4A is northernmost well (tan circle) in bottom plot, EWS2 is middle well, HPD1 is southernmost well shown on bottom plot.

Table 1. Northeast Colorado Seismic Station Deployment, Network XU (2014-15 and 2016-2020)

Station	Latitude	Longitude	Install Date	Demobilization Date	Sensor Model	Digitizer	Telemetry Start Date	Locations (CO, USA)
BR01	40.5181	-104.41	05/24/16	3/12/18	Guralp CMG40T	Reftek 130	5/24/16	Briggsdale Southeast
BR02	40.626	-104.126	08/13/16	7/28/18	Guralp CMG40T	Reftek 130	8/13/16	Briggsdale East
GR01	40.8122	-104.172	06/03/16	2/12/2020	Guralp CMG40T	Reftek 130	6/3/16	Grover South
GR02	40.8939	-104.354	08/13/16	4/12/19	Mark Products L22	Reftek 130	8/13/16	Grover West
GRCO	40.4466	-104.638	7/17/14	6/25/16	Mark Products L22	Reftek 130	5/19/16	Chill Station
GRCO	40.4466	-104.638	6/25/16 10/19/17	10/19/17 Active	Guralp CMG3T Guralp CMG40T	Reftek 130		Chill Station
GRRO	40.4654	-104.601	6/30/16 7/7/18	7/7/18 7/12/19	Mark Products L22 Guralp CMG40T	Reftek 130	6/30/16	Greeley Roth Farm
GRSO	40.4076	-104.602	6/5/14	7/12/17	Mark Products L22	Reftek 130	5/19/16	Greeley South
GRSO	40.4076	-104.602	7/12/17	6/27/19	Guralp CMG40T	Reftek 130		Greeley South
GRWE	40.4459	-104.617	6/20/14	7/17/17	Mark Products L22	Reftek 130	7/19/14	Greeley Well
GRWE	40.4459	-104.617	7/17/17	Active	Guralp CMG40T	Reftek 130		Greeley Well
GREP	40.4712	-104.641	6/3/14	4/28/15	Mark Products L22	Reftek 130	6/5/14	Greeley Epicenter
GRES	40.443	-104.668	6/4/14	6/30/16	Mark Products L22	Reftek 130	6/5/14	Greeley East
GRNE	40.5169	-104.509	6/4/14	6/20/15	Mark Products L22	Reftek 130	6/5/14	Gill
GRNW	40.5451	-104.791	6/4/14	6/20/14	Mark Products L22	Reftek 130	6/5/14	Eaton
HU01	40.1021	-104.565	5/26/16	7/7/16	Guralp CMG40T	Reftek 130		Hudson
KE01	40.3255	-104.583	5/20/16 6/23/17	6/23/17 2/10/20	Mark Products L22 Guralp CMG3T	Reftek 130	5/20/16	Kersey
KE02	40.3598	-104.439	6/23/17	1/10/2020	Guralp CMG40T	Reftek 130	6/17/16	Kersey
LS01	40.2856	-104.694	5/13/16	7/24/19	Mark Products L22	Reftek 130	5/13/16	LaSalle
LS02	40.2506	-104.706	6/21/16 7/18/17	7/18/17 6/20/19	Mark Products L22 Guralp CMG3TT	Reftek 130	6/21/16	LaSalle
ORC1	40.364	-104.148	7/18/17	Active	Guralp CMG40T	Reftek 130	11/8/16	Orchard
PV01	40.204	-104.706	5/7/2016	Active	Guralp CMG40T	Reftek 130	5/17/16	Platteville
RMA1	39.8533	-104.854	8/12/16	Active	Guralp CMG40T	Reftek 130	8/12/16	Rocky Mountain Arsenal

Stations marked as Active are still in the field as of 3/30/2020. Several stations had instrument swaps (outlined), dates for each sensor model used are given.

3. NE Colorado Seismic Catalog 2014-2019

A catalog of approximately 1200 earthquakes recorded by our seismic deployment in NE Colorado from 2014-2019 is provided with this technical report (Appendix 1). Earlier versions of this catalog were used in Yeck et al. (2016) and Brown et al. (2017). Event detections for our catalog were performed through a combination of manual daily inspection of seismic records (all dates), application of a machine learning event picker (Generalized Phase Detection system, Ross et al., 2018) (June 2014-July 2016 part of catalog), and use of an STA/LTA picker with subsequent subspace detection (Yeck et al., 2016) (June 2014-April 2015 part of catalog). For the catalog presented in this report, the detection methods vary as described in the previous sentence, but all events are located in the same manner, with the same velocity model, same location algorithm, and magnitudes are determined in the same manner. In an ongoing effort to reconcile the differing detection threshold produced through manual inspection, we are utilizing the Generalized Phase Detection system (Ross et al., 2018) and the USGS-developed Global Associator3 (Glass3) (Yeck et al., 2019) to subsequently recover overlooked events. This system utilizes recent developments in deep-learning approaches to seismic phases detection, as well as an experimental upgrade to the phase association algorithm currently employed in the National Earthquake Information Center (NEIC) real-time monitoring system. Preliminary results have

produced an additional 256 verified and catalogued events between June 2014 and July 2016, the majority of which are below Ml 0.5. This is in addition to the 643 events from June 2014-April 2015 detected by Yeck (2016). At the time of submission of this report, the Ross and Glass3 detection system has only been applied to data collected before June 29, 2016.

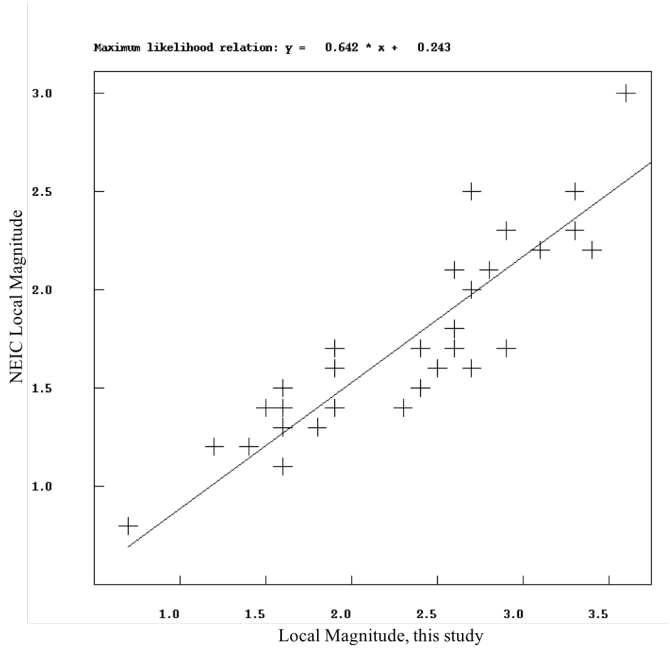

Figure 4. Comparison of USGS NEIC Local Magnitude vs Local Magnitude determined for this study, for Greeley area events in common to both USGS and CU catalogs.

To maximize consistency in the relocations and post-processing of the seismicity catalog through time, we have homogenized the seismic phase arrival time picks using a modified version of the PSIR Picker (Li and Peng, 2016). This picking method relies on a velocity model and origin time estimates to refine arrival time picks and reconstruct seismic catalogs. We improved on this method by adjusting the minimum signal-to-noise (SNR) requirement for pick consideration in their algorithm, and replaced the SNR ratio detector with the Akaike information criteria (AIC) picker of Zhang et al. (2016). For manual phase inspection, quality control of the automated phase picker results, and for final catalog processing, we utilized the SEISAN software framework (Ottemoller et al., 2014). The reported locations and local magnitudes were determined using the default SEISAN relocation program, HYPOCENTER (modified from Lienert *et al.* 1986). The P-wave velocity model used is from Yeck *et al.* (2016), with a Vp/Vs ratio of 1.78. The six-layer 1D crustal velocity model is based on reported models used in studies of the Rocky Mountain Arsenal [*Healy*, 1966] combined with information from local well logs. The implemented local magnitude scale is according to the latest IASPEI standard, whereby the SEISAN HYPOCENTER program calculates a magnitude consistent with the scale of Richter (1935) and derived from the work of Hutton and Boore (1987). Input shear wave amplitudes from instrument-corrected waveforms were measured on the horizontal records of ground displacement. A subset of the resulting magnitudes was compared with local magnitude values published by the NEIC (Figure 4). There is not a one-to-one relationship between magnitude

values, but values in general are within a half magnitude unit. Differences in magnitude may be due to the NEIC's use of seismic stations outside of the local seismic network, or different attenuation and distance correction values.

