Technical Memorandum 86-68330-2022-2

2021 Annual Report
Paradox Valley Seismic Network
Paradox Valley Unit, Colorado

Colorado River Basin Salinity Control Program
Upper Colorado Region

U.S. Department of the Interior May 2022

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Prepared by:

Bureau of Reclamation
Technical Service Center
Denver, Colorado

U.S. Department of the Interior **May 2022**

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LISA BLOCK Digitally signed by LISA BLOCK
Date: 2022.05.11 14:01:31 -06'00'

Prepared by: Lisa Block
Geophysicist, Geomorphology and Seismology Group, 86-68330

CHRISTOPHER WOOD
2022.05.11 14:57:59 -06'00'

Prepared by: Christopher Wood
Geophysicist, Geomorphology and Seismology Group, 86-68330

JUSTIN SCHWARZER Digitally signed by JUSTIN SCHWARZER
Date: 2022.05.12 09:12:55 -06'00'

Prepared by: Justin Schwarzer
Geophysicist, Geomorphology and Seismology Group, 86-68330

JUSTIN BALL Digitally signed by JUSTIN BALL
Date: 2022.05.12 09:05:05 -06'00'

Prepared by: Justin Ball
Geophysicist, Geomorphology and Seismology Group, 86-68330

JONG BEOM KANG Digitally signed by JONG BEOM KANG
Date: 2022.05.11 14:23:01 -06'00'

Prepared by: Jong Boem Kang
Civil Engineer, Geotechnical Laboratory and Field Support Group, 86-68550

GLENDA BESANA-OSTMAN Digitally signed by GLENDA BESANA-OSTMAN
Date: 2022.05.11 14:12:47 -06'00'

Prepared by: Glenda Besana-Ostman
Geologist, Geomorphology and Seismology Group, 86-68330

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2021 Annual Report Paradox Valley Seismic Network

Paradox Valley Unit, Colorado

Colorado River Basin Salinity Control Program
Upper Colorado Region

FENG SU Digitally signed by FENG SU
Date: 2022.05.13 11:57:31 -06'00'

Peer review by: Feng Su
Geophysicist, Geomorphology and Seismology Group, 86-68330

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Acronyms and Abbreviations

dB	decibel
EPA	Environmental Protection Agency
ft	feet
g	standard acceleration of gravity, equivalent to 9.80665 m/s^2
GMPE	ground motion prediction equation
gpm	gallons per minute
km	kilometers
l/min	liters per minute
MASIP	Maximum Allowable Surface Injection Pressure
M_D	duration magnitude
Mgal	millions of gallons
M_L	local magnitude
MPa	MegaPascal
MSL	Mean Sea Level
M_W	Moment magnitude
NGA	Next Generation Attenuation (Model)
NW	Northwest
psi	pounds per square inch
PGA	peak ground acceleration
PVB	Paradox Valley Brine
PVSN	Paradox Valley Seismic Network
PVU	Paradox Valley Unit
SE	Southeast
UIC	Underground Injection Code
USGS	United States Geological Survey

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Paradox Valley Seismic Network

I. Introduction

The Paradox Valley Seismic Network (PVSN) monitors earthquakes induced by injection operations at the Bureau of Reclamation's (Reclamation) Paradox Valley Unit (PVU) deep disposal well, as well as local naturally occurring earthquakes. This report summarizes PVSN operations and the data recorded during calendar year 2021. We provide project background information in Section II, including the history of PVU injection operations and details of the seismic network. In Section III, we present PVSN network operations during 2021, including maintenance of the seismic stations and data acquisition systems and annual network performance. The earthquake data recorded during the year are discussed in Section IV and compared to historical seismicity trends.

II. Project Background

A. Paradox Valley Unit

Reclamation's PVU, a component of the Colorado River Basin Salinity Control Program, intercepts salt brine that would otherwise flow into the Dolores River, a tributary of the Colorado River. PVU is in western Montrose County, approximately 90 km southwest of Grand Junction, Colorado and 16 km east of the Colorado-Utah border (Figure II-1). The Dolores River flows from southwest to northeast across Paradox Valley (Figure II-2), which was formed by the collapse of a salt-cored anticline (Figure II-3). Due to the presence of the salt diapir underlying Paradox Valley, groundwater within the valley is nearly eight times more saline than ocean water. To prevent this highly saline groundwater from entering the Dolores River and degrading water quality downstream, the brine is extracted from nine shallow wells within the valley near the Dolores River. The diverted brine is injected at high pressure into a deep disposal well, designated as PVU Salinity Control Well No. 1. The disposal well is located approximately 1.5 km southwest of Paradox Valley, near the town of Bedrock (Figure II-2).

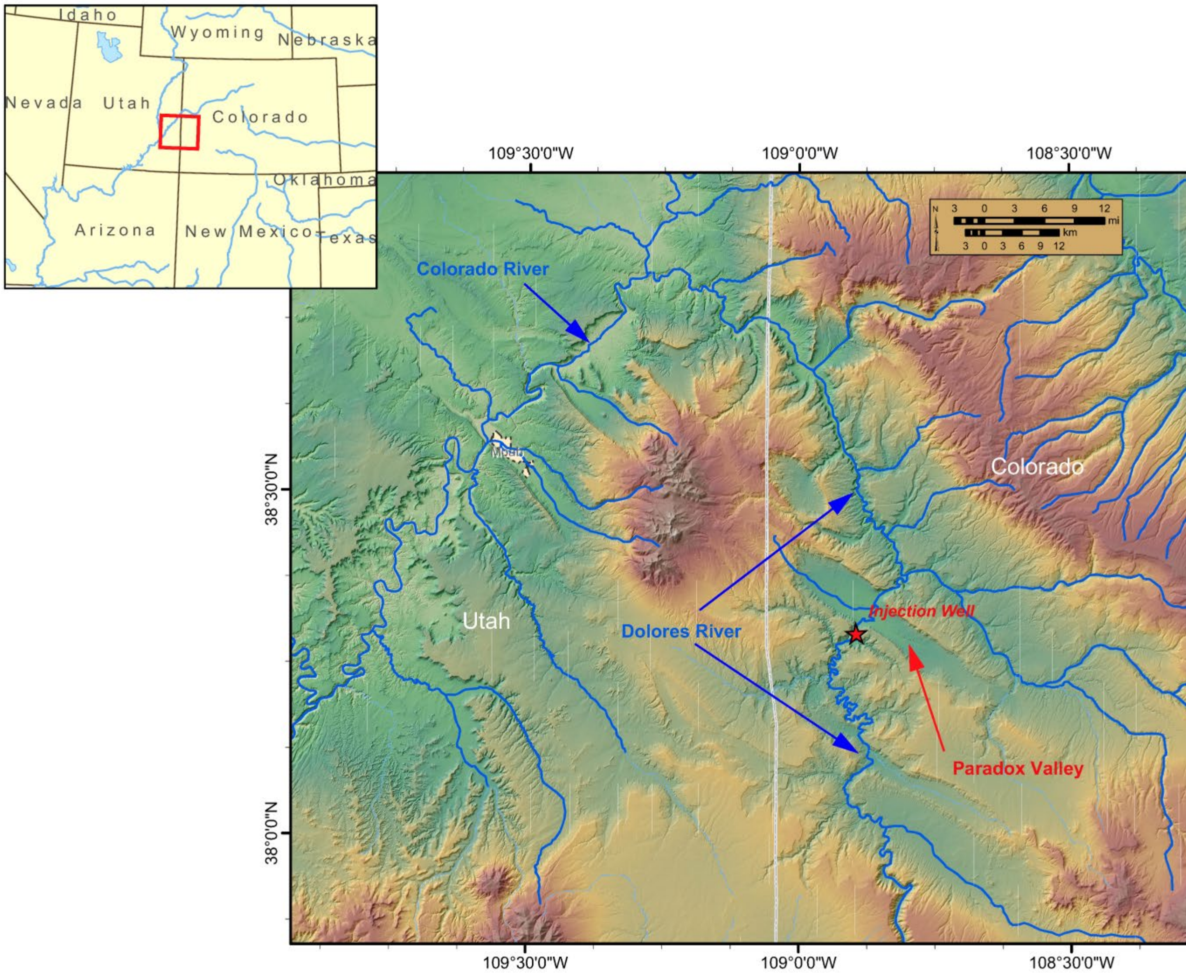
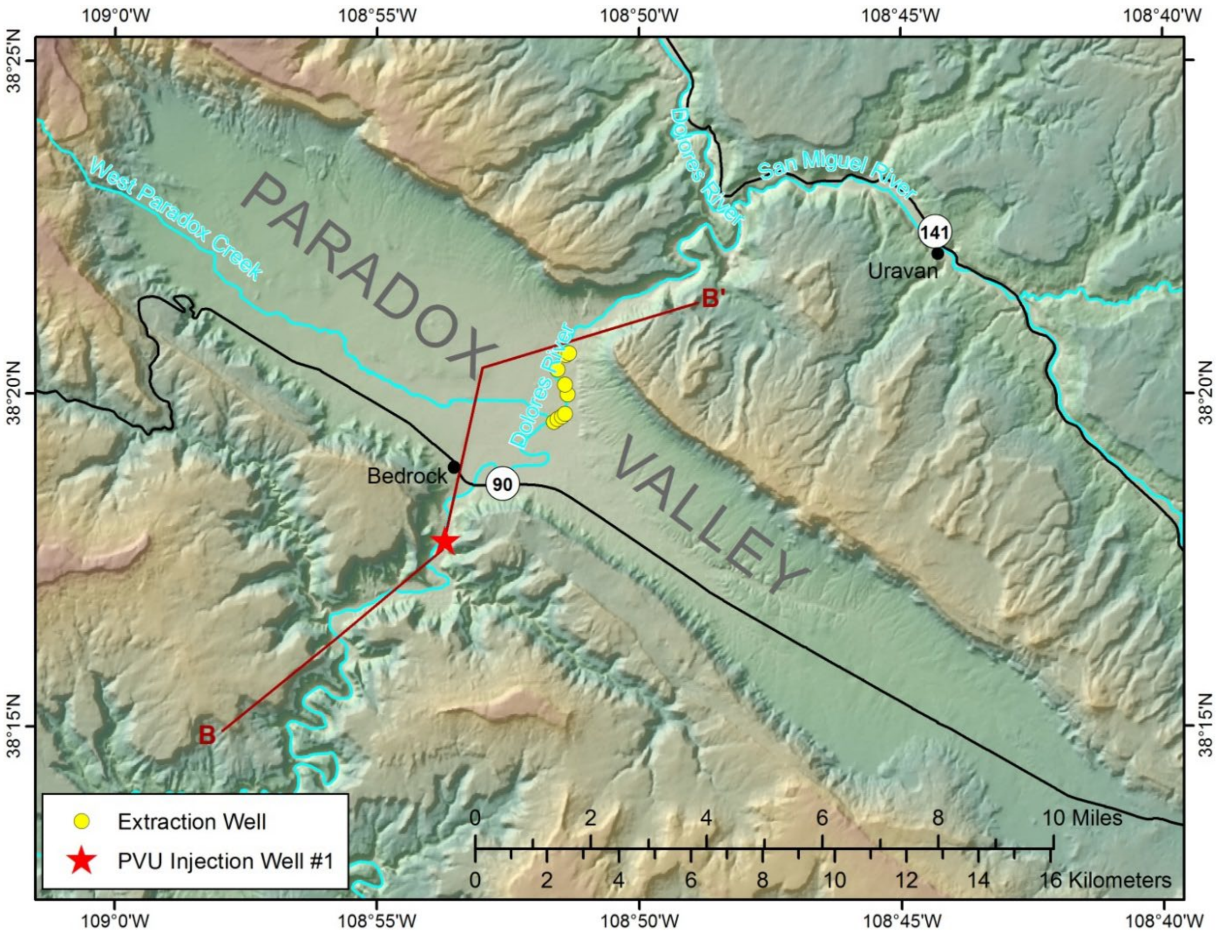


Figure II-1: Location of the deep injection well at Reclamation's Paradox Valley Unit in western Colorado (red star).



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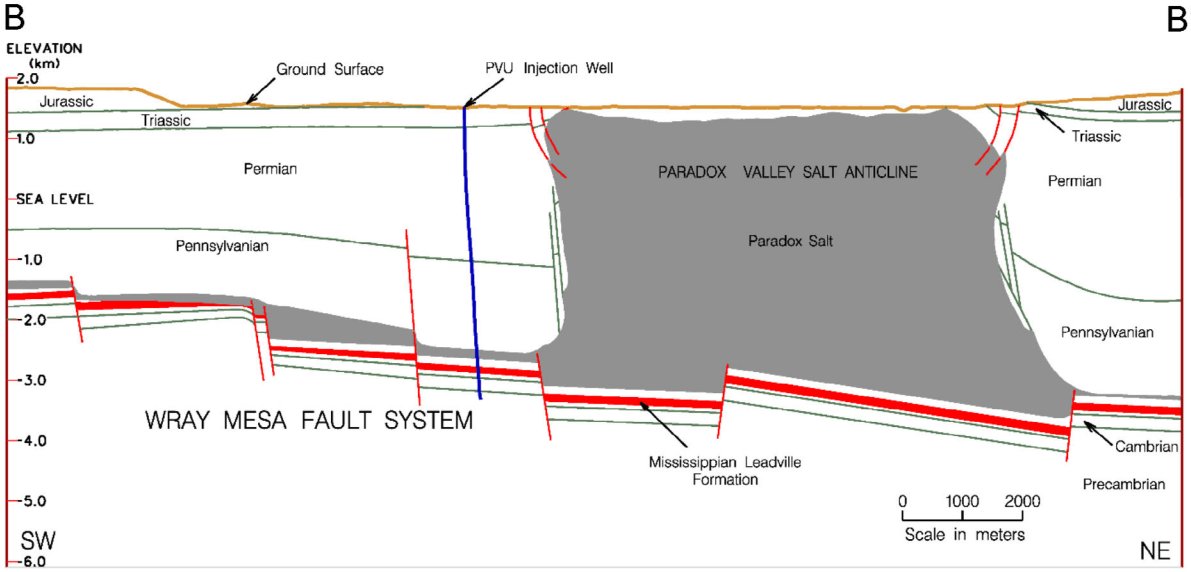
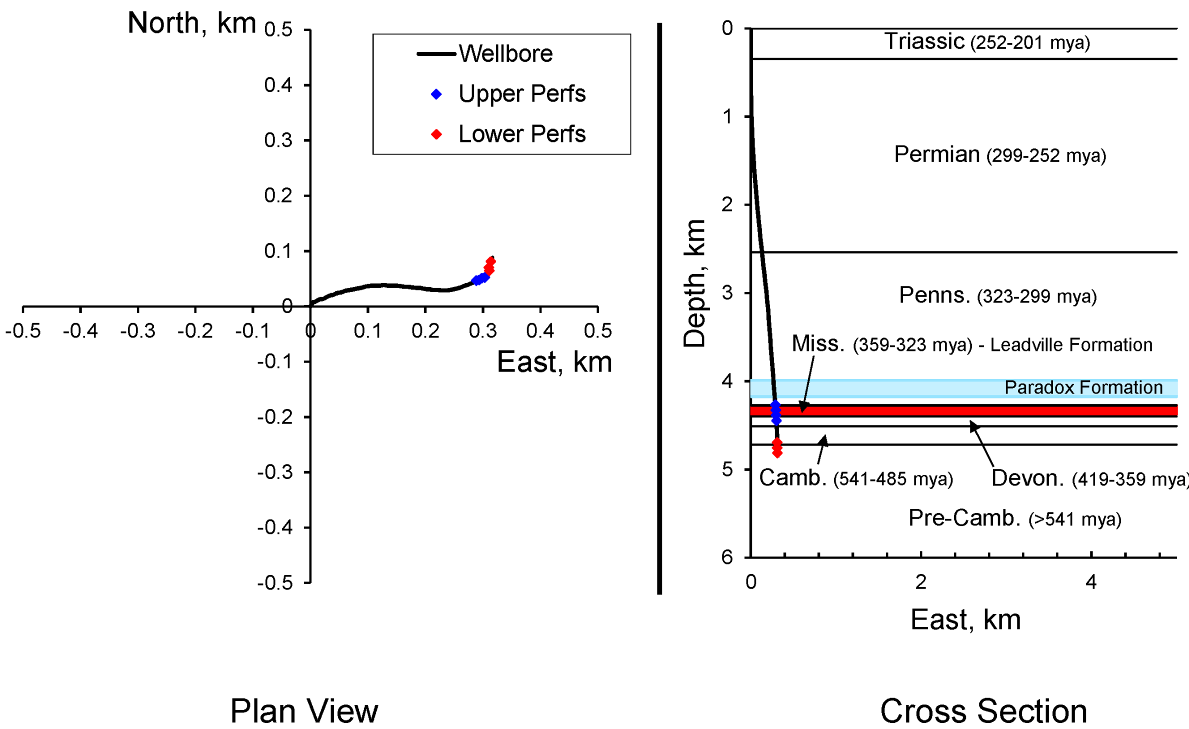


Figure II-3: Vertical cross section roughly perpendicular to Paradox Valley, looking to the northwest. The location of the cross section is shown in Figure II-2. Based on figure from Bremkamp and Harr (1988).

PVU Salinity Control Well No. 1 was completed in 1987 to a total depth of 4.88 km (approximately 16,000 ft). The well was built to Environmental Protection Agency (EPA) Underground Injection Code (UIC) Class I standards ("Isolate hazardous, industrial and municipal wastes through deep injection") but was permitted in 1995 by EPA as a Class V disposal well ("Manage the shallow injection of non-hazardous fluids"). The well penetrates Triassic- through Cambrian-age sedimentary rock layers and granitic Precambrian basement (Figure II-3). Based on regional core and log data interpretation, the Mississippian Leadville carbonate was selected as the primary injection zone with the upper Precambrian as a secondary zone (Bremkamp and Harr, 1988). The overlying Paradox salt formation acts as a confining layer. The well casing of PVU Well No. 1 (constructed of Hastelloy C- 276, a nickel-molybdenum-chromium alloy) was perforated at a spacing of ~20 perforations per meter in three major intervals between 4.3 km and 4.8 km depth. Plan and vertical views of the wellbore, with near-wellbore stratigraphy and the perforation intervals, are shown in Figure II-4.



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B. PVU Injection Operations

Between 1991 and 1995, Reclamation conducted a series of seven injection tests, an acid stimulation test, and a reservoir integrity test at PVU. These tests were conducted to qualify for a Class V permit for deep disposal from the EPA. Near-continuous, long-term brine disposal began in July 1996, after the EPA granted the permit. During long-term injection, Reclamation instituted six major changes in operations. Five of these changes were implemented to mitigate the potential for unacceptable seismicity, and one change was made to improve injection economics. The seven time periods defined by these operational changes are considered separate injection phases, as described below. Plots of the daily average injection flow rates, daily average surface injection pressures, daily average downhole pressures (at a depth of 4.3 km), and cumulative injected fluid volumes during PVU injection operations are shown in Figure II-5. The downhole pressures shown were computed from measured surface pressures using the density of the brine column in the wellbore.