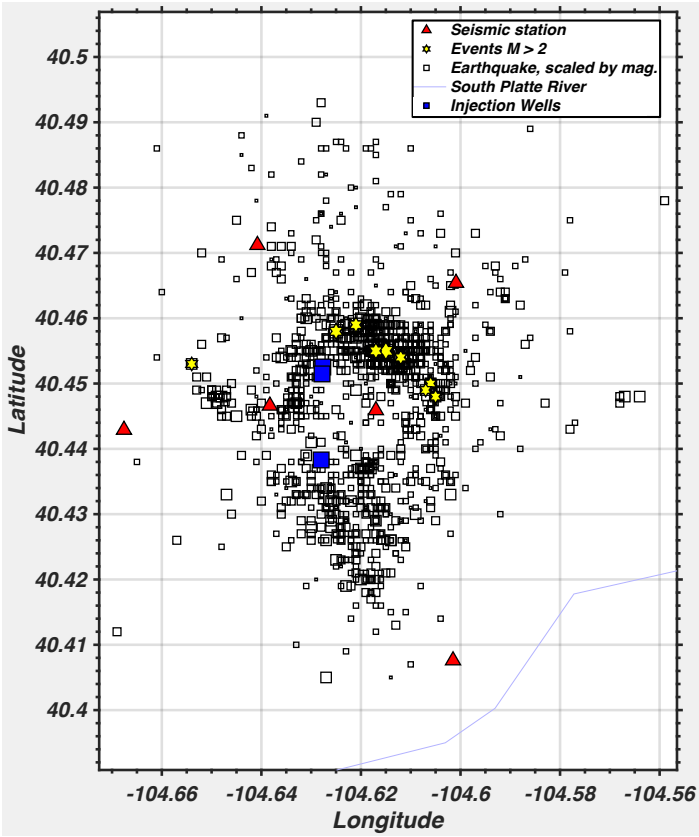

Figure 5. Map view of 2014-2019 Greeley area seismicity detected and located from our University of Colorado NE Colorado seismometer deployment. Black squares – earthquakes scaled by magnitude. Yellow stars – earthquakes with magnitude > 2.0. Red triangles – seismic stations. Blue squares – Class II Wastewater disposal wells, NGL C4A at north, and EWS2 approximately 1 km south.

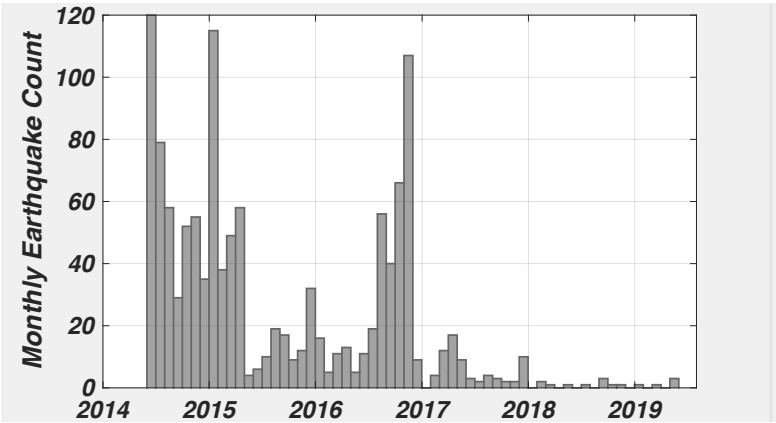

Figure 6. Histogram of number of earthquakes in monthly bins as a function of time. Increase in seismicity in mid-2016 was shortly after injection rates increased at the new wastewater disposal well EWS2 nearby.

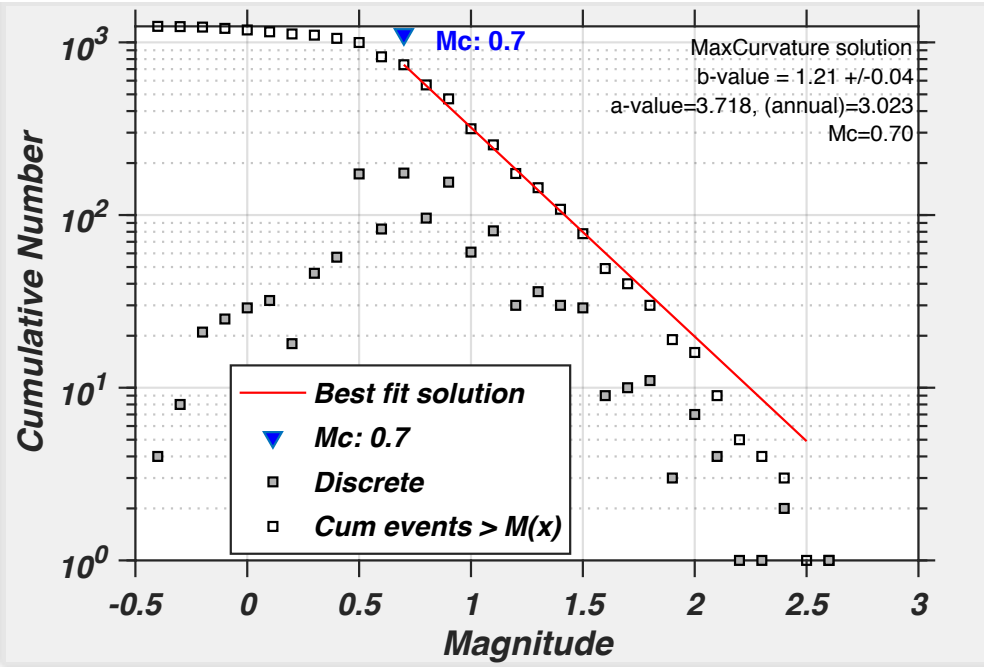

Figure 7. Frequency-magnitude plot for earthquakes detected and located by our NE Colorado seismic array from 2014-2019. Open squares at each x value denote cumulative events of magnitude > M(x). Solid squares denote number of events at each given magnitude. Inverted triangle labeled Mc denotes the magnitude of completeness. Red line denotes the resulting b-value of 1.2.

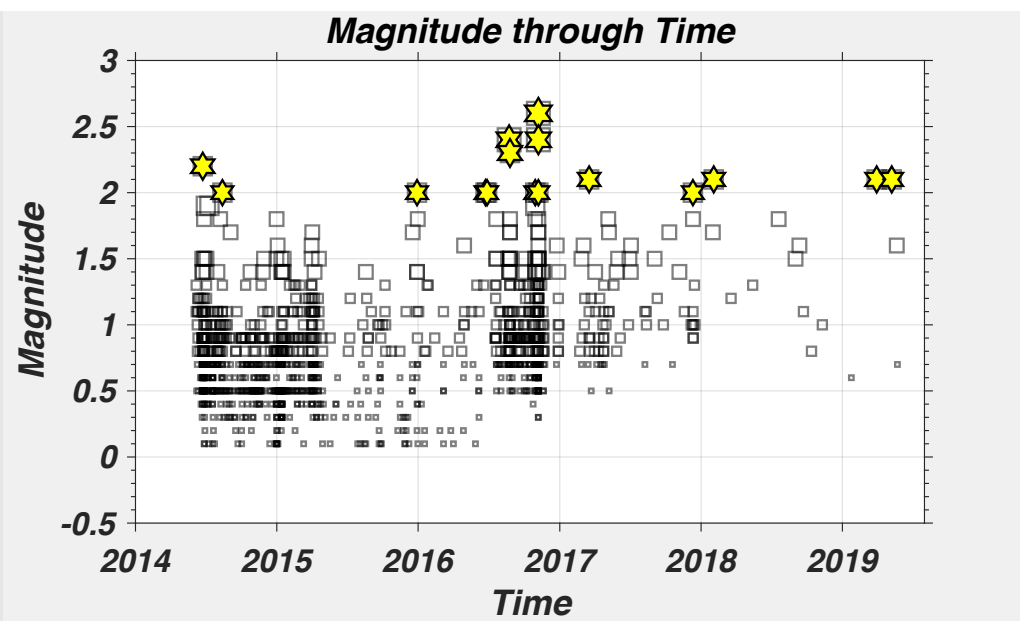

Figure 8. Magnitude vs time for our 2014-2019 catalog. Events larger than magnitude 2 denoted as yellow stars. Other earthquakes shown as black open squares, with size scaled by magnitude. The time 2014-mid-2016 has a higher detection threshold (more small events located) due to the use of both subspace detection and generalized phase detection.

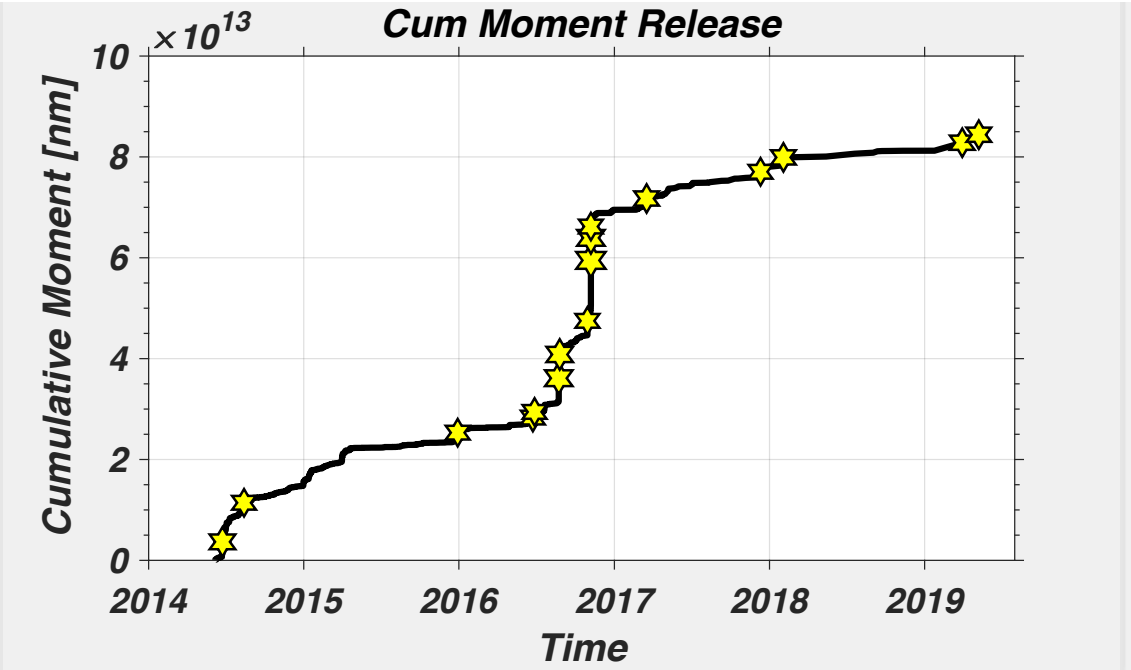

Figure 9. Cumulative moment release as a function of time for earthquakes detected and located by our NE Colorado seismic array from 2014-2019. Yellow stars denote earthquakes of magnitude > 2.

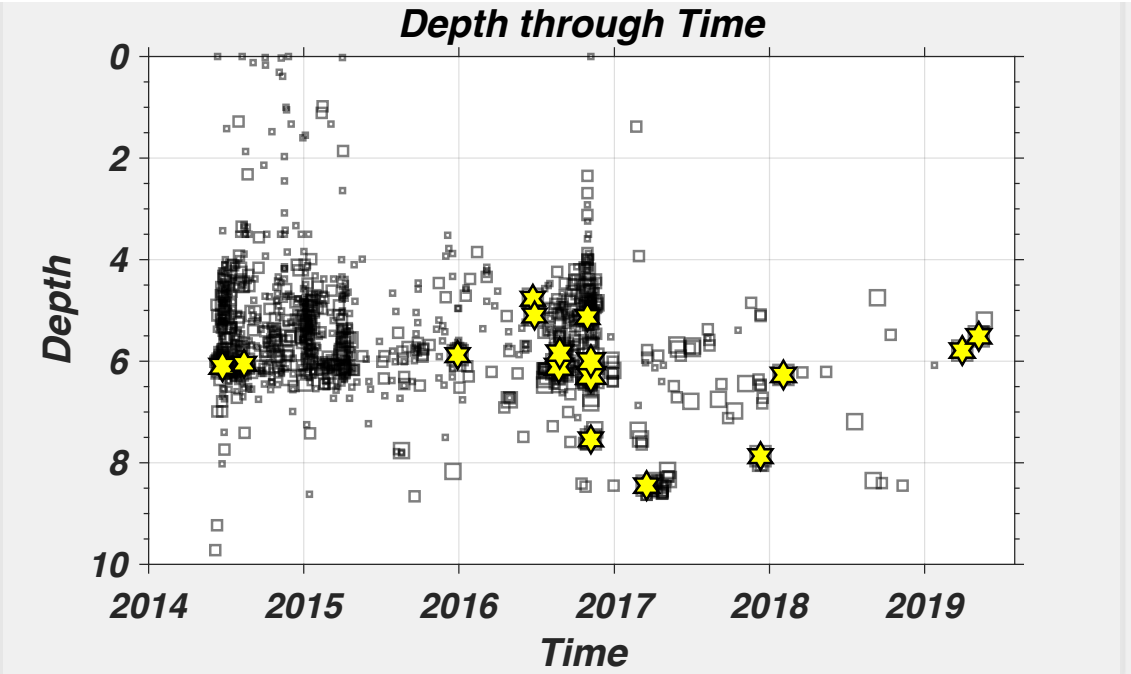

Figure 10. Earthquake depth relative to surface elevation for earthquakes detected and located by our NE Colorado seismic array from 2014-2019. Yellow stars denote earthquakes of magnitude > 2. Shallow outliers (< 1 km depth) reflect event detections with poorly constrained locations due to their small size and the poor signal-to-noise ratio of the data used for relocation.

4. Double-difference relocations and preferred alignment of faulting

After recompiling the seismic catalog in a consistent manner (Section 3 and Appendix 1), we performed high-precision relative relocations to analyze periods of time corresponding to major changes in injection parameters at Class-II wastewater injection wells in the epicentral region, NGL-C4A and EWS-2. Although the uncertainty of the absolute locations of the events in our catalog is on the order of kilometers in scale, the use of waveform cross-correlation and double-difference relocations allow us to map the relative locations of subsequent earthquakes with a precision on the order of tens of meters between events. We utilized HYPODD (Waldhouser and Ellsworth, 2000) to perform the inversion of differential phase arrival times derived from the cross correlation of all event waveform pairs recorded in the network. We used starting locations for the double-difference inversion derived from single-event absolute earthquake locations calculated using the seismic velocity model of Yeck et al. (2016). Figure 11 displays a map of the final hypodd locations, colored by the number of days following the first event in our catalog on June 6, 2014.

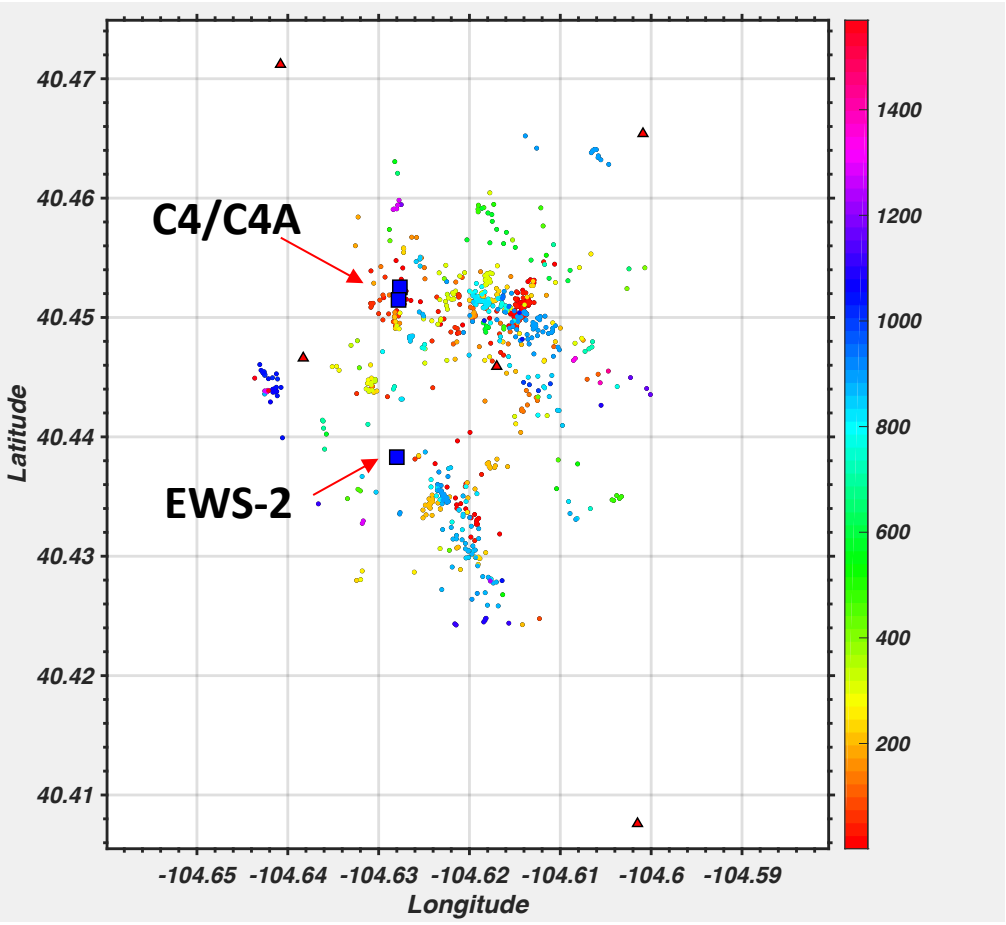

Figure 11. Map view of results from HypoDD relocations. Earthquakes are color coded according to their occurrence in days following June 6, 2014, 19:41:30 GMT. Red triangles are seismic stations and blue squares are nearby wastewater injection wells, EWS-2 and NGL C4/C4A.

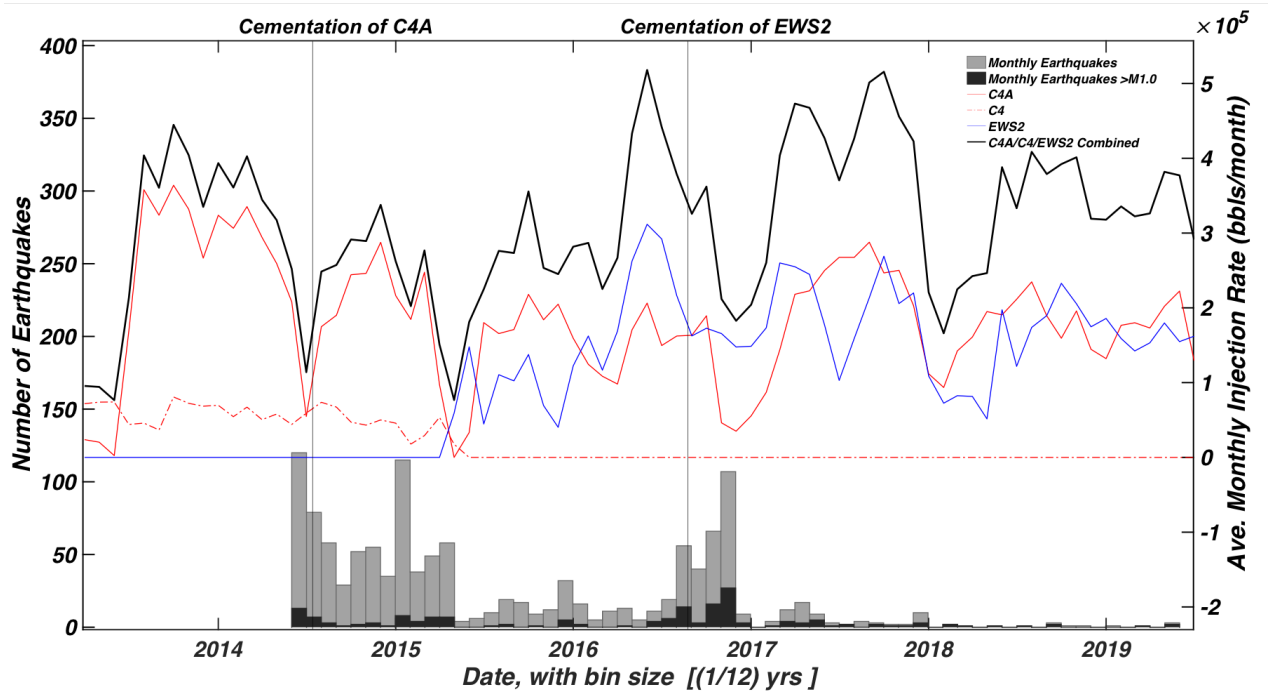

Figure 12. Plot of wastewater injection history at three wastewater disposal wells nearest to the seismicity (NGL C4, NGL C4A, EWS2). The location of the wells is shown in Figure 11. The histograms at the bottom show the number of earthquakes from our catalog, with the grey bins showing total number of earthquakes and the black bins showing only events > Ml 1.0. The vertical lines mark the dates when wells were temporarily shut in to have cement plugs added to the bottom of the well. The well cementation was to inhibit the hydraulic connection between injection and the crystalline basement in an attempt to reduce the risk of inducing earthquakes.