1. Phase I - July 22, 1996 to July 7, 1999

During this initial phase of near-continuous injection, brine was injected at a nominal flow rate of 345 gpm (~1306 l/min), resulting in an average surface pressure of about 4,950 psi (~34.1 MPa). This corresponded to approximately 11,800 psi (~81.4 MPa) downhole pressure at 4.3 km depth. To maintain this flow rate, three constant-rate pumps were used, each operating at 115 gpm. The surface pressure occasionally approached the wellhead pressure safety limit of 5,000 psi. This safety limit was based on the operational specifications of the injection and wellhead equipment. It also corresponded to the maximum allowable surface injection pressure (MASIP) defined in the injection permit issued by EPA, which is intended to prevent a breach of the geologic confining layer (the Paradox salt). When the surface pressure approached the MASIP, the injection rate was reduced by shutting down one or two of the injection pumps, allowing the pressure to drop a few hundred psi before returning to a three-pump operation. These partial shutdowns occurred frequently and had typical durations of a few minutes to a few days. This operational protocol resulted in relatively constant surface and downhole pressures (Figure II-5). Periodic maintenance shutdowns of all pumps also occurred and lasted for one to two weeks. In mid-1997, a 71-day total shutdown was needed to replace the operations and maintenance contractors. The *Phase I* protocols resulted in an overall average injection rate of roughly 300 gpm (1136 l/min), and the total volume of fluid injected was 427 Mgal (1.6 x 10^9 liters).

The injectate during *Phase I* was a mixture of 70% Paradox Valley Brine (PVB) and 30% freshwater from the Dolores River. A geochemical study had predicted that if 100% PVB were injected, it would interact with connate fluids and the dolomitized Leadville Limestone at the initial formation temperatures and pressures, resulting in the precipitation of calcium sulfate. This precipitation would lead to reduced permeability (Kharaka et al., 1997).

2. Phase II - July 8, 1999 to May 27, 2000

Following a local magnitude M_L 3.6 earthquake in June 1999 and an M_L 3.5 earthquake in July 1999, PVU altered the injection schedule to include a 20-day total shutdown (shut-in) every six months. Prior to these events, it was noted that the rate of seismicity in the near-wellbore region (i.e., within about a 2-km radius around the wellbore) decreased during and following unscheduled maintenance shutdowns. Similar decreases in seismicity also were observed during the shutdowns following the injection tests of 1991 through 1995. It was therefore hypothesized that the biannual shutdowns might reduce the potential for inducing large-magnitude earthquakes by allowing extra time for the injectate to diffuse from the pressurized fractures and faults into the formation rock matrix. When injecting during this phase, the average flow rate was the same as during Phase I. One hundred and eighteen Mgal (4.5 x 10^8 liters) of fluid were injected during Phase II.

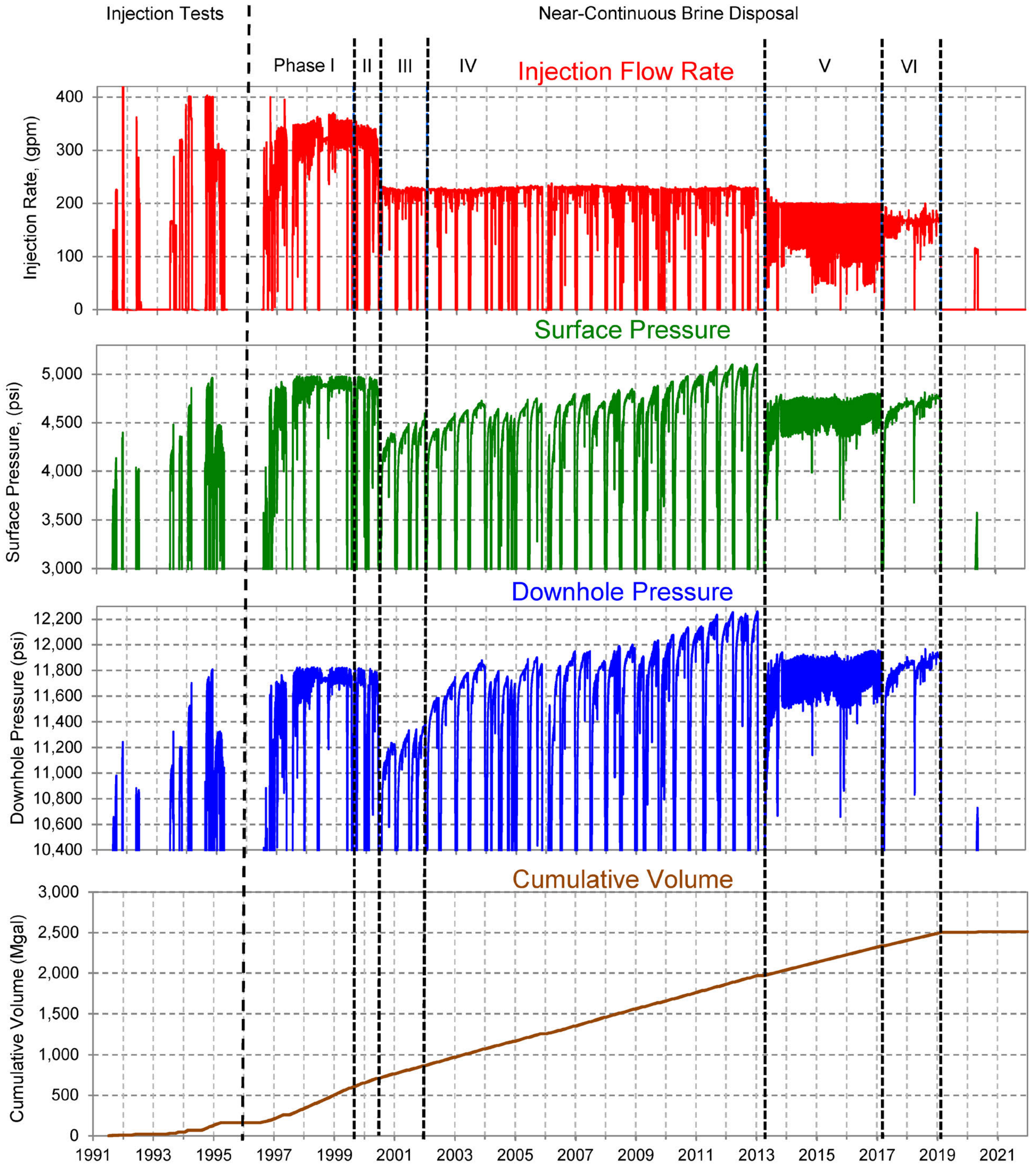


Figure II-5: Daily average injection flow rate, daily average surface injection pressure, daily average downhole pressure at 4.3 km depth, and cumulative volume of brine injected during PVU injection operations. The downhole pressures are computed from the measured surface pressures using the density of the brine column in the well. The vertical dashed lines delineate the injection phases discussed in the text.

3. Phase III - June 23, 2000 to January 6, 2002

Immediately following an M_L 4.3 earthquake on May 27, 2000, injection ceased for 28 days. During this shutdown period, Reclamation evaluated the existing injection protocol and its effect on induced seismicity. The decision was made to reduce the injection flow rate, expecting that this change would likely reduce the potential for inducing large-magnitude earthquakes. On June 23, 2000, PVU injection resumed using two pumps rather than alternating between two and three pumps. The biannual 20-day shutdowns were maintained. The nominal flow rate during *Phase III,* while injecting using two pumps, was 230 gpm (~871 l/min). Accounting for the two 20-day shut-ins per year, the average injection flow rate was approximately 205 gpm (776 l/min), a decrease of about 32% compared to *Phase I*. During this phase, 156 Mgal (5.9 x 10^8 liters) of fluid were injected.

4. Phase IV - January 7, 2002 to January 24, 2013

During October 2001, the need to dilute PVB with fresh water prior to injection was re-evaluated. Lab testing of drill cores conducted in 1993 detected no evidence of precipitation or plugging for either a 70 % brine / 30 % freshwater mixture or for a 100 % brine mixture, at temperatures of 270 °F or 300 °F (Envirocorp Services and Technology Inc., 1993). In addition, temperature logging was performed multiple times between 1992 and June 2001 and recorded substantial near-wellbore cooling at the depth of the Leadville Formation (~70° to ~130° F decrease) (Subsurface Technology, 2001). The temperature measurements recorded in the upper Leadville in 2001 indicated "a super-cooled buffer zone, some distance from the well, which will prevent the creation of conditions favorable to calcium sulfate precipitation" (Subsurface Technology, 2001, pg. 18). Hence, if precipitation were to occur, it would not be near the wellbore perforations where clogging might be a concern (Nicholas, 2001). In addition, the high PVU injection pressures would likely act to keep fractures open within the target injection formations, even if some precipitation were to occur (McKinley, 2001). Further analyses indicated that, if precipitation occurs, its maximum expected rate is ~8 tons of calcium sulfate per day (Mahrer et al., 2003). To put this amount into perspective, injecting at ~230 gpm and assuming a brine density of 9.86 lbs/gal (17% denser than freshwater) results in a daily injection mass of ~1633 tons. The maximum expected precipitate, therefore, is only ~0.5% of the daily injection mass.

After considering this new information, the decision was made to begin injecting 100% PVB to partially offset the reduction in salt disposal rates resulting from the decreased injection rate implemented in *Phase III.* Injection of 100% PVB began on January 7, 2002, following the December-January 20-day shutdown, and has been maintained since. The injection rate implemented in *Phase III* (230 gpm) and biannual 20-day shutdowns were continued. The volume of fluid injected during *Phase IV* was 1,110 Mgal (4.2 x 10^9 liters).

Because of the decreased flow rate in *Phase III* and *Phase IV* compared to the earlier phases, the surface pressure remained below the MASIP of 5,000 psi for over a decade (mid-2000 to 2011). Hence, there was no need to frequently alter flow rates, as had been done during *Phases I* and *II*. Nevertheless, the continued injection during *Phases III* and *IV* resulted in a trend of increasing maximum surface and downhole pressures (Figure II-5). In addition, because of the increased density of the 100% PVB injected during *Phase IV* over the 70% PVB / 30% freshwater mix injected previously, the computed downhole pressures increased by ~300 psi immediately following the change to 100% brine in January 2002.

In response to the increasing surface injection pressures, Reclamation submitted a request to EPA in 2004 to increase the MASIP. EPA approved the request, pending infrastructure upgrades to increase the injection equipment pressure safety limit. In 2009, the PVU injection wellhead equipment was upgraded to a pressure safety limit of 10,000 psi. An increase in the MASIP to 5350 psi was formally incorporated into the injection permit reauthorization issued by EPA in August 2011.

5. Phase V - April 17, 2013 to March 12, 2017

An induced earthquake with M_L 4.4 (corresponding to moment magnitude M_W 4.0) occurred ~8 km northwest of the PVU injection well on January 24, 2013 (Block et al., 2014). In response to this earthquake, injection was halted while a reassessment of the seismic hazard associated with PVU injection was performed. Analyses of the seismic and injection data indicated that the potential for inducing large felt events would be reduced by decreasing the long-term average injection pressures (Block and Wood, 2009; Wood et al., 2016). Pressure-flow modeling indicated that reducing the flow rate would lead to a corresponding reduction in wellhead pressures. Forward modeling was used to evaluate the effect of different flow rates on wellhead pressures (Wood et al., 2016). In addition, the pressure-flow modeling indicated that changing the injection well shut-in schedule to one with shorter, more frequent shut-ins would result in a reduction in the average wellhead pressure, compared to the biannual 20-day shut-ins previously used.

As a result of these analyses, the decision was made in April 2013 to reduce the injection flow rate and increase the frequency of injection well shut-ins. Due to the lag time in obtaining pump plungers that would allow injection at a lower flow rate, injection was initially resumed on April 17, 2013, maintaining the flow rate at 230 gpm and implementing a 36-hour shut-in every week. On June 6, 2013, following the installation of the new plungers, the flow rate was reduced to 200 gpm, and the shut-in length was reduced to 18 hours, maintaining the frequency of one shut-in per week. A shut-in duration of 18 hours was chosen so that the total annual shut-in time would be approximately equivalent to that scheduled previously with the biannual 20-day shut-ins. Hence, the nominal flow rate during *Phase V* (200 gpm) was decreased by 13 % from that during *Phase IV* (230 gpm), and the total duration of planned shut-ins remained the same.

Because of the frequency of the new shut-in schedule, the durations of any unplanned shut-ins (such as those periodically required for equipment maintenance) were tracked, and those hours were subtracted from the weekly scheduled 18-hour shut-ins. The durations of unplanned shut-ins had not been tracked and subtracted from the biannual

20-day shut-ins during earlier injection phases, and hence the total shut-in time during previous years had sometimes varied substantially, depending on the number and duration of unplanned shut-ins required. Hence, while the nominal flow rate during *Phase V* was decreased by 13% from that during *Phase IV*, the effective decrease in flow rate was less than this value due to the difference in total shut-in time. The average flow rate during *Phase V* was 177 gpm, which is ~9.7 % less than the average flow rate of 196 gpm during the preceding three years (2010-2012). Three hundred and sixty-four Mgal (1.4 x 10^9 liters) of fluid were injected during this phase.

6. Phase VI - April 8, 2017 to March 4, 2019

Beginning on March 12, 2017, the injection well was shut in for 27 days. Injection was resumed on April 8 at a ~5 % reduced effective flow rate. These changes were made partially in response to the observation that the rates and magnitudes of PVU-induced earthquakes had been increasing for ~1.5 years. The occurrence of an M_D 2.9 earthquake nearly 13 km from the injection well (on 3/12/17) further influenced the decision to reduce the effective flow rates.

The reduced effective flow rate was initially achieved by changing the size of the plungers from 2.000" to 1.875", which reduced the nominal flow rate from 200 gal/min to 174 gal/min. At the same time, the duration of the weekly shut-ins was reduced from 18 hours to 6 hours. Two pumps were run continuously, except for the weekly plant shutdowns. Considering the weekly shut-ins, the effective average flow rate was 168 gal/min.

In September 2017, premature wear of the new 1.875" plungers forced the reinstallation of larger plungers in two of the three pumps (one 2.125" plunger and one 2.000" plunger). As a result, injection operations were changed to accommodate the larger plungers (and corresponding rate increase) by eliminating the six-hour weekly plant shutdown and starting daily pump shutdowns on the pumps with larger plungers. The weekly shutdown of the single pump with the 1.875" plunger continued. Injection was then continuous, with either one or two pumps running at any given time. The target daily injection volume was 242,000 gallons, corresponding to a target average injection rate of 168 gpm. Hence, the effective average flow rate remained the same as with the smaller plungers. The total volume of fluid injected during *Phase VI* was 167 Mgal (6.3 x 10^8 liters).

An induced earthquake with moment magnitude M_W 4.5 occurred ~1.6 km southwest of the PVU injection well on March 4, 2019 (Block et al., 2020). This earthquake was the largest PVU-induced earthquake to date and was substantially larger than the M_W 4.0 earthquake of January 2013. More than 2,000 aftershocks occurred in the first five months following the main shock, resulting in the highest near-well seismicity rates in 20 years. Analyses indicate that aftershocks will continue to occur for several years at gradually decreasing rates (Block et al., 2020). The PVU injection well had been shut down for a few hours at the time of the M_W 4.5 earthquake to accommodate equipment maintenance activities. The well remained shut down for more than a year while detailed analyses of the *Mw* 4.5 earthquake and its numerous aftershocks were conducted. This extended shutdown also allowed formation pressures and aftershock rates to decay substantially.

7. Operations since March 2019

Injection resumed on April 21, 2020 for a planned six-month test period. The purpose of the test was to evaluate how the well would perform after being shut in for more than a year. Specifically, the pressure response of the well was monitored to determine whether any potential near-wellbore precipitation in the injection formations during the extended shutdown has altered the injection pressure response. In addition, seismicity was closely monitored for any changes in induced seismicity response. Injection during this test was at a near-constant rate of 115 gpm, a 32% reduction compared to the flow rate during *Phase VI.*

The injection test was prematurely terminated on May 29, 2020, in response to a request by Reclamation management for an external peer review of injection operations. According to a transient analysis of the wellhead pressure data immediately following the injection test and comparison to historical PVU pressure data, "parallel early-time slopes and equal durations of storage effects from 2017 to 2020 suggest that the extended 2019 shut-in did not significantly alter the early-time transient behavior of the well" (Petrotek, 2021). However, the injection test report also states, "It is clear that a comprehensive falloff analysis would require a significantly longer period of time and the application of downhole pressure gauges". No change in the induced seismicity attributable to the injection test was observed. The well has remained shut down since May 29, 2020, while analyses of the injection and seismic data are continuing.

C. Seismic Monitoring

1. Paradox Valley Seismic Network

During the planning for PVU, it was recognized that earthquakes could be induced by the high-pressure, deep-well injection of brine. This was based on a comparison to other deep-well injection projects in Colorado, including the Rocky Mountain Arsenal, near Denver, and oil and gas extraction projects near Rangley (Gibbs et al., 1973; Hsieh and Bredehoeft, 1981; Nicholson and Wesson, 1990; Raleigh et al., 1976).

In 1983, eight years before the first injection at PVU, Reclamation commissioned a seismic monitoring network to characterize the pre-injection, naturally occurring seismicity in the Paradox Valley region, and to monitor earthquakes that might be induced once injection operations began. The Paradox Valley Seismic Network (PVSN) was the product of these efforts. Field equipment for an initial 10-station network was acquired and installed in 1983 by the U.S. Geological Survey (USGS), under a Memorandum of Agreement with Reclamation. Nine of these original seismic stations were vertical-component, and the remaining station (PV08) was three-component. All stations used short-period seismometers (natural frequency of 1 Hz), and analog telemetry. Continuous data recording and archiving began in 1985. For the first several years of monitoring, seismic data from this network were acquired and processed by the USGS at their facilities in Golden, Colorado. In 1990, responsibility for data acquisition and analysis was assumed by Reclamation. The USGS continued to assist Reclamation with the maintenance of the field instrumentation and radio telemetry.

PVSN has been upgraded and expanded several times to modernize its instrumentation and improve the coverage of seismically active areas. In addition, some stations have been de-commissioned, either due to repeated vandalism or changing telemetry requirements. The locations of the original and current PVSN seismograph stations are shown in Figure II-6. Details about the stations are provided in Table II-1, including dates of operation, station type, and number of seismometer components. Table II-2 lists the station location names.

Upgrade and expansion of the original 10-station continuously telemetered, high-gain seismic network began in 1989. First, a three-component station (PV11) was installed on the mesa just south of the injection well to provide better focal depth control and to allow for more sensitive event detection. Three vertical-component stations (PV12-PV14) were added in 1989 to increase the density of stations surrounding the well. Station PV08 was downgraded in 1989 from a three-component station to a vertical-component-only station because it was determined that the equipment could be better used at the new stations closer to the injection well. Station PV15 was installed in 1995 to replace PV06, which had been vandalized in 1991, 1992, and 1994, when it was finally abandoned. A second three-component station (PV16) was installed on the mesa north of the injection well in 1999 to further improve near-well coverage.

In October 2000, a major upgrade to the data telemetry and acquisition was implemented. Up until this time, analog data from all stations had been radio-telemetered through PV08, which then relayed the data stream to Reclamation offices in Montrose, where it was transmitted via microwave and analog telephone links to Denver. In Denver, the analog data from all stations were digitized (using 12-bit digitizers) and processed. In October 2000, a wide-area network (WAN) link was established at the Hopkins Field Airport, near Nucla, Colorado, and new 16-bit digitizers were installed there. All analog radio links from the stations were reconfigured to terminate at Hopkins Field, and the use of analog telephone circuits to relay data was discontinued. Station PV08 was no longer used as a radio-telemetry relay. Station PV08 was temporarily removed in October 2003 to accommodate nearby construction activities and reinstalled in October 2007, at which time it was returned to a three-component configuration.