Injection History

There are three wastewater injection wells within one kilometer of the concentration of seismicity. Injection well NGL-C4 has an injection history that dates back to 2003, however seismicity did not begin until after collocated high-rate injector NGL-C4A began operation in 2013 (Yeck et al., 2016). Following the initial onset of felt seismicity in 2014, injection rates were adjusted and C4A was plugged back with cement to inject at a shallower depth. The well cementation was to inhibit the hydraulic connection between injection and the crystalline basement in an attempt to reduce the risk of inducing earthquakes. In April of 2015, injection was suspended at C4A following an accidental fire caused by a lightning strike. Interestingly, the seismicity rate exhibits a swift decrease shortly after, possibly due in part to the month-long repair time when no fluids were injected at this well. Within this time, a new high-rate injection well approximately one km south of NGL4, EWS2, began operation. With continued operation of C4A and EWS2 by mid-2015, the seismicity rate grew to previous high levels by late 2016. In response to a series of felt earthquakes, remediation efforts were also applied at EWS2. Documentation on the mitigation efforts at each well are available at the Colorado Oil and Gas Conservation Commission (COGCC) web page for each well, for example

https://cogcc.state.co.us/weblink/results.aspx?id=12335841 and
https://cogcc.state.co.us/weblink/results.aspx?id=12337808

Within months of the 2016 mitigation activity, the level of detected seismicity had fallen, and has remained low despite continued high rates of wastewater disposal. Also following this 2016 mitigation activity we observed an apparent change in the orientation of active structures that are delineated by the earthquake locations.

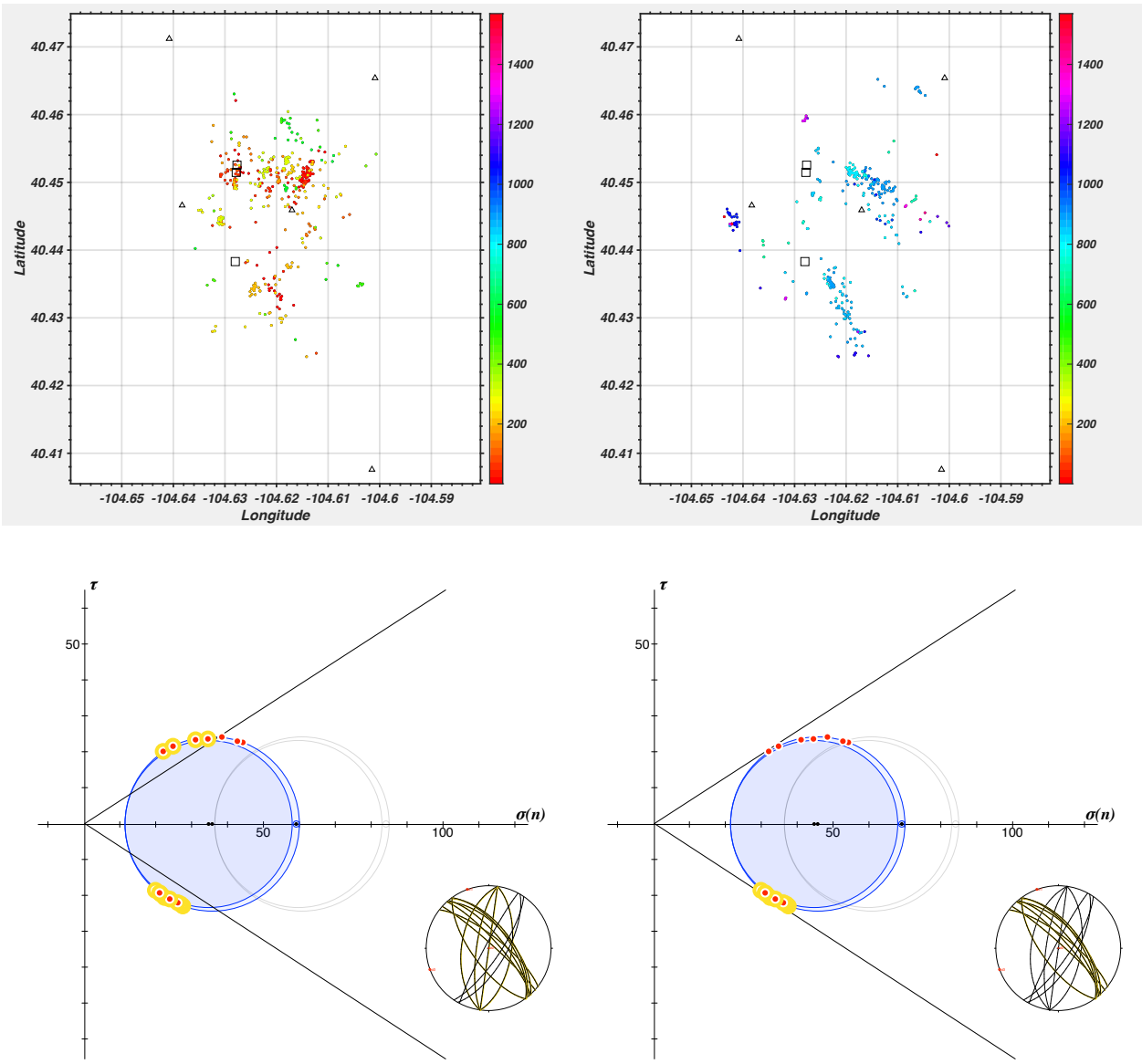

Figure 13. A. Same as previous map, split into two different time periods during the Denver earthquake study. Left: early earthquakes (2014-mid-2016) showing active faults in both a north-east and north-west to south-east orientation Right: later earthquakes (mid-2016-present) showing that north-east trending structures apparently become inactive following the mitigation efforts at EWS-2 in 2016. B. Corresponding Mohr circle diagrams for each time period in A. Points represent the orientation of structures interpreted from the

seismicity clouds, relative to an estimated regional state of stress. The stereonets provide an alternative view of the planes plotted in a lower-hemisphere projection. Planes that are highlighted in yellow represent those that are breaching the reactivation envelope, and thus are capable of hosting earthquakes. The position of the Mohr circles, relative to the reactivation line, is determined by the effective normal stress. As pore pressure decreases, the planes move farther from reactivation.

Seismicity Analysis and Deactivation of Preferentially Oriented Faults

As a whole, the map of relocated seismicity reveals a complex network of interconnected fractures and faults (Figure 11). However, marked changes in the behavior of seismicity become apparent through the analysis of seismicity during two different time periods in the experiment. Namely, there are distinct changes in the orientation of active and inactive structures before and after August of 2016. Coulomb stress theory suggests that these changes may correspond to a number of injection rate decreases and bottom-well cementations implemented at the two wastewater wells nearest to the seismicity. Under a given stress regime, only faults of a limited geometrical range are capable of slipping to cause an earthquake. When fluids are injected into the Earth, this raises the pore fluid pressure in the subsurface and increases the range of faults that can be activated. Conversely, when pore fluid pressure is decreased, for example when injected fluids are prevented from entering a layer of rock by mitigation, the range of potentially active fault geometries is limited (Figure 13B).

The points in Figure 13B represent preexisting faults and fractures at orientations representative of the seismogenic structures in the earthquake catalog. Their positions on the plot are defined by their strike and dip, relative to the principle stress directions and magnitudes estimated for the Denver Basin (regional stress tensor parameters taken from Dart 1985; McGarr & Gay, 1978). The orientation of planes in the plot were inferred directly from the relative relocations of seismic events above them in Figure 13A.

Planes and corresponding points on the Mohr Circle in Figure 13B are highlighted according to their tendency to slip. Under an assumed pore pressure gradient and static coefficient of friction on the fault, all planes are near the reactivation envelope. However, planes oriented in a NE direction require a slightly higher pore pressure increase before slip is induced. Planes imaged at similar orientations in our catalog become quiescent following mitigation efforts at injection well EWS2, while planes striking NW continue to slip. This suggests that the mitigation efforts were effective in preventing further diffusion of pore pressure into underlying seismogenic faults. As pore pressure slowly diffused near the faults, it is plausible that NE-striking structures became inactive first because of the slight difference in their slip susceptibility under the reservoir state of stress.