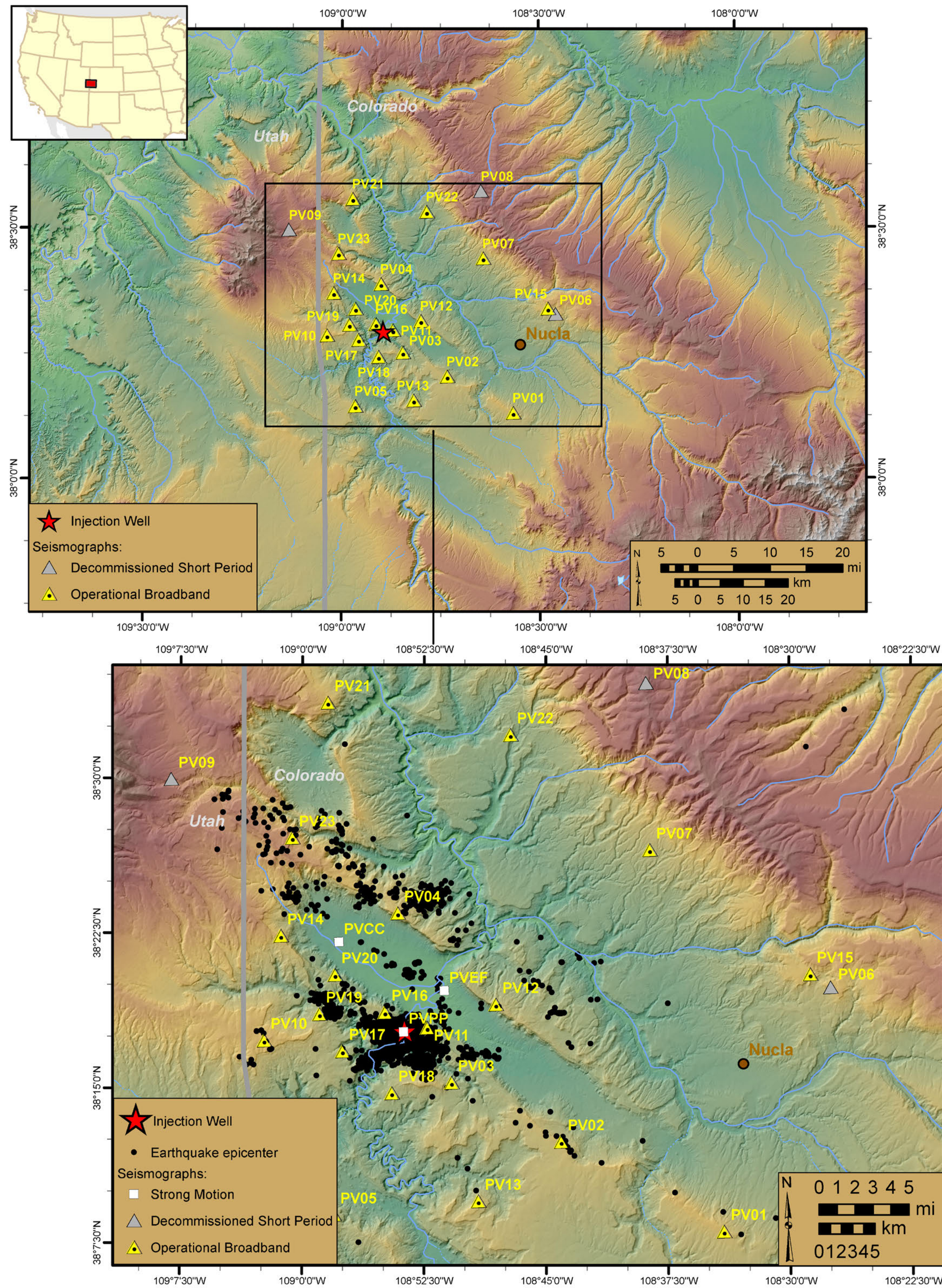


Figure II-6: Locations of the PVSN seismic stations, PVU injection well, and epicenters of earthquakes ≤ 10 km deep. PVCC, PVEF, & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Stations PV08 and PV09 were decommissioned when the network was upgraded to broadband digital instrumentation.

Table II-1: PVSN Station Locations and Characteristics

Station Name	Latitude deg., N	Longitude deg., W	Elev. m	Dates of Operation	Station Type	Sensor Direction
PV01	38.13	108.57	2191	5/83-7/16/15 5/10-present	short-period broadband	vertical triaxial
PV02	38.21	108.74	2177	5/83-8/27/11 10/08-present	short-period broadband	vertical triaxial
PV03	38.25	108.85	1972	5/83-7/16/15 10/08-present	short-period broadband	vertical triaxial
PV04	38.39	108.90	2176	5/83-6/06 5/07-present	short-period broadband	vertical triaxial
PV05	38.15	108.97	2142	5/83-7/16/15 5/10-present	short-period broadband	vertical triaxial
PV06	38.33	108.46	2243	5/83-8/94	short-period	vertical
PV07	38.44	108.64	2040	6/83-8/27/11 5/10-present	short-period broadband	vertical triaxial
PV08	38.58	108.65	2950	6/83-9/89 9/89-10/03 10/07-7/12/11	short-period short-period short-period	triaxial vertical triaxial
PV09	38.50	109.13	2662	6/83-7/16/15	short-period	vertical
PV10	38.29	109.04	2266	6/83-7/16/15 10/08-present	short-period broadband	vertical triaxial
PV11	38.30	108.87	1882	12/89-10/13 10/08-present	short-period broadband	triaxial triaxial
PV12	38.32	108.80	2092	12/89-7/05 11/05-present	short-period broadband	vertical triaxial
PV13	38.16	108.82	2158	12/89-7/16/15 5/10-present	short-period broadband	vertical triaxial
PV14	38.37	109.02	2234	12/89-4/02 6/07-present	short-period broadband	vertical triaxial
PV15	38.34	108.48	2234	6/95-8/27/11 7/11-present	short-period broadband	vertical triaxial
PV16	38.31	108.92	2025	7/99-7/16/15 5/10-present	short-period broadband	vertical triaxial
PV17	38.28	108.96	1991	11/05-present	broad-and	triaxial
PV18	38.25	108.91	1999	7/11-present	broadband	triaxial
PV19	38.31	108.98	2041	7/11-present	broadband	triaxial
PV20	38.34	108.97	1852	7/11-present	broadband	triaxial
PV21	38.56	108.97	2235	7/11-present	broadband	triaxial
PV22	38.54	108.79	1925	7/11-present	broadband	triaxial
PV23	38.45	109.01	2456	11/11-present	broadband	triaxial

Station Name	Latitude deg., N	Longitude deg., W	Elev. m	Dates of Operation	Station Type	Sensor Direction
PVPP	38.30	108.90	1524	12/97-present	strong motion	triaxial
PVEF	38.33	108.85	1513	10/03-present	strong motion	triaxial
PVCC	38.37	108.96	1617	6/05-present	strong motion	triaxial
Notes: Elevations are relative to mean sea level (MSL). The surface elevation of the injection well is 1540 m above MSL. Stations with vertical sensor direction are single-component; triaxial are 3-component (vertical, north, and east).						

Table II-2: Location Names of PVSN Seismic Stations

Station	Station Location Name
PV01	The Burn
PV02	Monogram Mesa
PV03	Wild Steer
PV04	Carpenter Flats
PV05	E. Island Mesa
PV07	Long Mesa
PV08	Uncompahgre Butte
PV09	North LaSalle
PV10	Wray Mesa
PV11	Davis Mesa
PV12	Saucer Basin
PV13	Radium Mtn
PV14	Lion Creek
PV15	Pinto Mesa
PV16	Nyswonger Mesa
PV17	Wray Mesa East
PV18	Skein Mesa
PV19	Morning Glory Mine
PV20	W. Nyswonger Mesa
PV21	Cone Mountain
PV22	Blue Mesa
PV23	Carpenter Ridge
PVPP	Paradox Valley Pumping Plant
PVEF	Paradox Valley Extraction Field
PVCC	Paradox Valley Community Center

Starting in 2005, upgrades to the high-gain seismic network focused on replacing the analog short-period seismic instrumentation with digital broadband instrumentation. The short-period instrumentation had become obsolete, both in terms of the data quality needed for ongoing analyses and in terms of maintaining equipment that was no longer manufactured. Two key characteristics of the instrumentation constrain data quality: bandwidth and dynamic range. The short-period instrumentation had an effective seismic signal bandwidth of 1-20 Hz. The low end of this range was determined by the natural frequency (1 Hz) of the seismometers used (Geotech model S-13), and the high end by the analog low-pass filter setting (nominally 25 Hz). The bandwidth of the analog stations was insufficient for many analysis purposes, such as accurately identifying complex seismic phases, accurately computing seismic moments of induced earthquakes (which require determination of long-period spectral levels), waveform modeling, or extracting time-domain Green's functions from ambient noise. Furthermore, the effective dynamic range of the analog stations constrained the ratio of the largest to smallest seismic signal that could be recorded on-scale to only a factor of about 1000, which corresponds to approximately two earthquake magnitude units. This resulted in seismic signals of earthquakes greater than about M 1.5 being clipped, which limited the use of this important data for magnitude and moment calculations, waveform cross-correlation, and identification of the S-wave arrival. Although 16-bit digitizers (with a dynamic range of 90 dB) were used after 2000, the effective dynamic range of the analog stations remained much less, approximately 10 or 11 bits (60 dB), because of the limited sensitivity of the voltage-controlled oscillators (VCOs) used at the stations to modulate the seismic signals onto the carrier tones used for analog radio telemetry. Modern broadband instrumentation provides much better characteristics, with typical bandwidths of 0.03 to 50 Hz, 24-bit digitizers providing a dynamic range of 135 dB or more, and seismometers typically packaged as a single unit with internal three-component sensors.

In November 2005, the first three-component broadband seismometer (Guralp model CMG-40TD) was installed at a new station southwest of the injection well (PV17). This instrument uses a 24-bit digitizer integrated within the seismometer case to minimize potential cable noise (digitizers and seismometers separated by a long analog cable can be sensitive to cross-talk at the microvolt level, which is difficult to protect against). Station PV12 was similarly upgraded at about the same time, and stations PV04 and PV14 were converted in May and July of 2007. These first-generation digital stations used digital radios that effectively behaved as a remote RS232 serial data link and which required the use of "combiner-repeater" modules (Guralp model CRM-6) to combine the serial signals from multiple stations. The first-generation stations exhibited a number of data quality problems, the most severe of which was crosstalk between the GPS antenna cabling (which provided timing for the internal digitizer) and the system providing power to the seismometer (O'Connell, 2008). The crosstalk inherent in the first-generation design resulted in significant spectral spikes in the data at frequencies of 1 Hz and greater, as illustrated in Figure II-7.

A new station design was developed in 2007 and 2008 based on experience from the first generation stations and from similarly instrumented seismic networks deployed at B.F. Sisk and Hungry Horse Dams (O'Connell, 2008). The new stations incorporated features to minimize the GPS antenna cable crosstalk problem, as well as to make the system more modular and robust. It included entirely new seismometer vaults, station enclosures, antennas, solar panels, and Ethernet packet radios. Deployment of the new instrumentation began in 2008, with upgrades of PV02, PV03, PV10, and PV11. In May 2010, stations PV01, PV05, PV07, PV13, and PV16 were upgraded. In July 2011, station PV15 was upgraded. In addition, six broadband digital seismic stations (PV18 to PV23) were installed at new sites in 2011. Two of these stations, PV22 and PV23, are replacements for old analog stations PV08 and PV09, which were decommissioned because they were noisy sites founded on thick alluvial deposits (all other sites are on rock). The other four new seismic stations (PV18, PV19, PV20, and PV21) were installed to improve coverage in seismically active areas of interest (including seismicity occurring within 9 km of the injection well and at the northern end of Paradox Valley).

The digital broadband upgrade of PVSN seismic stations was completed in late 2011. Consequently, Reclamation discontinued maintenance of the obsolete analog seismic stations. Four of those stations permanently went offline during 2011 (PV02, PV07, PV08, and PV15), and an additional analog station (PV11) ceased functioning in late 2013. The remaining analog stations were decommissioned in July 2014, when the data acquisition center at Hopkins Field was relocated into a new building.

During 2018, we began the replacement of the Guralp model CMG-40TD broadband seismometers with Guralp model 3ESPCDE seismometers, as some of the original seismometers began to fail and were no longer supported. For example, compatible GPS antennas could no longer be obtained for the oldest CMG-40TDs in the network, making continued maintenance of the stations with these old instruments impractical. The 3ESPCDE seismometers have several advantages over the CMG-40TD seismometers, including substantially less self-noise, considerably less power usage than the oldest CMG-40TDs, and Ethernet capability for future communications upgrades. In April 2018, the CMG-40TD seismometers at stations PV02, PV10, PV18, PV20, and PV23 were replaced with new 3ESPCDE seismometers. The seismometers at stations PV12 and PV19 were upgraded in May 2019. The seismometers at the remaining stations were upgraded in September 2020 (PV03, PV04, PV05, PV11, PV13, PV14, PV15, PV17, PV21, PV22) and October 2020 (PV01, PV07, PV16).

In addition to the continuously telemetered high-gain seismic array, three event-triggered strong-motion instruments were added to PVSN. The first strong-motion instrument (PVPP) was installed near the PVU injection wellhead in December 1997. A second strong-motion instrument was installed near the PVU extraction facilities (PVEF) in January 1998, and the third was installed at the nearby community of Paradox, Colorado (PVCC) in June 2005. Telemetry for the strong-motion instruments was provided by dial-up phone lines. The strong-motion array is designed to measure earthquake ground motions that are large enough to be felt or cause damage and which could saturate high-gain array stations closest to the epicenter.

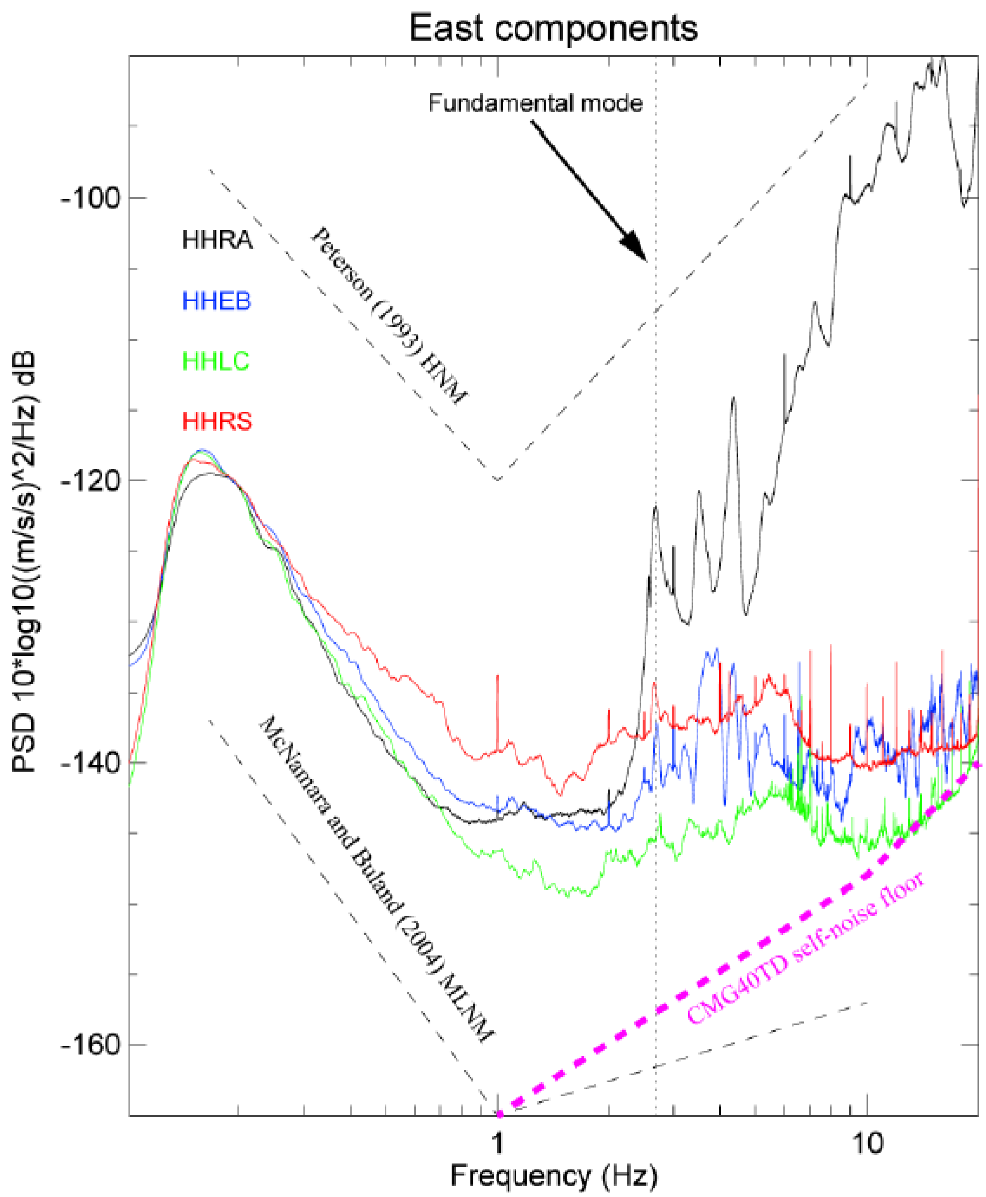


Figure II-7: Stacked multi-taper acceleration power spectra from the east-west components of Guralp model CMG40TD seismometers installed at four first-generation stations (HHRA, HHEB, HHLC, and HHRS) near Hungry Horse Dam, Montana. Windows were 400 seconds in length and represented ambient conditions. (Station HHRA was located close to the power generation plant at the dam, and therefore exhibited much higher ambient noise levels at frequencies above 2 Hz.) The obvious spikes in the spectra at frequencies of 1 Hz and higher were caused by GPS antenna crosstalk problems inherent in the first-generation stations. A new station design was implemented at PVSN to substantially reduce these crosstalk problems. Figure from O'Connell (2008).

The original instruments at PVPP and PVEF consisted of 12-bit data loggers (Kinemetrics model SSA-2 and Syscom model MR2002) and three-component force-balance accelerometers (FBAs), with the digitizers only approximately synchronized to Coordinated Universal Time (UTC). In November 1999, station PVEF was upgraded to use an 18-bit digitizer (Kinemetrics model K2), which was synchronized to UTC using a GPS receiver. Station PVPP was similarly upgraded in October 2003. Station PVCC had used a K2 data logger since its original installation in 2005.