5. Shear Wave Splitting

Observations of seismic anisotropy, the direction-dependent difference in elastic response to travelling energy, provide the potential means to gather insight on fluid-pressure interactions in inaccessible rocks and subsurface media. Specifically, shear wave splitting analysis (SWS) has been widely used to infer details about the state of stress at a variety of length scales in the earth.

However, work remains before establishing an unambiguous understanding of the mechanisms that cause this phenomenon.

Crampin *et al.* (1984) proposed SWS as a mechanism for stress forecasting large seismic events and eruptions, citing that the underlying cause of crustal shear wave anisotropy is a network of fluid-filled microcracks that pervade most shallow settings. Under the influence of differential stress, preferentially aligned cracks (i.e. those subparallel with minimum horizontal stress) are closed. Laboratory experiments demonstrate that this has the effect of polarizing shear wave energy such that wave components travel slower in the direction parallel to the cracks that remain open (Nur 1976).

We used a modified version of the SplitLab package in Matlab (Wustefield et al., 2008) to perform shear wave splitting measurements at the three stations within a 45° incidence window above the earthquakes (GRWE, GRCO, and GRRO). This ensures that the detected anisotropy signature is not sensitive to elastic anisotropy of layered media in the reservoir. The earthquakes were taken from the Greeley catalog between September 2016 and November 2017. Of the 385 earthquakes analyzed, 186 yielded acceptable shear wave splitting results. The only pre-processing that was implemented for each measurement was a detrending and normalization by the time series mean. No filters were used, and each measurement window was picked by hand. The SplitLab function package employs the eigenvalue method of Silver and Chan (1991) and the rotation-correlation method of Ando (1984) to determine SWS measurements. Figures 14 and 15 show example splitting results.

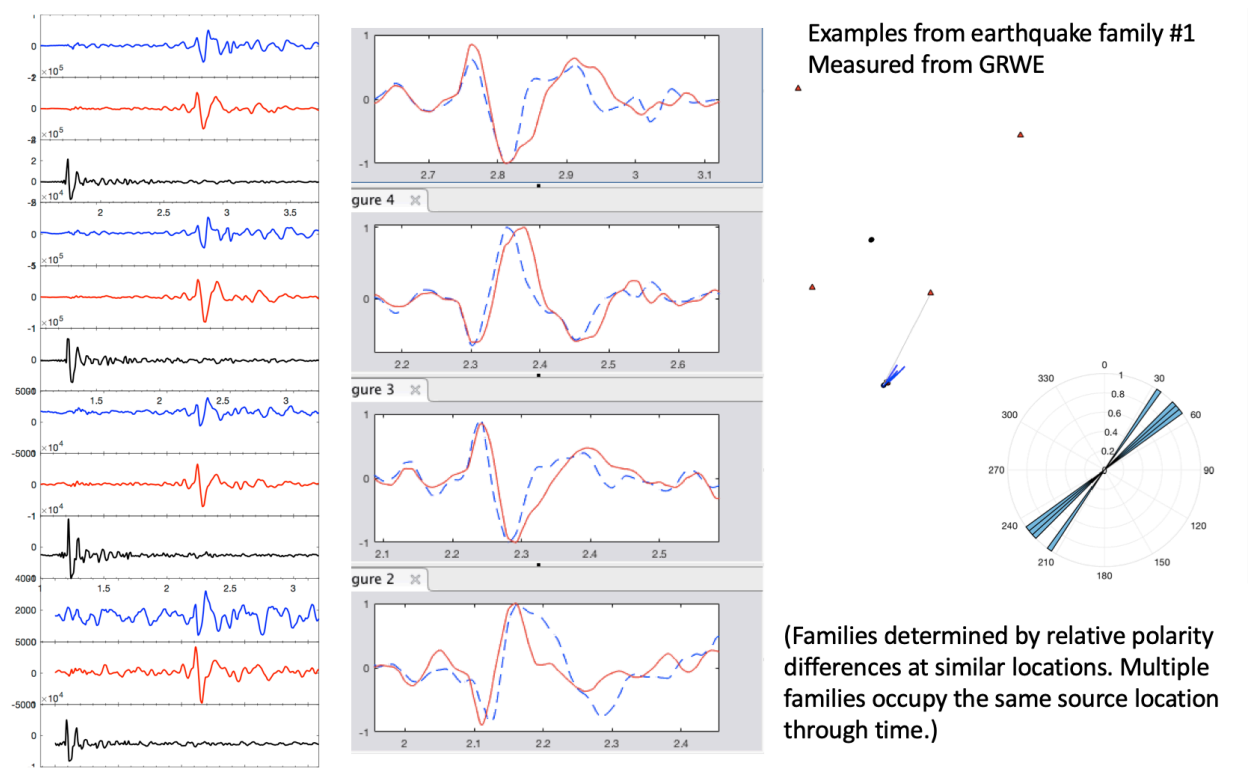

Figure 14. Shear wave splitting results for 4 nearly collocated earthquakes as recorded at station GRWE. Left plots show vertical components in black and horizontal components in red and blue. Fast axis polarization direction orientations are shown in right panel.

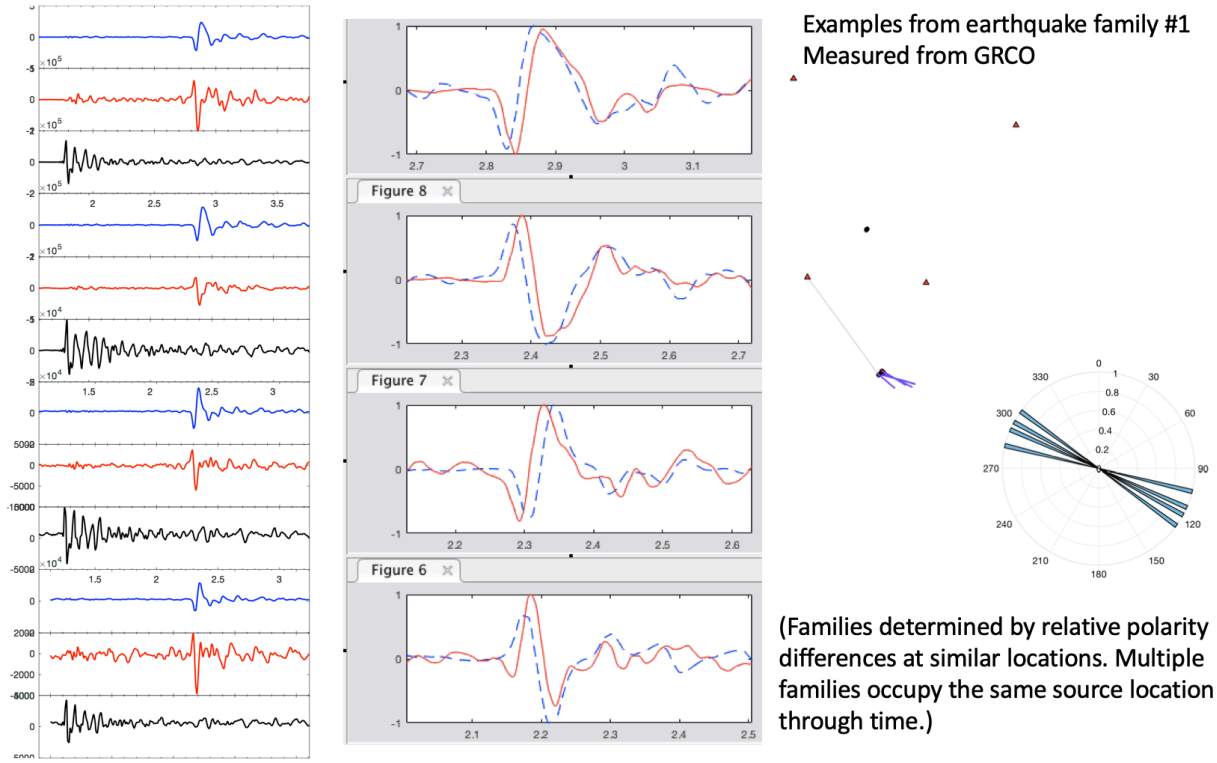

Figure 15. Shear wave splitting results for the same 4 earthquakes as in Figure 14, but now recorded at station GRCO. Left plots show vertical components in black and horizontal components in red and blue. Fast polarization axis direction orientations are shown in right panel. The change in splitting fast axis polarization orientation for the same events over such a small area indicates the strong path dependence of the splitting results.

We find that the shear wave splitting results are highly path dependent, and high quality event locations are necessary for accurate shear wave splitting analysis. We find that shear wave splitting measurements from Greeley suggest a high level of heterogeneity in the subsurface, perhaps indicating more than one dominant crack orientation in the basement. There is a strong dependence of SWS variability in event-station geometry, relative to structures in the subsurface. Potential changes become apparent by identifying clusters of similar measurements, and relating them to specific locations through time.