On February 28, 2019, the K2 was removed from station PVEF, and three different data loggers and accelerometers were installed for a temporary side-by-side comparison study. These included the following instruments: (1) Reftek model RT130 data logger with Silicon Audio model 203V accelerometer, (2) Reftek RT130 data logger with Nanometrics model Titan accelerometer, and (3) Guralp model Minimus data logger with Guralp model Fortis accelerometer. A wireless TCP/IP bridge was installed to provide continuous real-time radio telemetry. In May 2019, the Silicon Audio sensor and Reftek digitizer were removed, and the Titan sensor was replaced with a similar unit with an internal digitizer. From May 2019 to October 2020, the Guralp instruments and the Nanometrics Titan with internal digitizer were run side-by-side at PVEF with continuous telemetry.

Following the testing of strong motion sensors and digitizers in 2019-2020, the decision was made to upgrade all strong motion sites using a Silicon Audio model 203V accelerometer and a Guralp Minimus digitizer. These upgrades were implemented in October 2020. At the same time, real-time radio telemetry was established for stations PVPP and PVCC. The real-time data from all three strong motion sites are integrated with the data from the high-gain broadband sites at the PVSN communication center at Hopkins Field in Nucla, Colorado.

2. Induced Seismicity

More than 10,900 relatively shallow (≤ 10 km deep) earthquakes have been recorded in the vicinity of Paradox Valley since injection began in 1991. No shallow earthquakes were detected in six years of seismic monitoring prior to the start of injection operations. Most of these events have focal depth estimates between approximately 2.5 and 6.5 km (relative to the ground surface elevation at the PVU injection wellhead), close to the depth of the injection interval (4.3 to 4.8 km). The seismicity has been observed at increasing distance from the injection well over time (Figure II-8). The initial earthquakes were detected just four days after the start of the first injection test in July 1991 and occurred very close to the injection well. As injection continued, earthquakes occurred at progressively increasing radial distances. By 2002, earthquakes were occurring as far as 16 km from the well. The lack of shallow seismicity detected during six years of pre-injection seismic monitoring, the general correlation of the depths of the earthquakes and the depth of injection, and the spatiotemporal evolution of the seismicity since the start of injection demonstrated in Figure II-8 indicate that these earthquakes have been induced by PVU fluid injection.

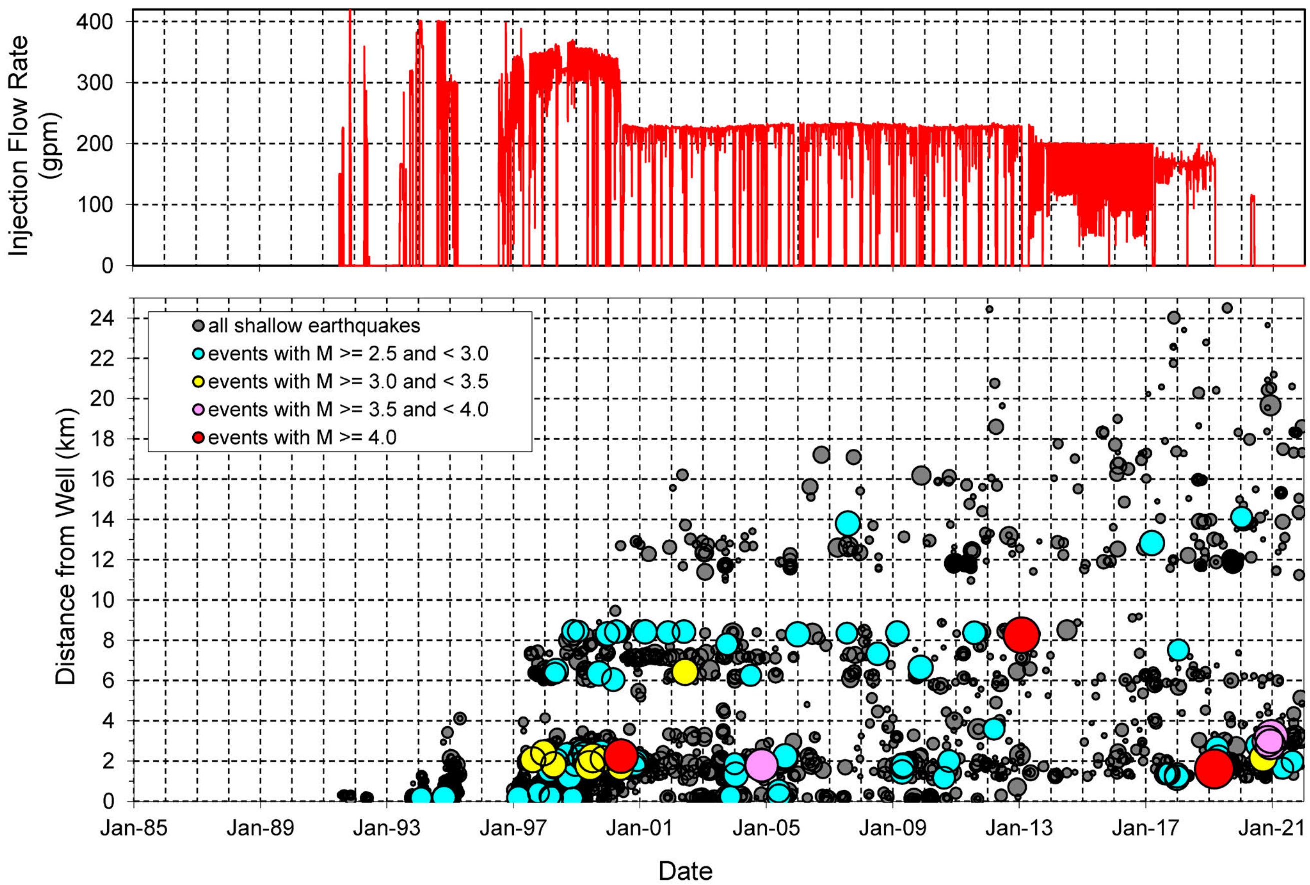


Figure II-8: Lower plot: scatter plot of earthquakes having magnitude ≥ 0.5 and depth ≤ 10 km (relative to the ground surface elevation at the injection wellhead), plotted as a function of date and distance from the PVU injection well. Each circle represents a single earthquake, with the width of the circle scaled by the event magnitude. The magnitudes shown are duration magnitudes for earthquakes with M_D < 3.0 and moment magnitudes for larger events. Upper plot: daily average injection flow rate.

Several distinct groups, or clusters, of induced seismicity have developed over the history of PVU injection operations. By the end of the injection tests in 1995, earthquakes were occurring to radial distances of roughly 4 km from the well (Figure II-9a). This area of induced seismicity immediately surrounding the injection well is referred to as the "near-well" region. In 1997, about one year after the start of continuous injection, earthquakes began occurring 6 to 8 km northwest of the injection well (Figure II-9b). This group of induced seismicity is called the "northwest (NW) cluster". In mid-2000, earthquakes were first detected 12 to 14 km from the injection well, along the northern edge of Paradox Valley (Figure II-9b). Several distinct clusters of earthquakes soon formed along the northern edges of the valley (Figure II-9c). The earthquakes occurring in all these groups are referred to as "northern valley events". Following the formation of these clusters (and a 32% decrease in the injection rate in mid-2000), the geographical expansion of induced seismicity greatly slowed for nearly a decade (Figure II-9c, d) but was renewed in 2010. For example, a single earthquake was first detected about 6 km southeast of the injection well in 2004 (Figure II-9c), but the seismicity rate in this area markedly increased beginning in 2010 (Figure II-9e). This tight group of earthquakes is referred to as the "southeast (SE) cluster". Earthquakes also began occurring in north-central Paradox Valley in 2010. (Figure II-9e). In the last several years, the rate of induced seismicity at the northern end of Paradox Valley has increased, and its geographical extent has expanded (Figure II-9e, f, g, and h). Earthquakes likely related to PVU brine injection are now occurring at distances up to ~27 km northwest of the injection well and up to ~7 km outside the northwest perimeter of the seismic network (Figure II-9g). In addition, seismicity potentially related to PVU brine injection has occurred in several previously aseismic areas, including: toward the southeast to a distance of ~37 km from the injection well, east to a distance of ~24 km from the well, and west to a distance of ~14 km from the well (Figure II-9f, g, h).

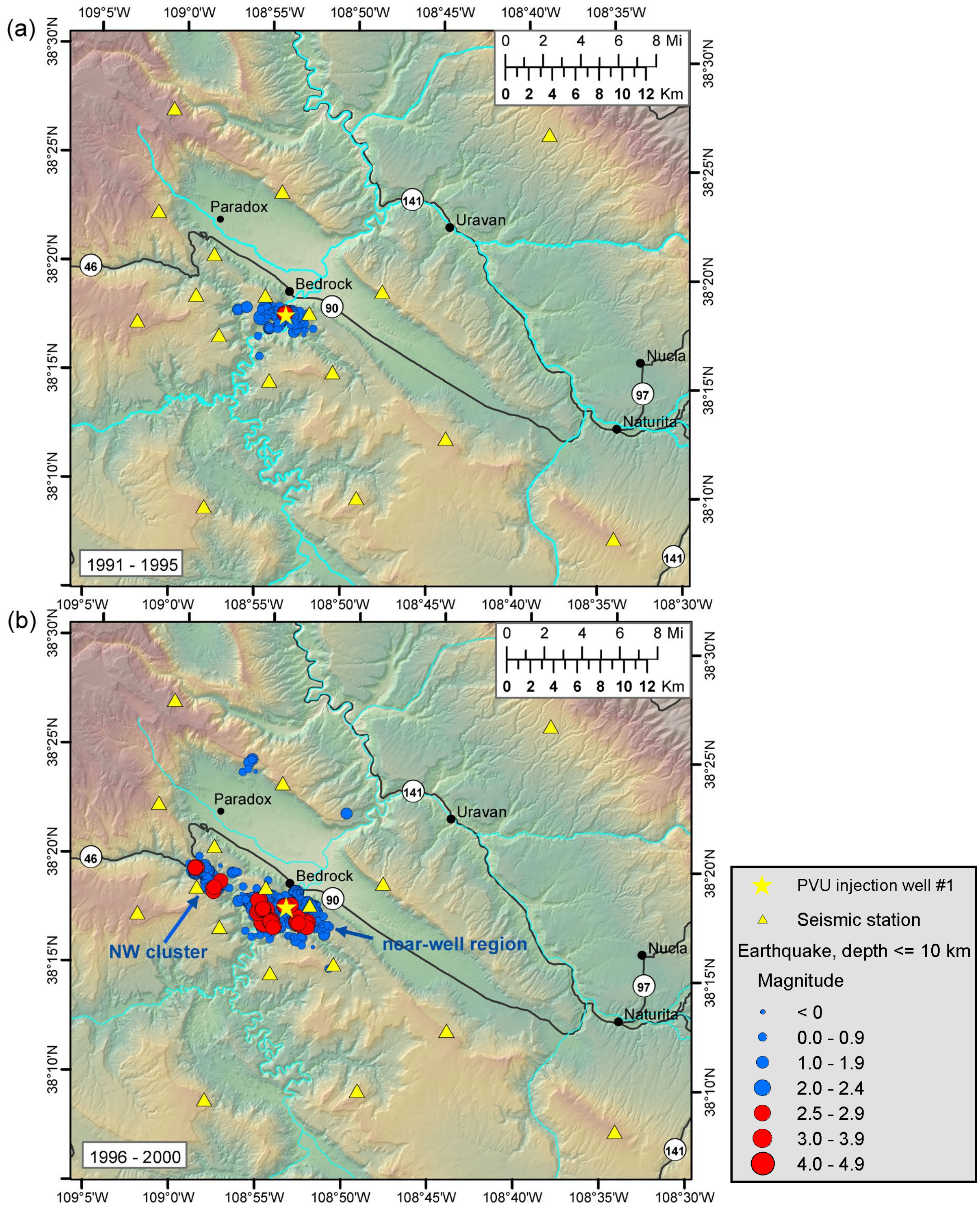
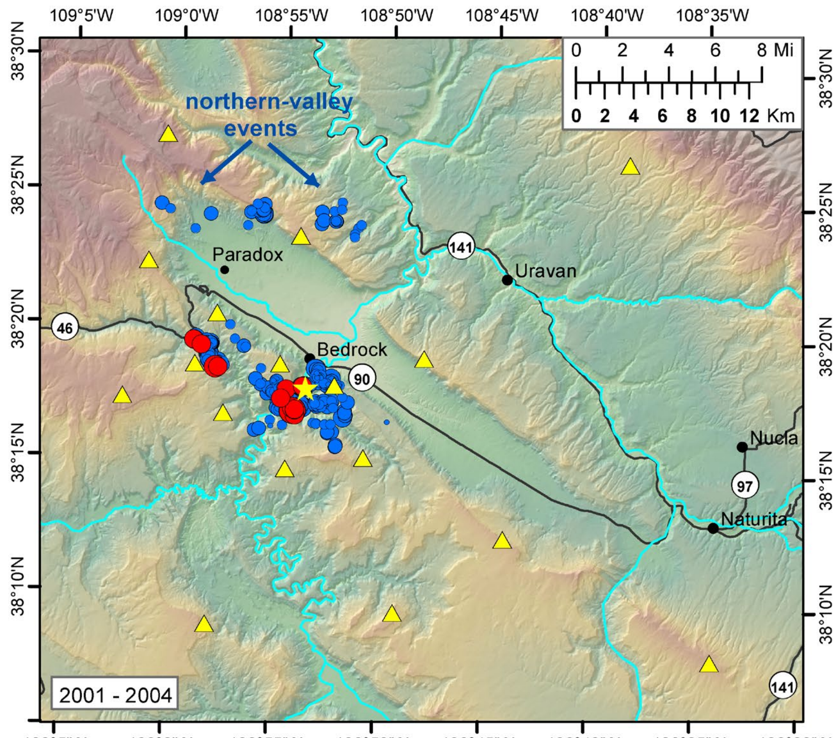


Figure II-9: Maps showing the spatial distribution of shallow seismicity (depth ≤ 10 km) over time: (a) 1991-1995 (b) 1996-2000 (c) 2001-2004 (d) 2005-2008 (e) 2009-2012 (f) 2013-2016 (g) 2017-2019 (h) 2020-2021. Earthquake symbols are sized according to magnitude, and earthquakes with magnitudes ≥ 2.5 are shown in red.

(c)


northern-valley events
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108°45'W
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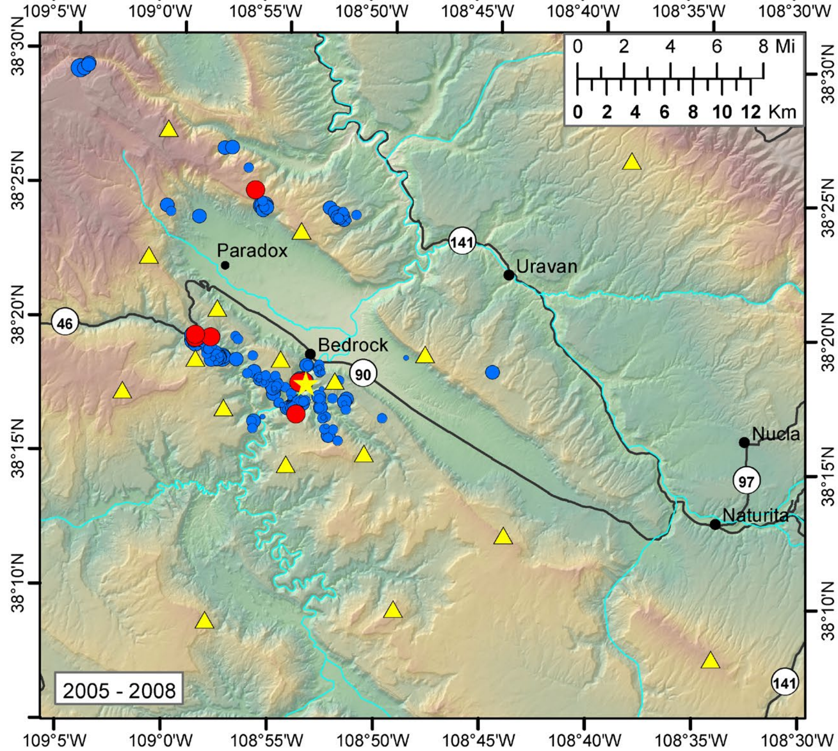
38°20'N
38°15'N
38°10'N