6. Temporal variation in seismic velocity via ambient noise interferometry

We have also begun to investigate temporal changes in upper crustal relative seismic velocity (dv/v) with the six years of continuous NE Colorado seismic data. Seismic velocity variations can be determined by calculating daily ambient noise cross-correlations using the Python package MSNoise (Lecocq et al. 2014.) Such velocity variations have been observed in other regions and have been associated with volcanic activity, geothermal deformation, groundwater fluctuation, and other processes that alter media over short timespans. The injection of wastewater into the Denver Basin induces earthquakes by increasing the pore pressure in the subsurface (Yeck et al., 2016; Brown et al., 2017.) This same mechanism may also result in

increases in the seismic velocity of the injection interval. Ugalde et al. (2014) performed a study of dv/v in the induced seismicity region near Paradox Valley, Colorado. They did not see a dv/v signal that they could attribute to injection in the one year of data that they observed. Instead, they found that variations in noise sources play a big role, as well as seasonal near surface changes. More recently, Ogwari (2019) reported seismic velocity increases prior to periods of seismicity in a region of induced seismicity. We have nearly six years of continuous seismic data as well as detailed injection reports in our study area east of Greeley, Colorado, and will use this to explore possible variations in dv/v. We will explore whether velocity changes, if observed, correlate with the temporal evolution of injection, pore pressure, and seismicity. In our initial analysis presented here we correlate ambient noise at 5 stations within 20 km of the center of Greeley seismicity for the month of February, 2019, as a sample quiet month. This was a month when no earthquakes were recorded and injection rates at the two nearby wastewater disposal wells (NGL C4A and EWS2) were at average values. By comparing a ten-day moving window average of dv/v to daily dv/v measurements (Figure 16) we can see that there is only minor short-term variation through the month of February. This indicates that the correlation remains relatively stable over short time periods during this month of background activity. We will explore whether dv/v measurements during 2014-2019 correlate with monthly injection activity or periods of seismicity, since these both modify the state of subsurface stress. These studies for the longer time period are still ongoing.

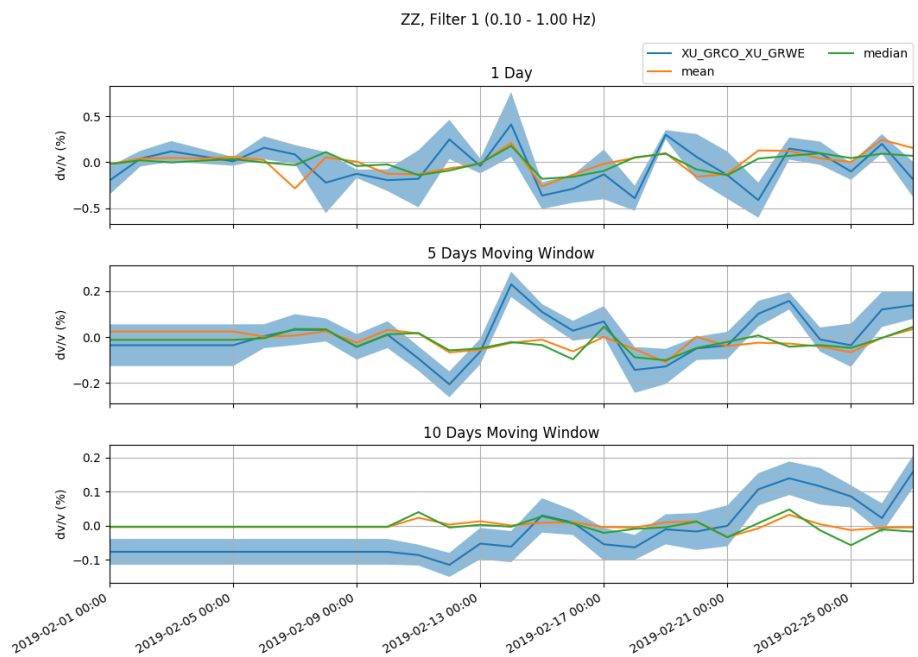

Figure 16. dv/v % - Percent velocity variations through the month of February, 2019. No seismicity was recorded during this month and local injection volumes were relatively average. The GRWE-GRCO correlation (blue line with faint blue error), the main station couple that transects the seismicity zone, exhibits greater short-term velocity variations than the mean and median of all five stations. The 10 Day Moving Window plot (bottom) indicates that there is only minor velocity variation through the month.

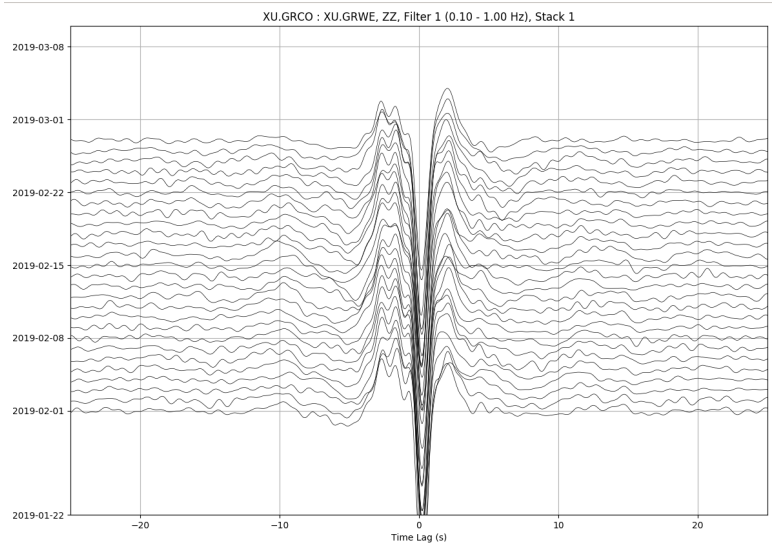

Figure 17. Daily ambient noise cross-correlation function between stations GRCO and GRWE (2 km apart) for the month of February 2019. Each daily cross-correlation function is a stack of 48 30-minute correlation functions, which are spectrally whitened and filtered from 0.1-1 Hz.

7. Presentations at Professional meetings

Chon, E. and A. Sheehan (2018), Shear Wave Anisotropy Measurements from Induced Earthquakes in the Wattenberg Disposal Zone, CO, Banff 2018 International Induced Seismicity Workshop, October 24-27, 2018, Banff, Alberta, Canada.

Chon, E., and A. Sheehan, (2018). Repeating Earthquakes and Shear Wave Anisotropy Measurements from an Induced Seismicity Case Study, Wattenberg Disposal Zone, CO, American Geophysical Union, poster S33C-0606. Washington D.C., December 2018.

Chon, Enrique, (2019). Repeating Earthquakes and Shear Wave Anisotropy Measurements from an Induced Seismicity Case Study, Wattenberg Disposal Zone, 3rd Schatzalp Workshop on Induced Seismicity, Davos, Switzerland, March 5-8, 2019. Oral presentation.

Chon, E., and A. F. Sheehan (2020), Effects of seismicity mitigation practices captured in time-lapse of induced earthquake fault activation (abstract), Seismological Society of America Annual Meeting, Albuquerque, New Mexico, April 2020.

Clifford, T., Sheehan, A. F., Ball, J. S. (2020), Temporal Variations in Seismic Velocity via Ambient Noise Interferometry: Application to Wastewater Injection and Induced Seismicity, Seismological Society of America Annual Meeting, Albuquerque, New Mexico, April 2020

8. Related service and outreach

Federal Emergency Management (FEMA) Quakesmart workshop, Golden, Colorado, 9/19/18. QuakeSmart is a FEMA National Earthquake Hazards Reduction Program (NEHRP) initiative to help businesses in at-risk earthquake communities implement earthquake mitigation actions. Gave a presentation and answered questions about induced earthquakes.

Arapahoe County land planning division, public works and development - contacted by them and provided them with background information on induced seismicity and wastewater disposal as they collected information for informing their wastewater disposal well policy. Answered questions, provided information. Arapahoe County is updating its Land Development Code, and was reaching out to operators, industry group representatives, science and engineering experts, and regulators to get information and perspective. 10/19/18.

Advisory Board and Stakeholders meeting, August 26, 2019. Held full-day meeting at CU to present results of Colorado induced seismicity research by department of Geological Sciences, Department of Civil Engineering, Colorado Natural Hazards Center. Attendees from industry (Apache, MEQ Geo, AECOM), state regulators, academics, USGS, Los Alamos National Lab, law firms, Keystone Policy Center, City of Greeley, FEMA.

On-camera interview by Fox31 about Colorado induced earthquakes, January 2018.
Operated 15 station telemetered seismic network in northeast Colorado. Data telemetered to CU and then to USGS and IRIS. Data immediately open to all and was used by USGS as well as by industry (contractors monitoring seismicity for wastewater disposal companies, for example).

Project website: https://earthquake.colorado.edu

9. Project Data

Seismic waveforms from this project are archived at the IRIS DMC and have been open to all users immediately.

1. Anne Sheehan (2016): USGS NEHRP - Greeley. International Federation of Digital Seismograph Networks. FDSN code XU (2016-2020) Other/Seismic Network. doi:10.7914/SN/XU_2016. http://www.fdsn.org/networks/detail/XU_2016/

2. Anne Sheehan (2014): Greeley Colorado RAMP Deployment 2014. International Federation of Digital Seismograph Networks. FDSN code XU (2014-2015) Other/Seismic Network. doi:10.7914/SN/XU_2014. http://www.fdsn.org/networks/detail/XU_2014/

Our earthquake catalog for 2014-2019 is published as an appendix to this report.

Our project web site is earthquake.colorado.edu, and includes links to helicorder views of the real-time data, station maps, and publications.