(d)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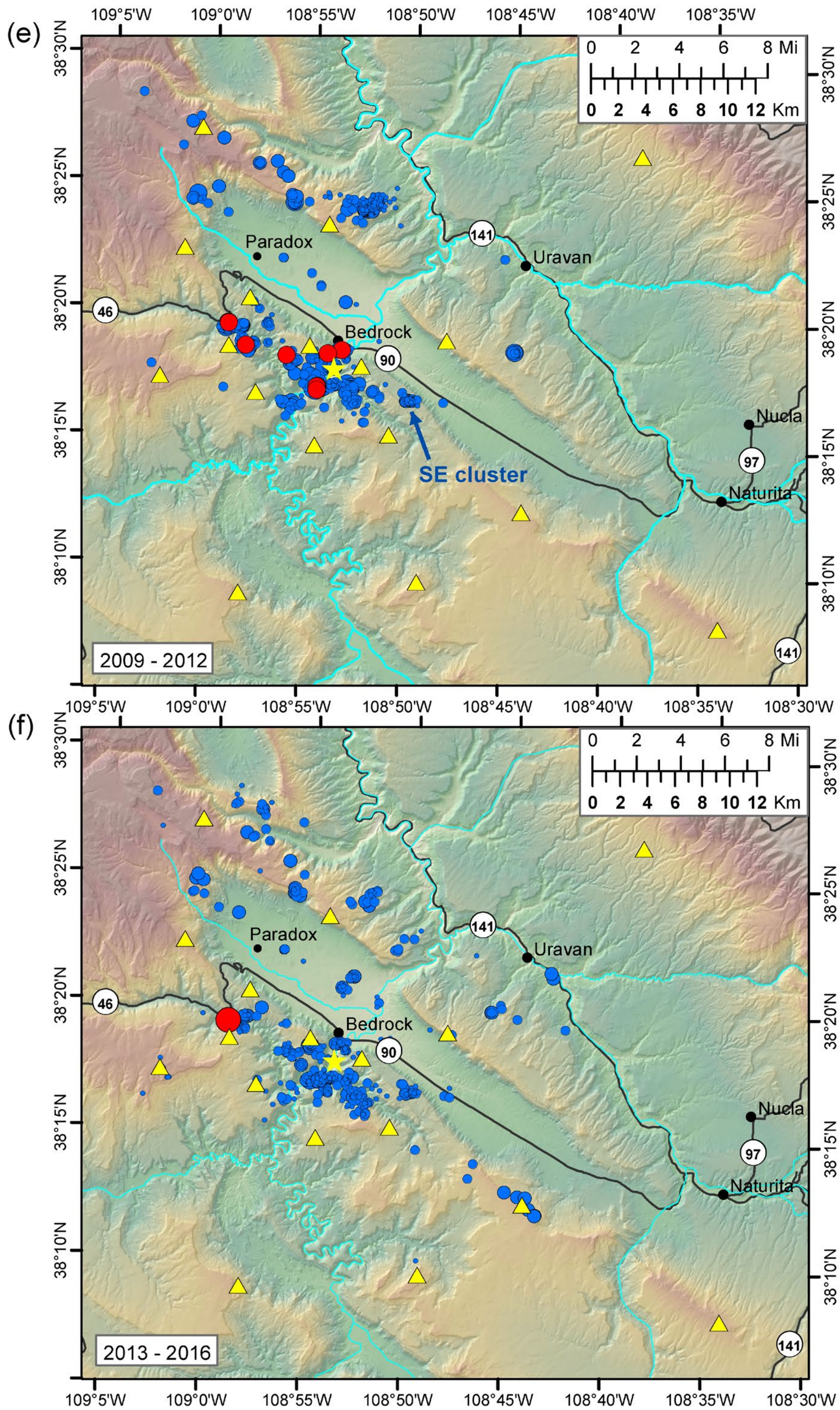
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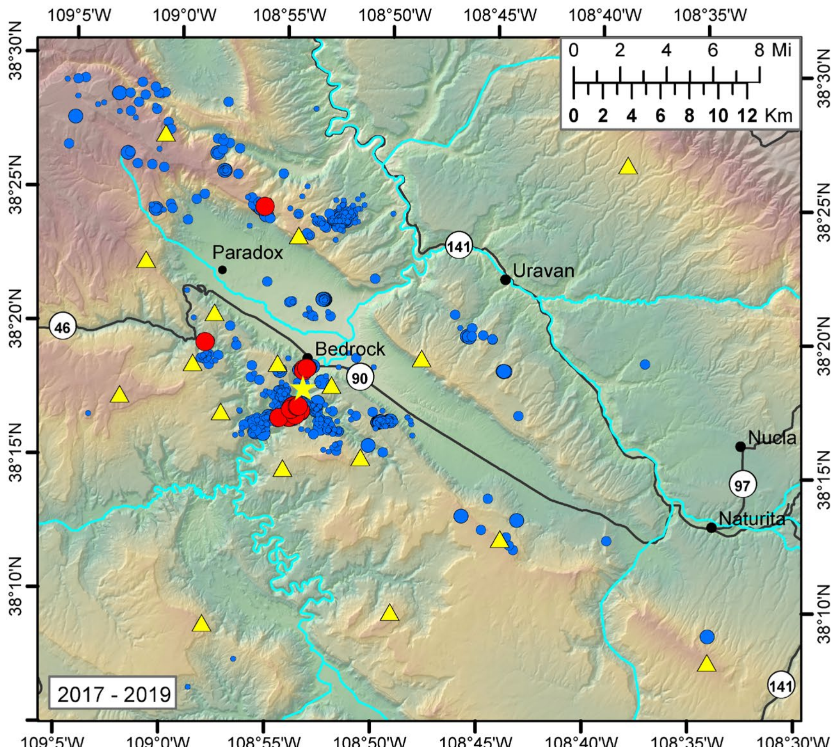
(g)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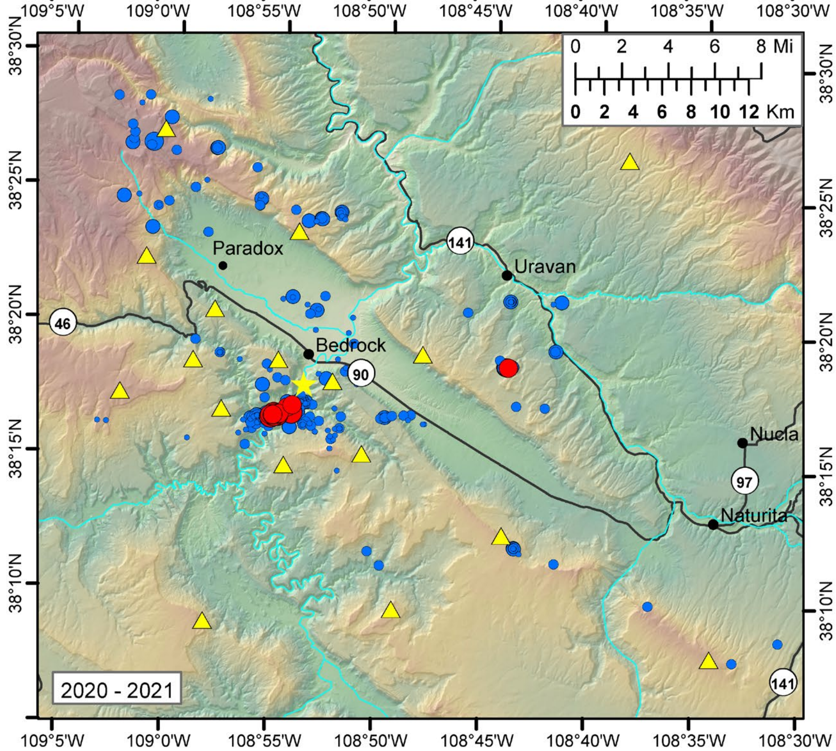
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III. Network Operations during 2021

A. Network Maintenance and Upgrades

Two site visits were conducted in 2021. During these site visits, preventive and remedial maintenance was performed at 12 of the 20 remote broadband seismic stations, the three strong motion sites, and the data communication center at Hopkins Field in Nucla, Colorado. The remaining eight broadband seismic stations were not visited during 2021 because of a lack of staff availability and poor weather conditions during the last site visit of the season. (These stations will be prioritized during the first field trip of 2022.) A summary of the activities performed at the sites during 2021 is given below. Additional details of the work performed at each site are included in the site visit reports in Appendix A.

The preventive maintenance performed at the seismic stations included: checking station power systems, replacing aging batteries, testing cables and antennas and replacing any degraded components, testing radios, and inspecting seismometer vaults. Remedial maintenance included replacing the surge protection block, drained batteries, and the solar power controller at station PV19.

In addition to the routine maintenance activities listed above, new grounding installations were completed at the three strong motion sites. This work completes the upgrade of the strong motion sites started the previous year.

At the Hopkins Field communication center, routine equipment testing was performed. In addition, the radio power supply was upgraded, and the camera for the environmental monitor was configured and adjusted for optimal monitoring.

B. Network Performance

PVSN network performance depends on the performance of the hardware at individual seismic stations, the robustness of the radio data communication between the stations and the communication hub at Hopkins Field, and the reliability of the data acquisition computer systems. The performance of each of these components during 2021 is discussed below.

Three of the 20 PVSN broadband seismic stations experienced hardware problems in 2021 (Table III-1). Station PV19 was offline for six months, from Nov. 2020 to May 2021, because of a failure of its power supply system. Seismic data transmission from this site subsequently ceased in early July 2021 and was restored in mid-October by a hard reset of the seismometer. Station PV18 went offline in mid-December and appears to have no power. A site visit is planned for May 2022 to repair this station. GPS timing at station PV12 was lost for dozens of very brief periods from January to March and during December, most likely due to reboots of its GPS antenna. This pattern suggests a

Table III-1: Performance of PVSN Seismic Stations During 2021

Station	Performance
PV01	Online and functioning normally throughout the year.
PV02	Online and functioning normally throughout the year.
PV03	Online and functioning normally throughout the year.
PV04	Online and functioning normally throughout the year.
PV05	Online and functioning normally throughout the year.
PV07	Online and functioning normally throughout the year.
PV10	Online and functioning normally throughout the year.
PV11	Online and functioning normally throughout the year.
PV12	Online and mostly functioning well. This station experienced dozens of very brief GPS timing failures during January – March and December, most likely due to reboots of the GPS antenna. These reboots appear to be related to a temperature-sensitive hardware problem.
PV13	Online and functioning normally throughout the year.
PV14	Online and functioning normally throughout the year.
PV15	Online and functioning normally throughout the year.
PV16	Online and functioning normally throughout the year.
PV17	Online and functioning normally throughout the year.
PV18	Online and function normally during most of the year. Went offline on 12/10/2021 and remained offline for the remainder of the year. A site visit will be conducted in May 2022 to determine the cause of the failure and repair the station.
PV19	Experienced two substantial periods of downtime:11/3/2020 to 5/4/2021 and 7/8/2021 to 10/19/2021. The first downtime was caused by a problem with the station power system, most likely related to a failure of the solar power regulator or surge protection block. During the second downtime, radio communication to the station was maintained, but communication to the seismometer failed. The cause of this problem could not be determined; the seismic data transmission was restored via a hard reset of the seismometer.
PV20	Online and functioning normally throughout the year.
PV21	Online and functioning normally throughout the year.
PV22	Online and functioning normally throughout the year.
PV23	Online and functioning normally throughout the year.
PVEF	Online and functioning normally throughout the year.
PVPP	Online and functioning normally during most the year. The station was offline from 5/12/21 to 5/25/21 because of a loose or disconnected power cable.
PVCC	Online and functioning normally throughout the year.

temperature-sensitive hardware problem at the site. A similar pattern was also observed during 2020. Diagnostic tests have been performed several times to resolve this issue, and various components have been replaced. Additional work will be performed in 2022 to try to correct this problem. In the meantime, station PV12 is otherwise operating normally and providing useable data. No stations experienced night-time power failures during 2021, and no stations experienced significant periods of interrupted GPS timing. Hardware improvements, such as more energy-efficient electronics and GPS monitoring and automatic reboot capability, have largely resolved these issues which had been experienced in previous years.

The three strong motion sites did not experience any substantial hardware problems during 2021. However, station PVPP was offline for about two weeks in May because of a loose or disconnected power cable.

Most stations experienced robust radio communications during 2021, which maintained the network's ability to continuously transmit the seismic data. Stations PV07 and PV21 experienced minor data loss, ~2% and ~1%, respectively, due to slightly degraded radio communications (Figure III-1). In addition, radio transmission into Hopkins Field on Access Point (AP) no. 3, which receives data from the PV04 and PV12 radio repeater subnets, was interrupted for more than two hours on December 1st (~2:46 – 5:07 UTC). This radio link receives data from 14 of the 20 broadband seismic stations and all three strong motion stations. Either a temporary hardware problem or radio interference interrupted data transmission for this radio link during this time period. Data transmission resumed following this short outage, and radio signal strength and signal-to-noise values have remained normal since then. The problem has not recurred.

The PVSN data acquisition computer systems were online and functioning normally throughout the year. The two servers in PVSN's data communication center at Hopkins Field in Nucla, Colorado, are past their serviceable life. New servers were purchased two years ago, but the deployment of the servers has been delayed because of the long wait time to get the network connection between Nucla and Denver upgraded, which must be done through the Department of the Interior's contract with Lumen Technologies. These servers are being configured with virtual machine environments for improved management, but the current 1.5 Mbps network line cannot support this configuration. Lumen is in the process of upgrading the network connection to 9.2 Mbps, and the Paradox Valley Unit project is independently working with the Nucla-Naturita Telephone Company to install a fiber optic cable to the site.

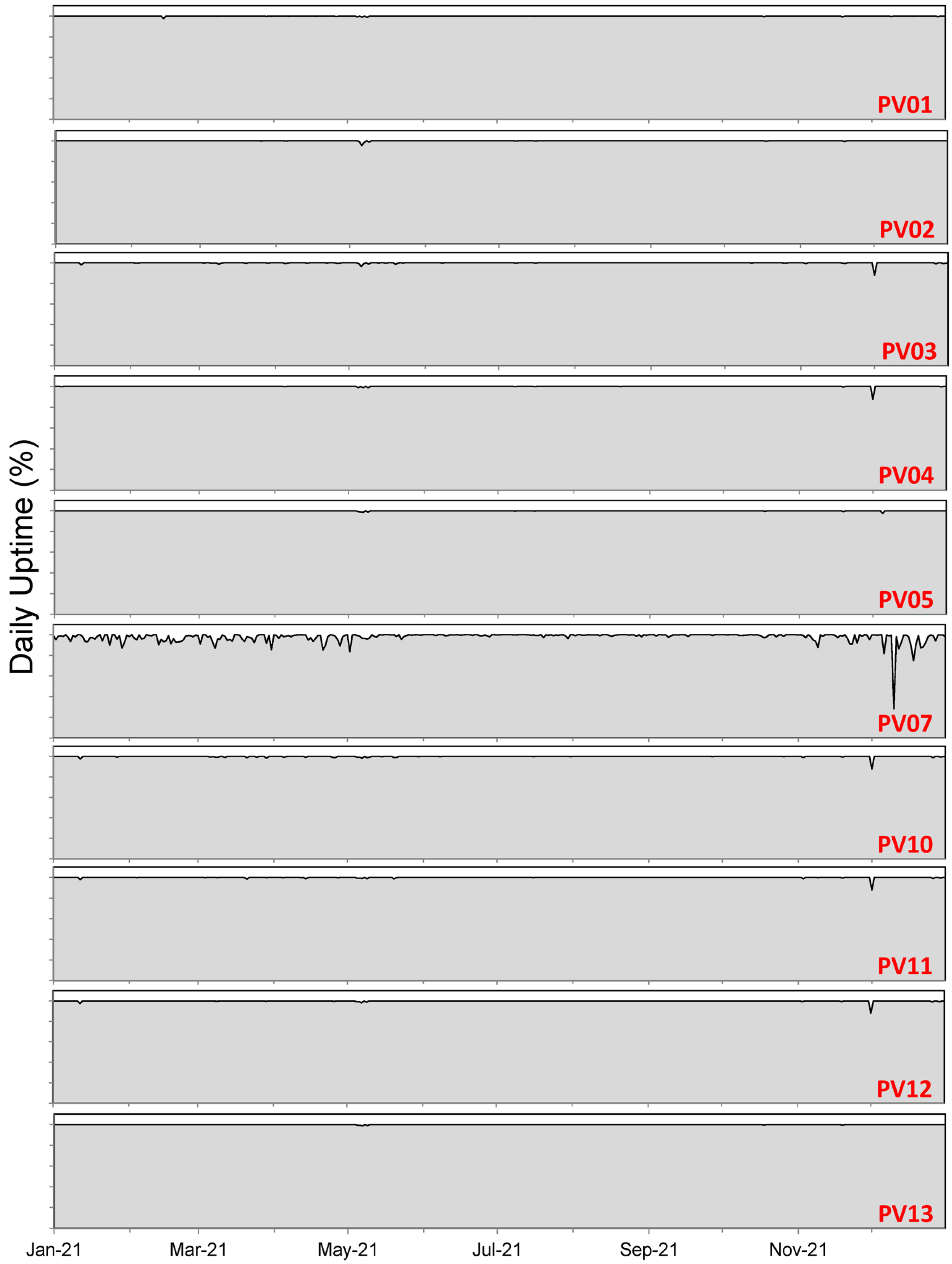

Figure III-1: Daily uptime (%) for the PVSN seismic stations during 2021. The uptime values represent the percent of the day for which data from a given station were recorded. The vertical axes on the plots are scaled from 0 to 110%. Filled gray areas represent daily uptime, while dips in the filled volume show decreases in uptime (lack of data).

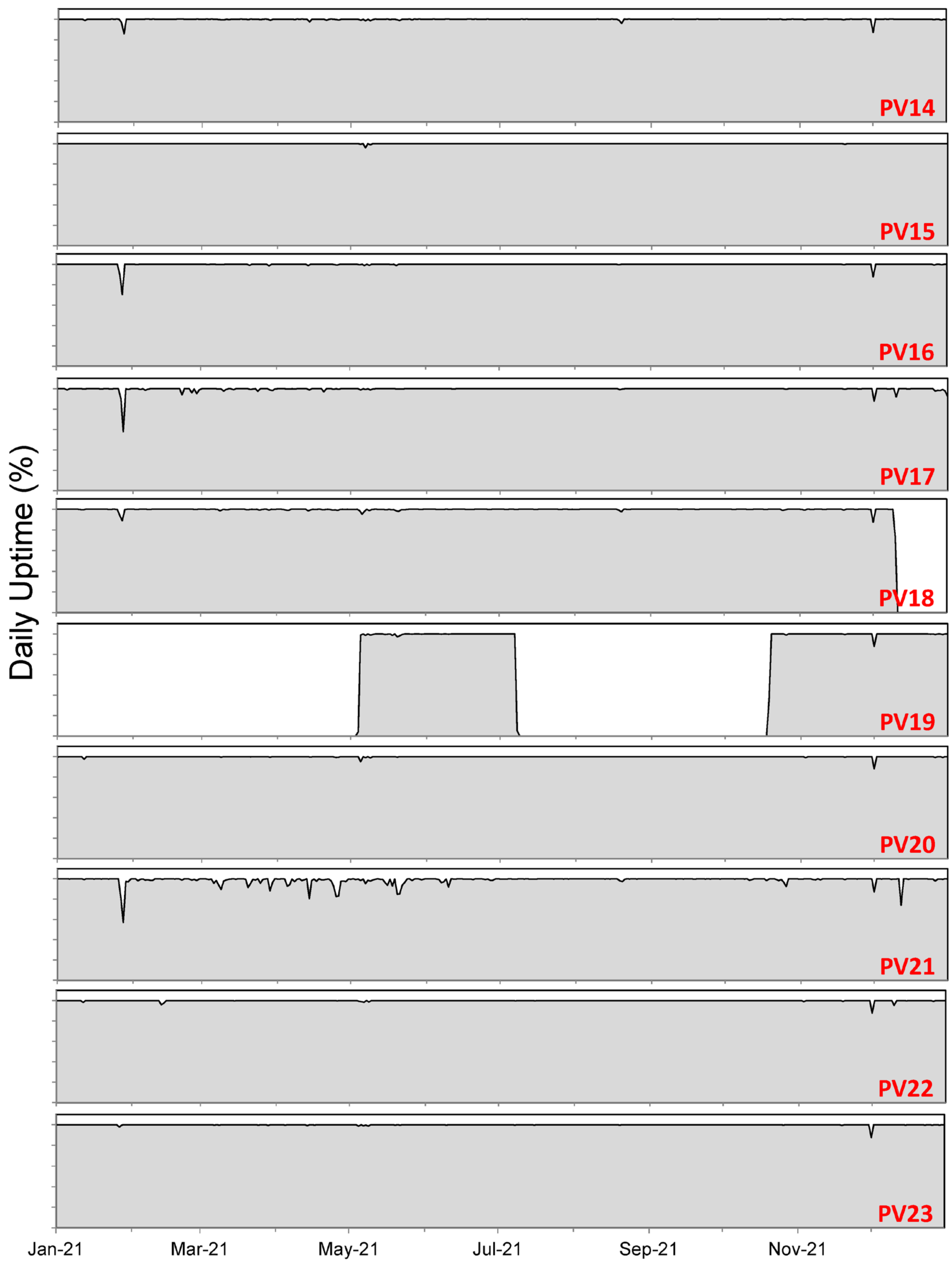

Figure III-1, continued.

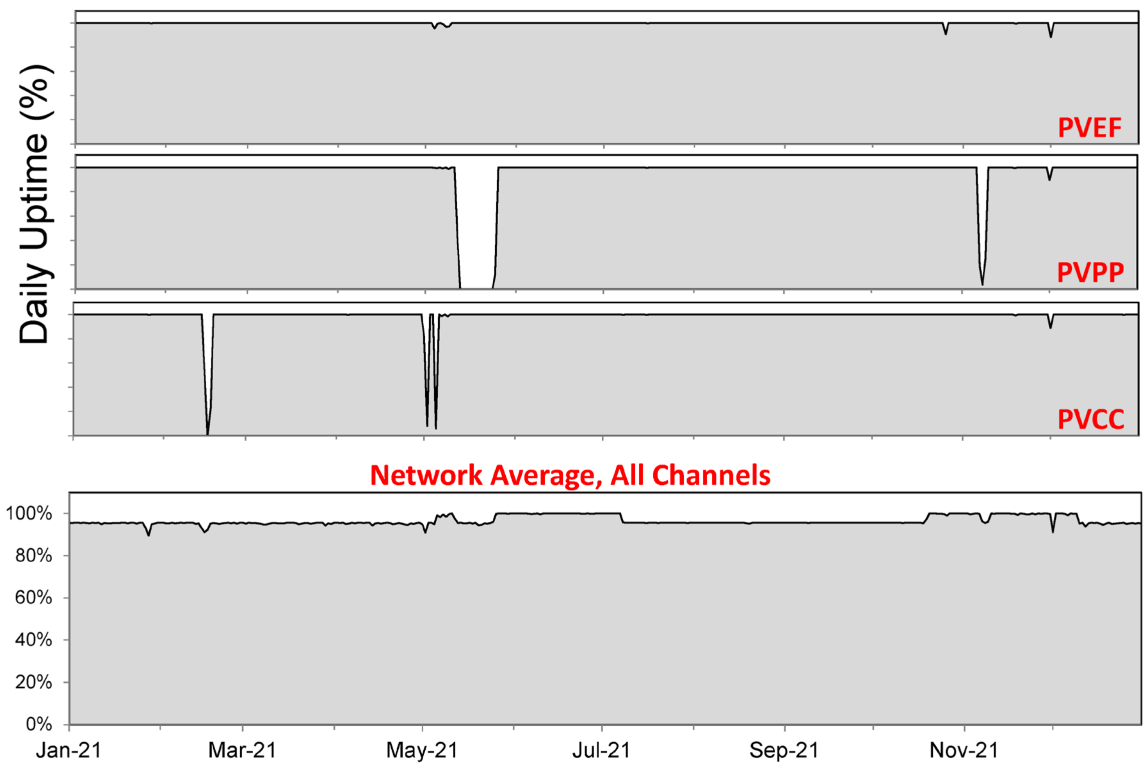

Figure III-1, continued. The bottom plot shows the daily average performance for all PVSN channels.

Considering data loss from hardware failures at individual seismic stations, radio communication data drop-outs, and PVSN system downtimes, the 2021 annual uptimes for the PVSN broadband and strong motion seismic stations range from 38% to 100%, with 20 of the 23 stations having uptimes ≥ 98% (Figure III-2; Table III-2). These uptimes represent the percent of the year for which data from a given station were recorded.

We have been computing and tracking the overall annual uptimes of PVSN since 2000. These annual uptimes are estimates of the percent of each year during which PVSN was reliably detecting and recording earthquakes. They generally represent the percent of the year during which the PVSN data acquisition systems were operating. During 2021, there were no time periods when the entire seismic network was offline. However, 14 of the broadband stations and all three strong motion stations were effectively offline for about 2 hours on December 1st because of a radio communication failure. Because of the substantial impact of this failure on PVSN's seismic monitoring capability, we classify it as a short PVSN downtime (Table III-3). However, because this downtime was so short, the annual PVSN uptime for 2021 is still 100.0% (rounded to the nearest 0.1%, Table III-4).

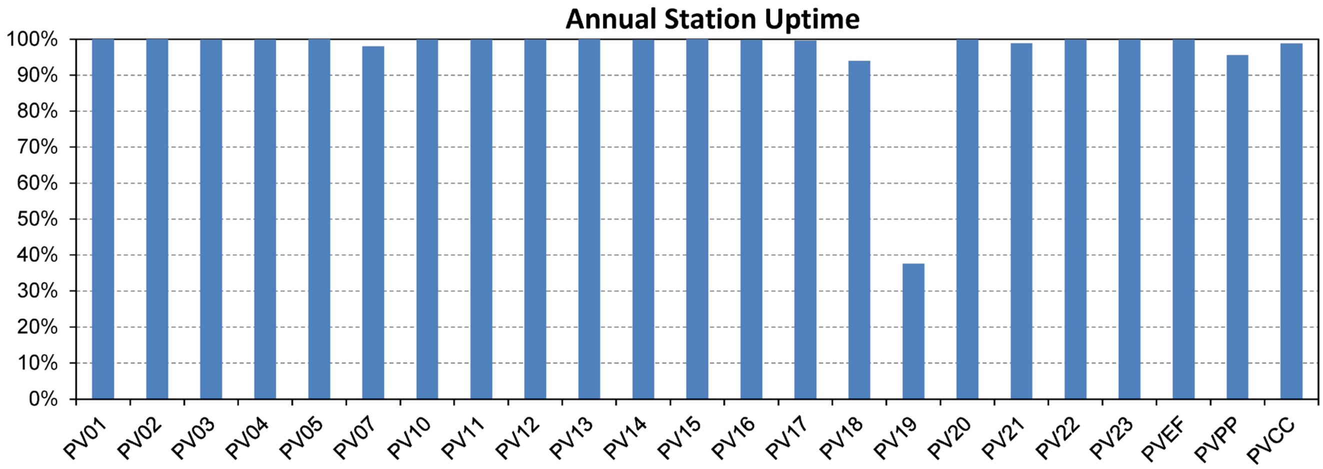

Figure III-2: Graph of annual (2021) uptime for each PVSN seismic station.

Table III-2: Annual PVSN Station Uptimes in 2021

Station	Annual Station Uptime
PV01	100%
PV02	100%
PV03	100%
PV04	100%
PV05	100%
PV07	98%
PV10	100%
PV11	100%
PV12	100%
PV13	100%
PV14	100%
PV15	100%
PV16	100%
PV17	100%
PV18	94%
PV19	38%
PV20	100%
PV21	99%
PV22	100%
PV23	100%
PVEF	100%
PVPP	96%
PVCC	99%

Table III-3: Times When PVSN Was Down in 2021

Approximate Time Period (UTC)	Reason
12/01/2021, ~2:46 – 5:07 UTC (~2.3 hours)	Failure of the radio link from the PV04 and PV12 radio repeater subnets into the Hopkins Field data communication center

Table III-4: Annual PVSN Uptimes

Year	Annual Number of Days with Monitoring Absent or Substantially Degraded	Percent Uptime
2000	24	93.4%
2001*	**	**
2002	5	98.6%
2003	14.5	96.0%
2004	16	95.6%
2005	34	90.7%
2006	47	87.1%
2007	37	89.9%
2008	10	97.2%
2009	6.5	98.2%
2010	0	100.0%
2011	12.2	96.7%
2012	2.2	99.4%
2013	4.6	98.8%
2014[1]	10.3	97.2%
2015[2]	8.7	97.6%
2016[3]	17.3	95.3%
2017[4]	1.2	99.7%
2018	2.4	99.3%
2019	0.03	100.0%
2020	2.3	99.4%
2021	0.1	100.0%

**not tabulated in 2001
[1] includes 40.5 hours of downtime in September 2014 when the network was operating but event detection was severely degraded due to malfunctioning of the data acquisition software
[2] includes a 50% rating for 12 days in February and 5 days in December when the network was operating but monitoring was substantially degraded due to the absence of data from 8-12 stations simultaneously.
[3] includes a 50% rating for 9 days in August and 22 days in September when network was operating but monitoring was substantially degraded due to absence of data from 14 stations simultaneously.
[4] includes 50% rating for 31 hours in January when network was operating but monitoring was substantially degraded due to absence of data from ≥ 5 stations simultaneously.

IV. Seismic Data Recorded in 2021

A. Annual Summary

In 2021, 356 earthquakes were recorded within or near the perimeter of PVSN. The map in Figure IV-1 shows the epicenters of these events (colored circles), as well as the epicenters of all earthquakes recorded in previous years (gray and white circles). The local earthquakes are classified into four categories based on their depths (relative to the ground surface elevation of 1.524 km above MSL at the PVU injection well) and distances from the injection well:

1. Shallow near-well: depth ≤ 10 km, distance from the injection well ≤ 5 km
2. Shallow intermediate: depth ≤ 10 km, distance from injection well > 5 km and ≤ 10 km
3. Shallow distant: depth ≤ 10 km, distance from injection well >10 km
4. Deep: depth > 10 km, any distance from the injection well

The earthquakes recorded during 2021 are color-coded using these categories in the map presented in Figure IV-1, and the numbers and magnitudes of the earthquakes in each category are summarized in Table IV-1. The 2021 local earthquake catalog is included in Appendix B.

All but three of the 356 local earthquakes recorded during 2021 have depths ≤ 10 km. Of these relatively shallow earthquakes, 273 occurred within 5 km of the injection well, 17 occurred at distances between 5 and 10 km from the well, and 63 occurred > 10 km from the well. Based on the relatively shallow depths of these earthquakes and the geographical expansion of the seismicity since injection began, we interpret most, and potentially all, of these earthquakes as being induced by PVU brine injection.

Two of the three deep earthquakes recorded during 2021 occurred in seismicity clusters just outside the perimeter of PVSN, one immediately southwest of seismic station PV10 and the other about 5 km north of station PV23 (Figure IV-1, purple circles). The depth estimates of these two earthquakes are ~12-13 km (relative to the ground surface at the PVU injection well). Earthquakes at similar depths have been recorded in these clusters since the early (west cluster) to late (north cluster) 1990s. We interpret the earthquakes in these clusters, including the two events recorded in 2021, as naturally occurring. The other deep earthquake recorded during 2021 occurred ~9.3 km northeast of the injection well, at an estimated depth of 13.7 km below the PVU wellhead. No earthquakes in a similar depth range have been recorded in this area in the past. The relation of this earthquake to PVU injection, if any, is unclear.

Table IV-1: Summary of Earthquakes Recorded During 2021 by Location Category

Location Category	Depth	Distance from well	Number of Earthquakes	Number of Earthquakes with $M_D \geq 0.5$	Magnitude Range[1]	
					Min.	Max.
shallow near-well	≤ 10 km	0 to 5 km	273	52	-1.3	2.6
shallow intermediate		> 5 to 10 km	17	3	-0.9	1.7
shallow distant		> 10 km	63	26	-0.5	1.7
Deep	> 10 km	all distances, within or near the perimeter of PVSN	3	1	-0.5	0.6
TOTAL SHALLOW			**353**	**81**	**-1.3**	**2.6**
TOTAL			**356**	**82**	**-1.3**	**2.6**

[1] Duration magnitudes (M_D) are used for events with $M_D < 3.0$, and moment magnitudes (M_W) are used for larger events.

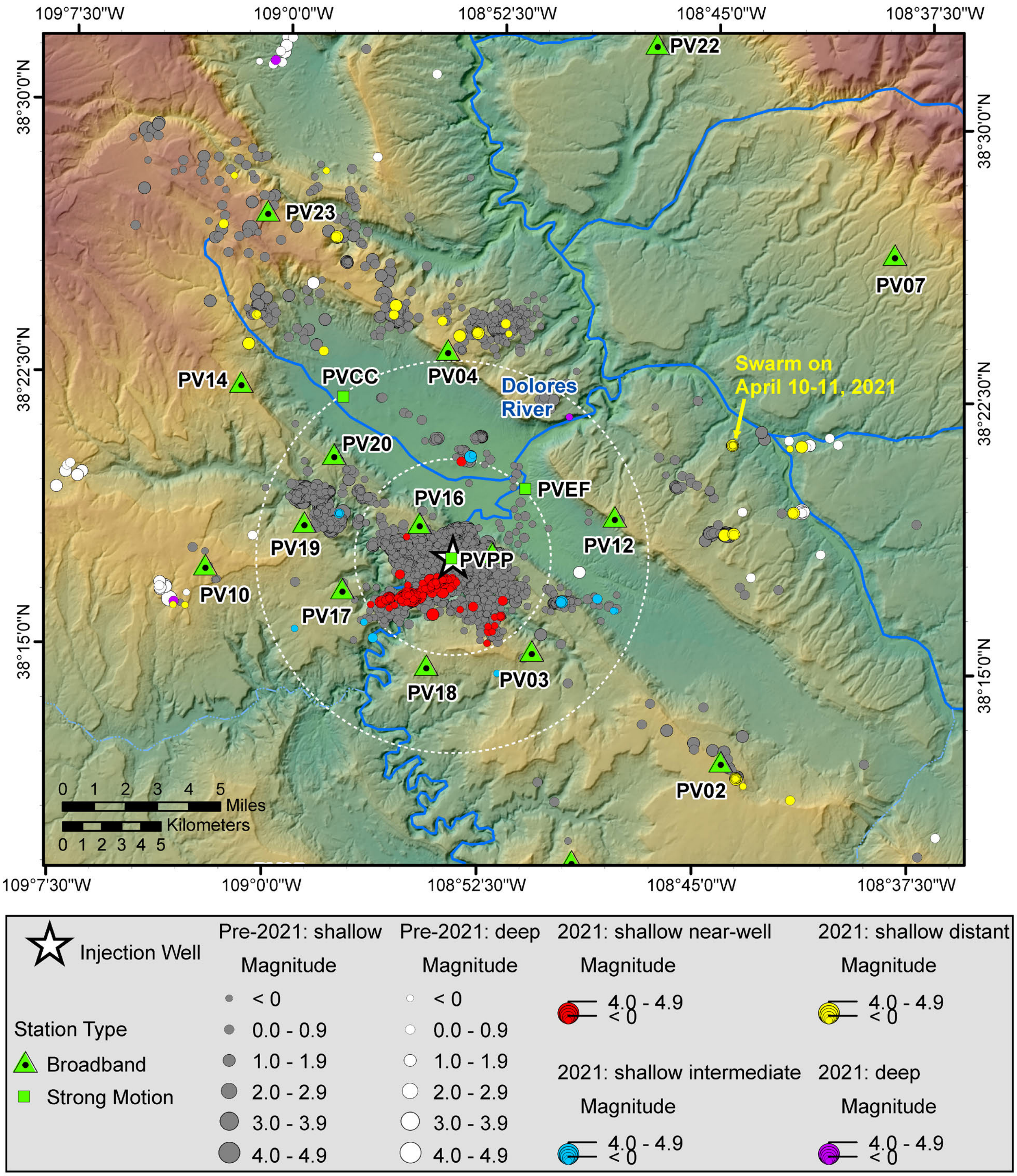

Figure IV-1: Locations of local earthquakes recorded by PVSN during 2021 (colored circles) and previous years (gray and white circles). The events that occurred during 2021 are color-coded using the event location categories described in the text. Events identified as "shallow" have depths ≤ 10 km (relative to the ground surface elevation at the injection well); those identified as "deep" have depths > 10 km. The white dashed circles represent radial distances of 5 and 10 km from the injection well.

Three local earthquakes with duration magnitude (M_D) ≥ 2.5 occurred during 2021 (Figure IV-2, red circles). This magnitude threshold is significant because it is the approximate minimum magnitude for ground shaking to be felt in the Paradox Valley area. These earthquakes occurred 1.6 to 2.7 km southwest of the injection well. Two of the earthquakes occurred in the immediate vicinity of the rupture plane of the March 2019 M_W 4.5 earthquake, on 5/1/2021 and 8/21/21. The duration and moment magnitudes for the May event are M_D 2.5 and M_W 2.2, respectively. The August event has magnitudes of M_D 2.6 and M_W 2.2. Based on the locations of these earthquakes, we interpret them as aftershocks of the March 2019 main shock. The third earthquake with M_D ≥ 2.5 occurred on 1/3/21, approximately 500 m southwest of the rupture plane of the March 2019 M_W 4.5 earthquake. It has magnitude estimates of M_D 2.6 and M_W 2.5. This earthquake occurred in a seismicity cluster that formed shortly after the March 2019 main shock and subsequently experienced substantially increased rates and magnitudes from November 2020 to January 2021. Recent geomechanical and fault rupture analyses indicate that earthquakes within this cluster may be triggered by a combination of stress redistribution from the March 2019 main shock fault rupture and stress changes related to reservoir depressurization associated with the extended injection well shut-in (personal comm., L. Block, 3/18/21).

The local earthquakes recorded by PVSN during 2021 are plotted as a function of date, earthquake magnitude, and location category in Figure IV-3. The most obvious swarm of seismicity occurred on April 10-11, when 20 earthquakes in the shallow distant category (yellow diamonds) occurred in a 22-hour period. These earthquakes occurred 15.3-15.4 km northeast of the injection well, on the far side of Paradox Valley (Figure IV-1, cluster labeled). All but one of these earthquakes tied into our standard event relative location procedure, which nearly collapsed their hypocenters to a point location at a depth of 5.4 km (relative to the ground surface at the injection well). The earthquakes have magnitudes of M_D -0.5 to M_D 1.4. Earthquakes have been detected in this general area east of Paradox Valley and south of the Dolores River since 2007, and their rates have generally increased in recent years. They have been interpreted previously as induced by PVU injection (Block et al., 2021).

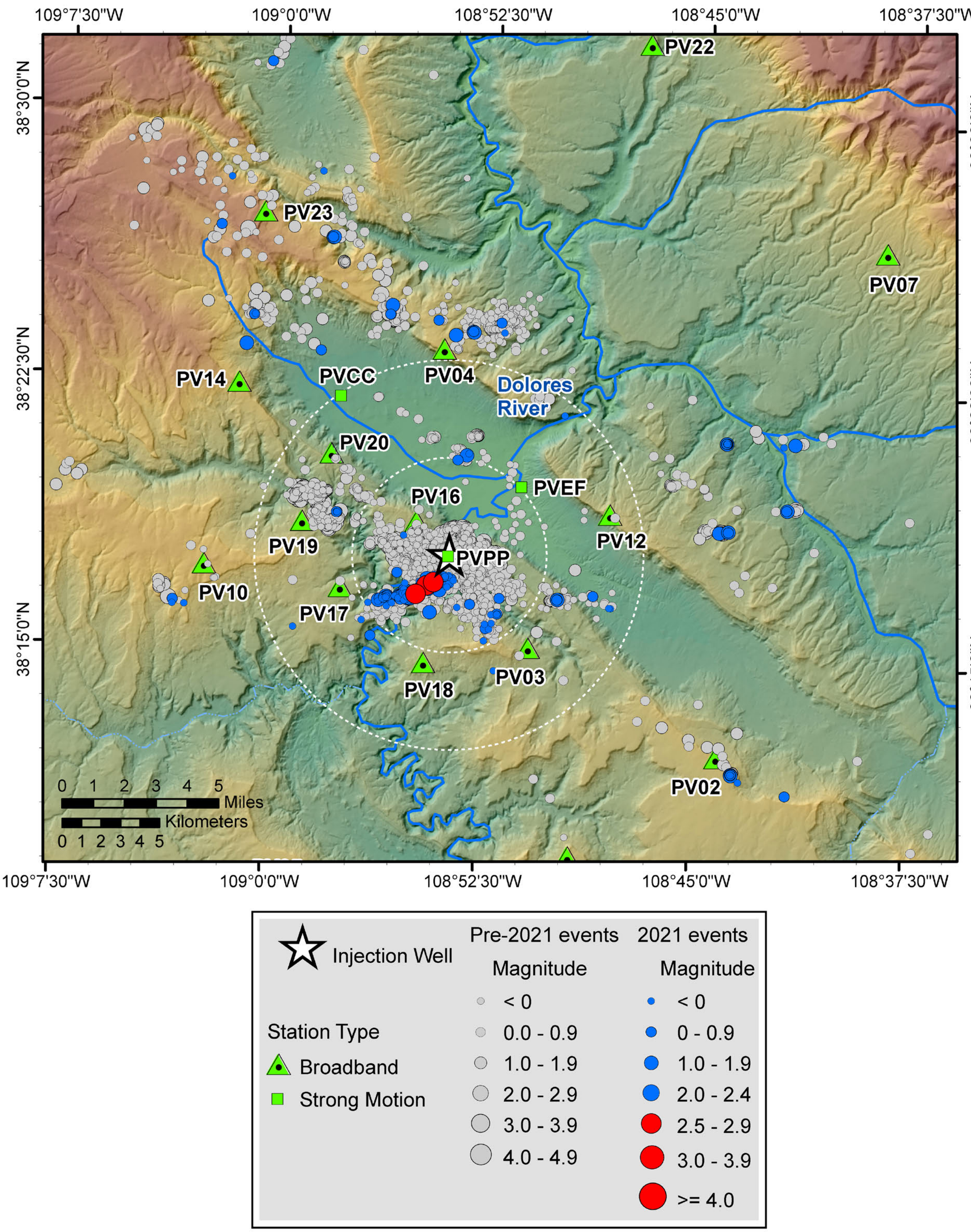

Figure IV-2: Locations of local earthquakes recorded by PVSN by magnitude. The earthquakes in 2021 with $M_D \geq 2.5$ are shown in red; those with smaller magnitudes are shown in blue. The epicenters of earthquakes recorded prior to 2021 are shown in gray for reference.