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Appendix 1: NE Colorado Earthquake Catalog, June 2014-May 2019

Year,MM,DD,HR,MM,Sec,Latitud,Longitud,Depth (km, rel to surface),Ml
2014,6,6,19,1,48.4,40.504,-104.689,9.72,1.3
2014,6,6,19,41,30.3,40.47,-104.652,6.01,1
2014,6,7,21,25,31.2,40.455,-104.631,6.18,0.2
2014,6,9,11,32,50.3,40.426,-104.618,5.37,0.4
2014,6,9,13,41,29,40.453,-104.618,4.89,0.9
2014,6,9,23,20,53,40.457,-104.627,5.98,1
2014,6,9,23,46,25.4,40.456,-104.628,6.24,0.6
2014,6,10,23,25,47.1,40.421,-104.615,9.23,1.2
2014,6,11,14,10,55.1,40.454,-104.621,5.1,0.8
2014,6,11,15,13,41.1,40.455,-104.632,6.99,1
2014,6,12,6,1,21.3,40.455,-104.627,5.95,1.2
2014,6,12,6,25,48.6,40.47,-104.679,0,0.1
2014,6,16,15,7,36.2,40.439,-104.631,6.37,0.8
2014,6,17,11,18,16.5,40.454,-104.628,5.88,1.2
2014,6,17,12,58,21.9,40.454,-104.626,5.72,0.3
2014,6,19,7,17,17.8,40.432,-104.623,5.32,0
2014,6,19,22,38,27.1,40.427,-104.617,5.18,1
2014,6,20,10,56,11.8,40.452,-104.613,5.45,0.6
2014,6,21,10,22,38.1,40.456,-104.617,5.2,0.5
2014,6,21,16,35,14.8,40.435,-104.626,4.22,0.5
2014,6,22,2,1,16,40.437,-104.622,5.21,-0.2
2014,6,22,4,48,37,40.453,-104.628,6.03,0.5
2014,6,22,6,46,12.6,40.437,-104.621,5.34,0.7
2014,6,22,9,5,54.8,40.431,-104.616,4.5,0.2
2014,6,22,9,29,28.2,40.454,-104.61,5.87,1.7
2014,6,22,10,10,55.7,40.455,-104.605,5.28,0.1
2014,6,22,12,55,17.8,40.454,-104.609,4.34,0.5
2014,6,22,13,26,32,40.452,-104.612,5.97,1.5
2014,6,22,14,11,59.1,40.452,-104.614,5.87,0.8
2014,6,22,14,19,12.9,40.452,-104.613,5.81,0.8
2014,6,22,19,28,12.5,40.448,-104.623,8.02,0.5
2014,6,22,21,0,37.1,40.454,-104.614,6.79,1.1
2014,6,22,21,2,29,40.453,-104.613,6.06,0.7
2014,6,22,21,26,39.2,40.455,-104.607,6.01,0.7
2014,6,22,22,36,45.8,40.453,-104.613,5.93,0.8
2014,6,22,22,40,33.7,40.451,-104.594,6.99,0.7
2014,6,22,23,3,52.3,40.454,-104.61,6.12,0.4
2014,6,23,0,31,25.7,40.436,-104.623,5.37,0.4
2014,6,23,4,10,13.7,40.453,-104.611,6.02,0

2014,6,23,6,5,8.2,40.454,-104.625,4.77,0.3
2014,6,23,8,13,51,40.444,-104.619,4.85,0.1
2014,6,23,8,38,18.9,40.44,-104.623,6.29,0.2
2014,6,23,12,10,32.1,40.452,-104.613,4.86,0.3
2014,6,23,12,36,10.1,40.437,-104.62,5.51,0.5
2014,6,23,18,3,58.5,40.453,-104.61,6.1,1
2014,6,23,18,10,49.6,40.452,-104.612,6.04,0.6
2014,6,23,18,16,15.6,40.455,-104.604,4.9,0.3
2014,6,23,18,27,13.4,40.454,-104.612,6.1,2.7
2014,6,23,18,58,15.8,40.453,-104.611,4.67,1
2014,6,23,19,1,27.6,40.454,-104.613,6.08,1.5
2014,6,23,19,25,29.7,40.456,-104.603,5.14,0.5
2014,6,23,19,38,55.8,40.454,-104.608,5.27,0.8
2014,6,23,19,58,57.9,40.457,-104.604,5.22,0.5
2014,6,24,1,9,2.8,40.455,-104.611,6.03,0.6
2014,6,24,1,9,35.6,40.454,-104.612,6,1.2
2014,6,24,1,21,39.1,40.455,-104.612,6.16,1.1
2014,6,24,3,14,28.1,40.456,-104.608,5.97,0.6
2014,6,24,3,45,55,40.453,-104.598,6.69,0.2
2014,6,24,3,46,15.7,40.454,-104.616,6.54,0.2
2014,6,24,5,26,20.8,40.475,-104.578,3.43,0.3
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2014,6,24,21,27,23.9,40.454,-104.614,6.23,0.5
2014,6,24,22,57,32.9,40.453,-104.61,5.53,0.3
2014,6,25,0,28,59.5,40.456,-104.609,5.94,0.4
2014,6,25,0,34,46.4,40.453,-104.615,6.03,0.7
2014,6,25,1,4,29,40.455,-104.612,5.98,0.4
2014,6,25,1,10,21.4,40.455,-104.608,5.94,0.3
2014,6,25,1,21,37.3,40.452,-104.615,6.02,0.4
2014,6,25,2,26,7.1,40.453,-104.611,4.23,0.5
2014,6,25,5,6,24.4,40.456,-104.61,5.92,0.6
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2014,6,26,10,53,27.4,40.429,-104.611,4.44,0.5
2014,6,26,16,3,32.5,40.456,-104.616,4.59,1.5
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2014,6,26,22,6,9.3,40.43,-104.615,4.94,0.6
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2014,6,26,22,11,50.6,40.431,-104.618,5.12,1
2014,6,26,22,14,55,40.432,-104.616,4.55,0.7

2014,6,26,22,27,54.5,40.431,-104.615,4.81,0.4
2014,6,26,23,37,6.8,40.43,-104.617,5.1,0.3
2014,6,27,1,11,9.1,40.455,-104.611,6.01,0.4
2014,6,27,1,21,10.8,40.429,-104.617,4.99,0.7
2014,6,27,1,30,45.4,40.431,-104.62,5.13,0.9
2014,6,27,1,34,29,40.433,-104.618,4.72,0.9
2014,6,27,1,54,48.5,40.432,-104.62,5.18,0.6
2014,6,27,1,58,12.1,40.434,-104.619,4.89,0.4
2014,6,27,4,2,40.3,40.43,-104.617,4.7,0.5
2014,6,27,4,4,9.4,40.433,-104.62,5.14,0.2
2014,6,27,4,34,35.9,40.432,-104.621,5.2,0.1
2014,6,27,4,35,58.9,40.437,-104.619,6.55,0.1
2014,6,27,5,1,54.9,40.433,-104.618,4.85,0
2014,6,27,5,38,5.7,40.457,-104.612,6.08,0.6
2014,6,27,7,32,20.3,40.45,-104.619,4.63,-0.3
2014,6,27,15,55,14.8,40.459,-104.627,6.04,1.2
2014,6,27,16,13,58,40.414,-104.604,7.4,0.6
2014,6,28,5,54,53.9,40.457,-104.625,6.17,0.2
2014,6,28,6,7,27.4,40.46,-104.632,5.53,0.8
2014,6,28,7,13,53.1,40.46,-104.602,4.58,0.2
2014,6,28,7,30,14.9,40.427,-104.683,4.86,0
2014,6,28,8,5,17.3,40.456,-104.628,5.25,-0.1
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2014,6,28,12,15,6.2,40.454,-104.63,6.04,0.1
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2014,6,28,14,25,39.3,40.459,-104.628,6,1.6
2014,6,28,23,29,16.5,40.455,-104.617,4.73,0.1
2014,6,29,5,25,24.4,40.427,-104.616,4.26,0.3
2014,6,29,6,34,10.7,40.43,-104.623,4.11,0.2
2014,6,29,6,35,56.5,40.433,-104.62,4.64,0.5
2014,6,29,6,36,47.5,40.432,-104.623,4.1,0.3
2014,6,30,6,23,31.6,40.458,-104.616,4.32,-0.3
2014,6,30,9,22,7.7,40.429,-104.613,5.15,1.1
2014,6,30,11,48,59.7,40.455,-104.62,4,0.4
2014,7,1,2,44,30.7,40.43,-104.624,4.49,0.2
2014,7,1,13,21,41.2,40.431,-104.616,4.85,1.1
2014,7,1,18,47,15.8,40.455,-104.616,4.8,2.3
2014,7,2,14,34,21.8,40.451,-104.618,4.41,0.9
2014,7,3,10,32,8.9,40.453,-104.614,5.93,1.5
2014,7,3,10,33,29.7,40.461,-104.601,4.85,0.2
2014,7,3,10,35,37.4,40.455,-104.618,4.95,0
2014,7,3,10,36,0,40.453,-104.617,5.81,1.6