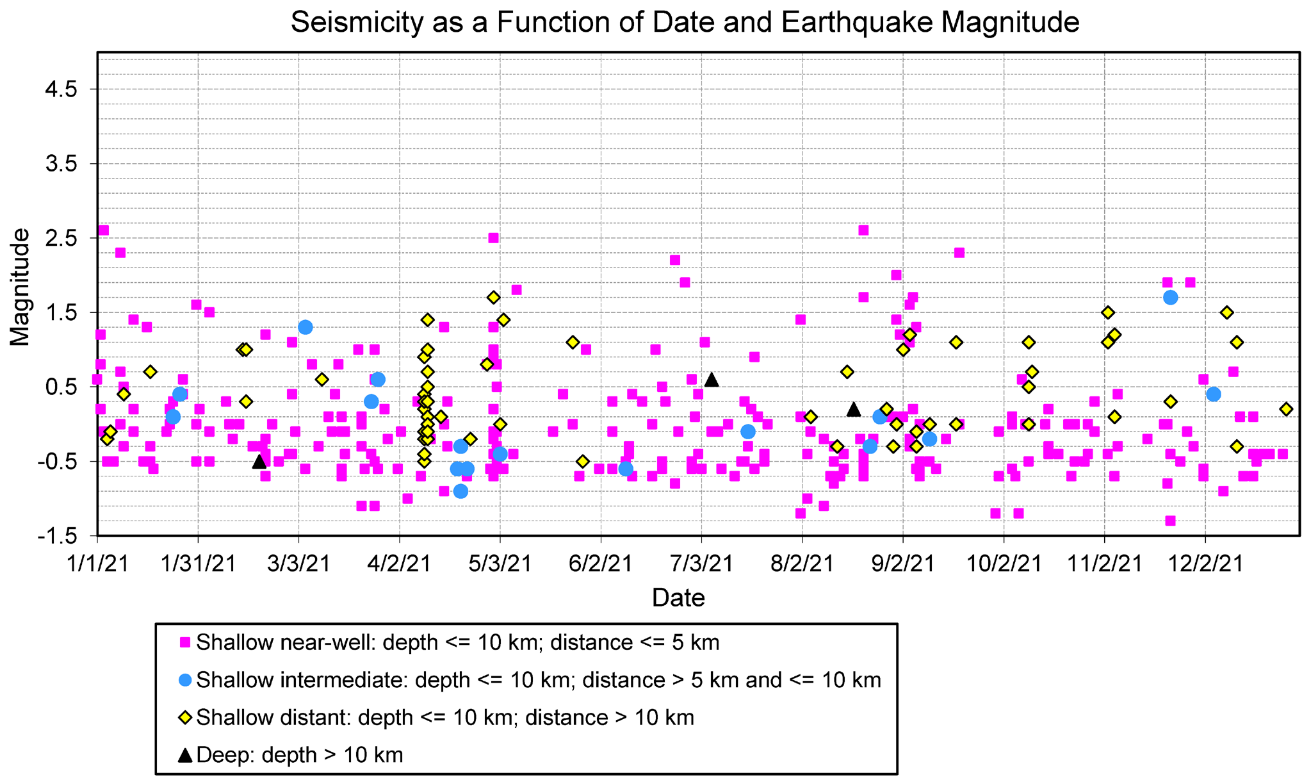

Figure IV-3: Earthquakes recorded by PVSN during 2021 plotted as a function of date, magnitude, and event location category. Duration magnitudes are used for events with M_D < 3.0, and moment magnitudes are used for larger events.

B. Seismicity Near the Injection Well

Hypocenters of the earthquakes that occurred in 2021 within 7 to 9 km of the injection well are compared to those from previous years in the map in Figure IV-4 and in the vertical cross sections in Figure IV-5. In these figures, the earthquakes that occurred in 2021 and those that occurred in previous years are each separated into two categories based on how precise the computed hypocenters are relative to the other events. The best earthquake locations were computed using a relative earthquake location method employing precise arrival time differences between pairs of earthquakes (computed using waveform cross-correlation). The poorer earthquake locations were computed independently using manually determined absolute arrival times because their waveform data were either not of sufficient quantity or quality to include these events in the relative location.

As seen in the map and cross sections, most of the earthquakes induced within ~7-9 km of the injection well during 2021 occurred either near the rupture plane of the March 2019 M_W 4.5 earthquake (white rectangle in Figure IV-4) or in a cluster southwest of the rupture plane (blue circle in Figure IV-4 and Figure IV-5b). Seismicity in the western cluster first began within days of the March 2019 M_W 4.5 earthquake, consistent with aftershock activity expected based on models of Coulomb stress transfer from the main shock fault rupture (Block et al., 2020). However, earthquake rates and magnitudes increased unexpectedly in November 2020. Recent geomechanical modeling indicates that stress changes associated with depressurization of the reservoir following the shut-in of the injection well in March 2019 may be contributing to the higher-than-expected rates of earthquakes in this area (personal comm., L. Block).

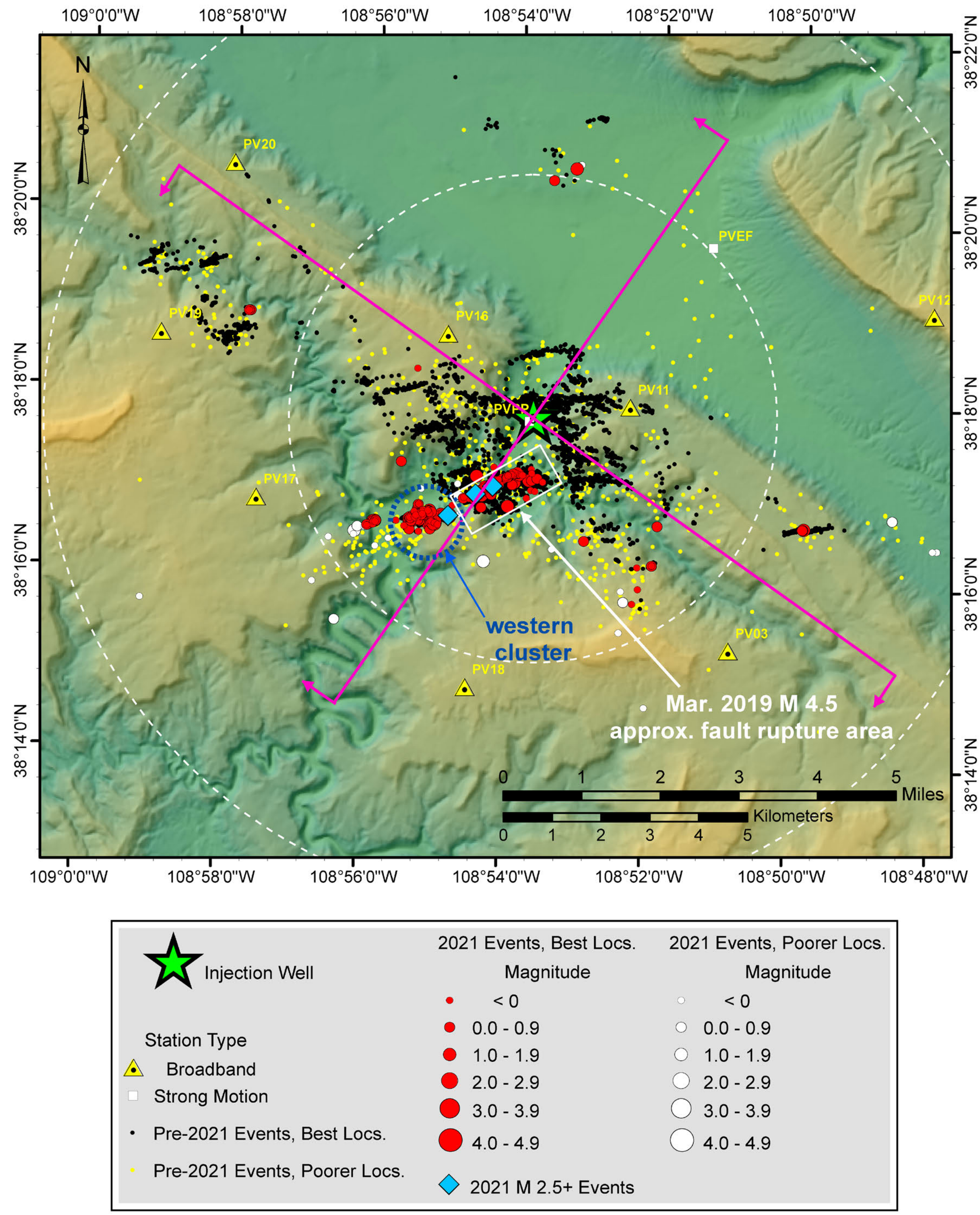

Figure IV-4: Map showing the epicenters of earthquakes (≤ 10 km depth) in the vicinity of the injection well in 2021, compared to the locations of previously induced events. The white dashed circles indicate radial distances of 5 and 10 km from the injection well. The magenta lines indicate the orientations of the cross sections presented in Figure IV-5.

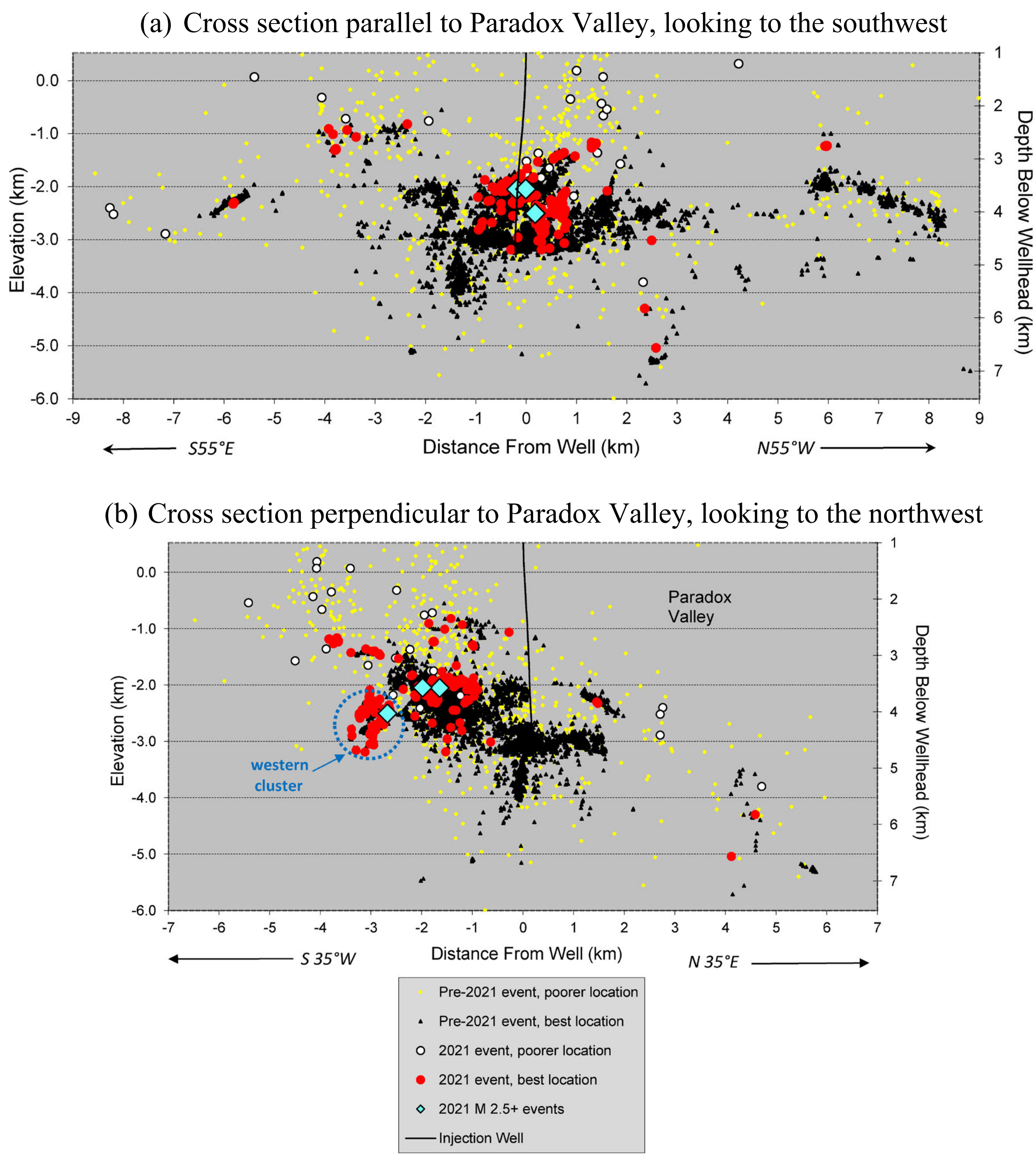

Figure IV-5: Vertical cross sections showing the hypocenters of earthquakes occurring within approximately 7-9 km of the injection well in 2021, compared to the locations of previously induced events: (a) section parallel to Paradox Valley (b) section perpendicular to Paradox Valley. The orientations of the cross sections are indicated by the magenta lines in Figure IV-4.

C. Distant Earthquakes

In 2021, 66 local earthquakes were detected at distances greater than 10 km from the injection well. Of these, 63 earthquakes have depths ≤ 10 km (relative to the ground surface at the injection well). Based on the spatiotemporal evolution of the earthquakes observed since monitoring began in 1985, we interpret these 63 shallow distant earthquakes as likely induced by PVU brine injection. Two of the three distant earthquakes with depths > 10 km have been interpreted as naturally occurring, and any potential relation of the third deep event to PVU injection is unclear (Section IV-A). These deep events are not included in the discussion below.

Of the 63 shallow distant earthquakes, 20 occurred at or near the northern end of Paradox Valley (Figure IV-1), where seismicity has been detected every year since 2000. For comparison, 30 events occurred in this northern-valley region in 2020, and 725 events occurred in 2019. Historically, the annual number of northern-valley events has varied widely, ranging from 2 to 725 events per year from 2000 to 2021. The northern-valley earthquakes recorded during 2021 range in magnitude from M_D -0.3 to M_D 1.2. Depth estimates of 18 of the 20 earthquakes range from 3.6 to 7.9 km (relative to the ground surface at the PVU injection well), consistent with depth estimates of previous northern-valley events. The remaining two earthquakes, which occurred near seismic station PV04, have anomalously shallow depth estimates of 1.6 to 1.8 km.

The seismicity in the northern-valley area is expanding to the northwest, beyond the northwestern perimeter of the Paradox Valley Seismic Network (Figure IV-1). Uncertainties in the computed locations and depths of earthquakes greatly increase when they occur outside the perimeter of the seismic monitoring network. Earthquakes are already occurring up to roughly 7 km outside the northwestern perimeter of PVSN. Hence, it will be difficult to monitor the further expansion of the seismicity to the northwest with the current network configuration.

In 2021, 26 earthquakes occurred east of Paradox Valley and south of the Dolores River, at distances of ~14 km to ~19 km from the well (Figure IV-1, yellow circles east of seismic station PV12). These earthquakes include the previously discussed swarm of 20 events that occurred on April 10-11 (Section IV-A; Figure IV-1). The magnitudes of the 26 eastern events range from M_D -0.5 to M_D 1.7, and their depth estimates range from 5.4 to 9.9 km (relative to the ground surface at the PVU injection well). Earthquakes have occurred in this area since 2007. Seismicity rates have generally increased over time, although the number of earthquakes recorded during 2021 (26) is less than the number recorded during the previous year (32). These earthquakes are interpreted as being induced by PVU injection.

Fifteen earthquakes occurred 18.3 to 21.2 km southeast of the PVU injection well during 2021 (Figure IV-1, yellow circles near seismic station PV02). The magnitudes of these events range from M_D -0.3 to M_D 1.1, and their depth estimates range from 5.8 to 8.8 km. Earthquakes have only been detected in this general area since 2014, and their occurrence is interpreted as a geographical expansion of the induced seismicity related to PVU injection.

The remaining two shallow distant earthquakes occurred west of the injection well, at distances of 13.9 and 14.5 km (Figure IV-1, yellow circles near seismic station PV10). These two earthquakes have magnitudes of M_D -0.5 and M_D -0.3 and depth estimates of 1.9 and 2.2 km, respectively. The epicenters and depth estimates of these earthquakes have relatively high uncertainty because these events are outside the perimeter of the seismic network. Despite the relatively poor constraints on the hypocenters of these earthquakes, they are clearly much shallower than nearby earthquakes that have been interpreted as naturally occurring (nearby white and purple circles in Figure IV-1). They may be related to PVU injection operations, potentially triggered by stress changes associated with reservoir inflation/deflation.

D. Seismicity Trends

The total number of earthquakes observed within 5 km of the injection well decreased substantially in 2021 compared to 2020, while the number of earthquakes at greater distances changed only slightly (Table IV-2). During 2021, 273 earthquakes were detected within 5 km of the injection well, compared to 464 events in 2020, a decrease of 41%. A decrease in near-well seismicity rates was expected because the rates of aftershocks of the March 2019 M_W 4.5 earthquake are decaying over time. At distances greater than 5 km from the well, the number of induced earthquakes recorded in 2021 changed by less than 10% compared to the previous year (Table IV-2, second and third rows).

Table IV-2: Number of Earthquakes of All Magnitudes Recorded in 2020 and 2021

Distance Range (km)	Number of Events Recorded in 2020	Number of Events Recorded in 2021	Percent Change
0 to 5	464	273	-41%
> 5 to 10	16	17	6%
> 10	68	63	-7%

Because the ability to detect very small earthquakes can vary over time, depending on both the operating status of the seismic network and background seismic noise levels, more robust estimates of the variation in seismicity rate are determined by comparing the occurrence of earthquakes with magnitude ≥ M_D 0.5 (PVSN's approximate magnitude completeness threshold). These values for the last two years are presented in Table IV-3. A substantial decrease in seismicity rate is still observed within 5 km of the well (49%). This table indicates a 40% decrease in seismicity rate in the 5-to-10-km distance range, but this statistic is not robust because of the small number of events in the data sets. At distances greater than 10 km from the well, the rate of earthquakes with magnitude ≥ M_D 0.5 decreased by 16% in 2021 compared to 2020.