2014,7,3,10,42,32.1,40.453,-104.613,6.02,0.3
2014,7,3,10,45,7.6,40.453,-104.617,4.55,0.4
2014,7,3,11,18,18.7,40.453,-104.614,5.91,0.8
2014,7,3,13,29,23.4,40.454,-104.612,5.82,1.4
2014,7,3,13,30,0.4,40.469,-104.587,1.42,0.2
2014,7,3,13,32,34.4,40.455,-104.611,5.55,0.9
2014,7,3,14,33,55.5,40.457,-104.607,6.05,1.2
2014,7,3,14,36,9.5,40.455,-104.61,6.19,0.9
2014,7,3,14,40,8.7,40.455,-104.613,5.56,0.8
2014,7,3,18,4,41.9,40.456,-104.605,6.28,0.5
2014,7,4,19,43,55.1,40.429,-104.612,4.75,0.5
2014,7,5,14,36,36.7,40.452,-104.616,4.97,0.3
2014,7,5,20,20,29.6,40.454,-104.626,4.62,0.3
2014,7,6,14,11,12.4,40.453,-104.621,4.37,0.4
2014,7,7,20,51,1.9,40.453,-104.629,6.2,0.8
2014,7,8,8,11,50.8,40.445,-104.627,6.39,0.4
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2015,4,18,18,5,42.4,40.454,-104.615,6.73,0.4
2015,4,18,18,8,5.4,40.458,-104.606,5.06,0.3
2015,4,18,22,24,8.3,40.454,-104.605,5.88,0
2015,4,19,0,2,15,40.431,-104.619,3.91,-0.2
2015,4,19,0,48,44.7,40.459,-104.608,4.75,-0.3
2015,4,19,20,36,9.6,40.459,-104.617,5.58,1.6
2015,4,19,20,44,23.6,40.459,-104.618,5.54,0.9
2015,4,19,21,34,54.6,40.461,-104.615,5.88,1
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2015,4,24,6,1,46.7,40.445,-104.636,6.51,-0.2
2015,4,24,8,49,57,40.447,-104.628,5.81,0
2015,4,24,9,1,8.6,40.447,-104.629,5.77,0
2015,4,27,21,45,13.1,40.447,-104.633,6.17,0.8
2015,4,29,3,6,27.2,40.446,-104.634,6.15,0.1
2015,4,29,8,15,53,40.448,-104.634,6.17,0.8
2015,4,29,15,17,52.1,40.457,-104.608,4.1,0.5
2015,5,1,12,2,58.5,40.432,-104.611,4.82,0.4
2015,5,6,2,53,46.6,40.454,-104.623,6.41,0.3
2015,5,18,17,42,54,40.409,-104.623,3.99,0.1
2015,5,18,21,38,23.8,40.456,-104.615,5.9,0.9
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2015,6,3,9,0,39.4,40.447,-104.632,6.4,0.4
2015,6,6,7,18,12.7,40.444,-104.622,4.99,0
2015,6,7,3,16,42.4,40.446,-104.641,6.55,0.6
2015,6,28,3,7,28.2,40.446,-104.606,5.61,0.3
2015,6,28,5,50,58.2,40.453,-104.605,4.4,-0.4

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2015,7,8,11,13,26.4,40.452,-104.624,6.34,0.9
2015,7,9,17,32,0.9,40.444,-104.608,5.9,1.2
2015,7,10,18,10,11.5,40.451,-104.611,6.68,0.4
2015,7,26,12,46,47.1,40.476,-104.624,1.75,0
2015,7,27,4,46,37.3,40.438,-104.617,7.36,0
2015,7,27,12,26,52.5,40.436,-104.625,6.38,0.5
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2015,8,25,11,7,57.9,40.438,-104.612,6.01,0.5
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2015,9,18,20,5,49.8,40.467,-104.642,8.66,1
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2015,9,22,7,6,36.7,40.46,-104.618,5.46,0.2
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2015,10,22,7,27,43.5,40.463,-104.635,5.26,0
2015,10,24,4,32,57.5,40.457,-104.627,5.68,0.8
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2015,12,5,16,26,8,40.464,-104.594,3.52,0.3
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2015,12,16,16,40,36.8,40.447,-104.631,6.16,0.7
2015,12,17,5,24,4.6,40.463,-104.625,4.33,0.6
2015,12,17,6,37,38.6,40.476,-104.628,3.88,0.5
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2015,12,29,5,7,11.5,40.455,-104.615,5.63,0.2
2015,12,29,5,16,5.5,40.459,-104.615,6.04,1.5
2015,12,29,5,16,52.7,40.456,-104.616,5.85,1.5
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2015,12,30,10,19,14,40.454,-104.617,4.43,-0.4
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2016,1,23,3,18,31,40.476,-104.628,4.3,-0.4
2016,1,24,8,51,30.9,40.439,-104.614,6.3,1.4
2016,1,24,9,50,46.5,40.443,-104.638,6,0
2016,1,27,8,13,21.8,40.465,-104.602,4.38,1.3
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2016,3,6,11,50,47.8,40.46,-104.631,4.22,0.5
2016,3,6,13,10,15.9,40.432,-104.622,4.32,-0.2
2016,3,6,15,18,41.8,40.462,-104.626,4.15,0.5
2016,3,6,15,53,42,40.455,-104.623,4.93,0
2016,3,6,16,30,43.7,40.462,-104.628,4.82,0.1
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2016,4,23,2,32,54,40.446,-104.607,5.32,0
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2016,5,21,18,22,49.3,40.433,-104.625,5.87,0.7
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2016,6,6,8,26,30.7,40.447,-104.605,5.78,0.5
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2016,7,18,7,29,12.6,40.454,-104.633,6.14,0.7
2016,7,18,7,29,19.9,40.452,-104.632,6.14,1.4
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2016,7,19,23,27,10.3,40.452,-104.614,6.18,0.7
2016,7,20,16,17,58.4,40.458,-104.619,6.47,2.1
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2016,7,21,10,5,24.2,40.457,-104.617,6.16,0.2
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2016,8,14,16,47,35.2,40.428,-104.621,4.87,0.6
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2016,8,20,6,52,35.1,40.435,-104.634,5.7,1.7
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2016,8,23,3,16,39,40.458,-104.621,6.2,0.6
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2016,8,23,3,36,34.1,40.458,-104.625,6.07,1.5
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2016,8,23,5,12,51.8,40.458,-104.624,6.07,1
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2016,8,23,9,15,2.7,40.454,-104.623,5.71,0.4
2016,8,24,21,25,18.1,40.455,-104.623,6.06,0.8
2016,8,24,21,29,16.2,40.457,-104.62,5.42,1.3
2016,8,24,22,31,6.3,40.457,-104.623,6.24,1.7
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2016,8,24,23,6,27.8,40.453,-104.62,6.36,0.8
2016,8,24,23,9,2.3,40.454,-104.621,6.46,1.6
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2016,8,25,8,20,53.8,40.459,-104.624,5.24,0.7
2016,8,25,8,25,19.1,40.459,-104.623,6.05,2
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2016,8,25,8,48,21.6,40.461,-104.628,5.93,0.9
2016,8,25,9,13,41,40.458,-104.623,6.14,0.9
2016,8,25,10,0,55.2,40.455,-104.622,6.24,0.8
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2017,5,27,15,59,32.3,40.421,-104.618,5.68,1.5
2017,5,27,22,30,5,40.426,-104.627,6.71,0.6
2017,5,31,15,44,6.4,40.42,-104.62,5.76,1.6
2017,6,6,5,22,42.9,40.42,-104.618,5.89,0.8
2017,6,27,11,50,14.7,40.418,-104.619,5.75,0.9
2017,6,29,21,36,50.6,40.433,-104.647,6.79,1.7
2017,7,3,13,59,34.2,40.419,-104.622,5.75,1.5
2017,7,3,23,44,54.2,40.419,-104.623,5.7,1.8
2017,8,8,20,34,22.7,40.442,-104.592,5.37,1.1
2017,8,8,20,34,54.1,40.443,-104.593,5.55,0.4
2017,8,12,8,21,24.2,40.472,-104.629,5.58,1
2017,8,12,19,58,13.1,40.447,-104.599,5.69,0.9
2017,9,2,20,54,56.6,40.43,-104.609,6.75,1.7
2017,9,9,20,4,3.9,40.471,-104.634,6.45,1.2
2017,9,25,13,35,45.1,40.436,-104.638,7.12,0.9
2017,10,10,21,46,25.6,40.454,-104.636,6.98,2
2017,10,19,1,24,10.5,40.426,-104.611,5.39,0.5
2017,11,5,23,29,22.4,40.426,-104.657,6.44,1.5
2017,11,18,17,44,18.3,40.457,-104.648,4.85,1
2017,12,6,7,18,29.4,40.468,-104.636,6.36,0.9
2017,12,10,21,11,2.1,40.447,-104.651,7.87,2.5
2017,12,10,22,26,31,40.447,-104.649,8.01,2.2
2017,12,11,1,2,43.1,40.468,-104.638,6.46,1.1
2017,12,11,1,7,40.6,40.467,-104.637,6.48,0.9
2017,12,11,2,45,27.5,40.471,-104.636,5.08,0.7
2017,12,11,2,45,33.1,40.471,-104.638,5.11,0.9
2017,12,12,1,27,4.2,40.446,-104.648,8.05,0.8
2017,12,14,19,54,34.8,40.431,-104.636,6.83,1.4
2017,12,16,0,57,57.9,40.43,-104.636,6.72,0.9
2018,1,31,8,47,45.6,40.45,-104.606,6.29,2

2018,2,2,17,5,52.8,40.45,-104.606,6.27,2.6
2018,3,19,11,2,27.7,40.449,-104.604,6.22,1.2
2018,5,14,6,46,9.9,40.449,-104.605,6.21,1.4
2018,7,20,9,26,37.8,40.439,-104.621,7.19,2.2
2018,9,1,23,23,16.9,40.448,-104.649,8.35,1.7
2018,9,12,0,17,9.1,40.405,-104.627,4.75,1.8
2018,9,22,9,9,27.7,40.448,-104.647,8.4,1
2018,10,13,5,5,21,40.415,-104.611,5.48,0.8
2018,11,10,5,21,41.2,40.447,-104.646,8.45,1
2019,1,24,3,51,21.6,40.436,-104.623,6.08,0.6
2019,3,30,13,36,5.9,40.449,-104.607,5.79,2.1
2019,5,8,11,3,36.9,40.448,-104.605,5.51,2.1
2019,5,21,12,0,33.1,40.426,-104.614,5.19,1.6
2019,5,23,3,37,9.5,40.426,-104.614,5.37,0.7