Table IV-3: Number of Earthquakes With Magnitude ≥ M_D 0.5 Recorded in 2020 and 2021

Distance Range (km)	Number of Events Recorded in 2020	Number of Events Recorded in 2021	Percent Change
0 to 5	102	52	-49%
> 5 to 10	5	3	-40%*
> 10	31	26	-16%

*Not reliable because of the small number of earthquakes in the data sets.

The maximum earthquake magnitudes observed in each distance range for the previous two years are compared in Table IV-4. As with other plots presented in this report, duration magnitudes are reported for M_D < 3.0, and moment magnitudes are used for larger events (because the duration magnitude scale saturates above ~M_D 3.0). In the near-well area, the maximum observed earthquake magnitude decreased from M_W 3.9 in 2020 to M_D 2.6 in 2021. The maximum magnitude also decreased for the distant earthquakes (greater than 10 km from the injection well), from M_D 2.5 in 2020 to M_D 1.7 in 2021. In contrast, the maximum observed magnitude in the intermediate distance range (5 to 10 km from the well) increased from M_D 1.0 in 2020 to M_D 1.7 in 2021.

Table IV-4: Maximum Earthquake Magnitudes in 2020 and 2021

Distance Range (km)	Mmax in 2020	Mmax in 2021
0 to 5	M_W 3.9	M_D 2.6
> 5 to 10	M_D 1.0	M_D 1.7
> 10	M_D 2.5	M_D 1.7

Longer-term trends of earthquake rates and magnitudes are presented in three plots described below. Events with M_D ≥ 0.5 and depth ≤ 12 km are included in these plots. First, the bubble plots in Figure IV-6 show the historical occurrence of seismicity as a function of date and earthquake magnitude during long-term injection at PVU (since 1996). The area of each circle in these plots is scaled by the number of earthquakes in a given quarter-year and magnitude range. Individual bubble plots are included for earthquakes occurring within 5 km of the injection well, between 5 and 10 km from the well, and more than 10 km from the well. The daily average injection rates are included in Figure IV-6 for reference. In order to better observe the trends in recent years, similar plots that only include data from 2011 to 2021 are presented in Figure IV-7. Lastly, we show the annual seismicity rates for the last 15 years, for the different distances from the well, in Figure IV-8.

These plots show that the seismicity rates and maximum magnitudes for the near-well area (within 5 km of the well) remained fairly high in 2021 compared to other periods following extended injection well shut-ins, such as the 2-month shut-in in 2005-2006 and the 3-month shut-in in 2013 (Figure IV-6b). These elevated rates are due to the continued occurrence of aftershocks of the March 2019 M_W 4.5 earthquake and the continued seismic activity in the relatively new seismicity cluster west of this main shock (discussed in Section IV-B). Although the annual rate of near-well seismicity decreased in 2021 compared to 2020 and 2019, it was still higher than any of the nine years preceding the March 2019 M_W 4.5 earthquake (Figure IV-8a).

The seismicity rates at distances of 5 to 10 km from the injection well in 2021 were low compared to historical trends. Annual seismicity rates in this distance range have been relatively low for the last three years, since the injection well was shut down in early 2019 (Figure IV-8b). The rates were also low in 2014-2015, following a 3-month injection well shut-in in early to mid-2013 (Figure IV-8b). This pattern suggests that earthquakes at these distances may be more sensitive to injection operations than a simple pore pressure diffusion model would suggest.

The annual rate of distant M 0.5+ events, those occurring more than 10 km from the injection well, have historically been highly variable (Figure IV-6d). The annual rate observed in 2021 was neither exceptionally high nor low (Figure IV-8c).

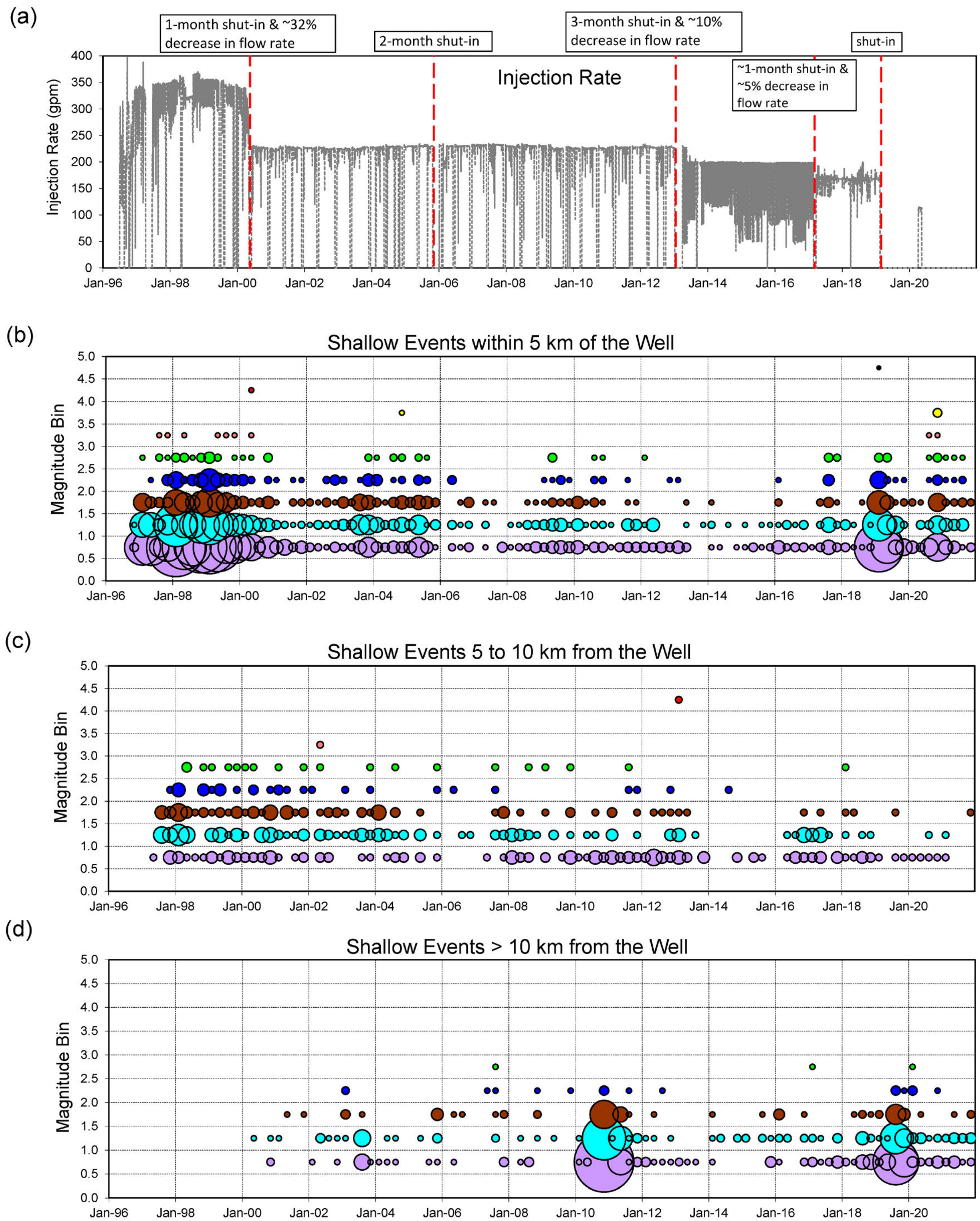

Figure IV-6: Injection flow rates (a) and occurrence of seismicity with $M_D \geq 0.5$ and depth ≤ 12 km as a function of date and magnitude: (b) within 5 km of the injection well, (c) at distances of 5 to 10 km from the well, and (d) more than 10 km from the well. In the seismicity plots, the area of each circle is scaled by the number of earthquakes in a given quarter-year and magnitude range; each plot is scaled independently. Duration magnitudes are used for events with $M_D < 3.0$, and moment magnitudes are used for larger events.

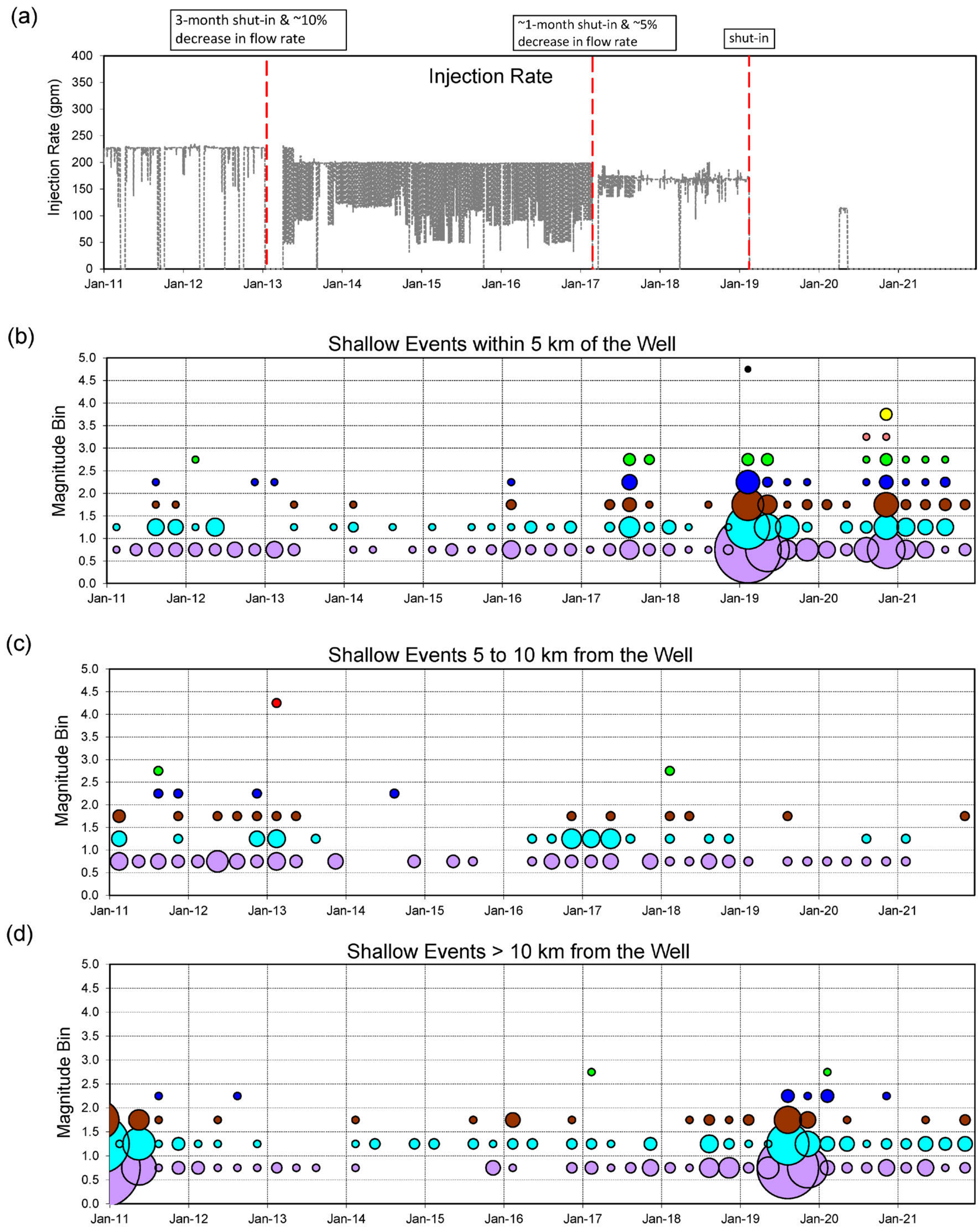

Figure IV-7: Same as Figure IV-6, but only showing data from 2011-2021.

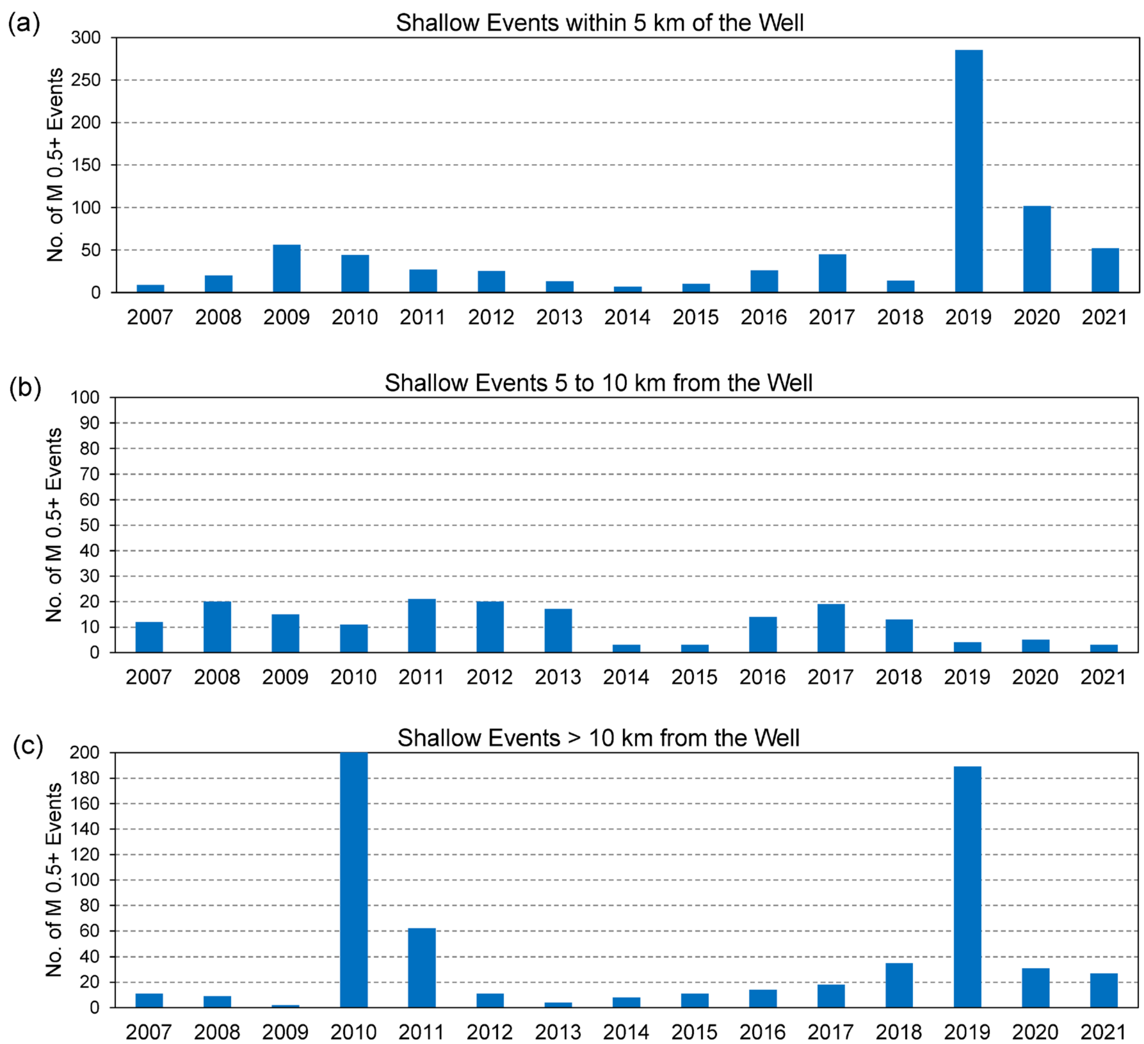

Figure IV-8: Annual numbers of earthquakes with $M_D \geq 0.5$ and depth ≤ 12 km: (a) within 5 km of the injection well, (b) 5 to 10 km from the well, and (c) more than 10 km from the well. Data for the last 15 years are shown.

V. Conclusions

PVSN recorded 356 local earthquakes during 2021. The spatiotemporal seismicity trends observed since 1985 provide strong evidence that 353 of these events were induced by PVU brine injection. Two of the remaining three earthquakes are interpreted as naturally occurring, while any potential relation of the third event to PVU injection is unclear.

Three of the induced earthquakes recorded during 2021 have magnitudes ≥ M_D 2.5. This magnitude threshold is significant because it is the approximate minimum magnitude for ground shaking to be felt in the Paradox Valley area. Two of these M_D 2.5+ earthquakes occurred near the rupture plane of the March 2019 M_W 4.5 induced earthquake and are interpreted as aftershocks of that event. The remaining M_D 2.5+ earthquake occurred about 500 m west of this rupture plane. This event occurred in an area where aftershocks of the March 2019 M_W 4.5 earthquake were observed in the days following the main shock and where aftershocks are expected based on models of Coulomb stress transfer from the main shock fault rupture. However, earthquake rates in this area have been higher than expected based on aftershock rate models since late 2020, and recent geomechanical modeling indicates that stress changes related to reservoir depressurization may be contributing to the seismic activity here.

Near-well seismicity rates declined ~49% in 2021 compared to 2020, as the rate of aftershocks of the March 2019 M_W 4.5 earthquake decayed. However, the annual seismicity rate was still higher than any of the nine years preceding the 2019 M_W 4.5 earthquake.

Seismicity rates at distances greater than 5 km from the PVU injection well changed relatively little in 2021 compared to the previous year. At distances of 5 to 10 km from the well, the seismicity rate was relatively low relative to longer-term historical trends. The rate of induced seismicity at distances greater than 10 km from the well decreased by approximately 16% in 2021 compared to 2020 and was moderate compared to longer-term historical trends. Induced seismicity is occurring several km outside the perimeter of PVSN, decreasing the ability of the seismic network to detect and provide accurate locations for all of the induced earthquakes.

PVSN performed well during 2021, with an annual network uptime of 100%. Uptimes of individual seismic stations ranged from 38% to 100%, with 20 of the 23 stations having uptimes ≥ 98%.

VI. References

Block, L., Wood, C. K., Besana-Ostman, G., Schwarzer, J., Ball, J., and Kang, J. B., 2021, *2020 Annual Report, Paradox Valley Seismic Network, Paradox Valley Unit, Colorado:* Technical Memorandum No. 86-68330-2021-7, Bureau of Reclamation, Denver, Colorado, 101 pp.

Block, L. V., Besana-Ostman, G., and Wood, C. K., 2020, *Analysis of the March 4, 2019 Earthquake and Its Aftershocks:* Technical Memorandum No. 86-68330-2020-07, Bureau of Reclamation, Denver, Colorado, 149 pp.

Block, L. V., and Wood, C. K., 2009, *Overview of PVU-Induced Seismicity from 1996 to 2009 and Implications for Future Injection Operations: Technical Memorandum No. 86-68330-2009-22:* Technical Memorandum No. 86-68330-2009-22, Bureau of Reclamation, Denver, Colorado, 16 pp.

Block, L. V., Wood, C. K., Yeck, W. L., and King, V. M., 2014, The 24 January 2013 ML 4.4 Earthquake near Paradox, Colorado, and Its Relation to Deep Well Injection: *Seismological Research Letters*, v. 85, no. 3, p. 609-624.

Bremkamp, W., and Harr, C. L., 1988, *Area of Least Resistance to Fluid Movement and Pressure Rise:* Report to the Bureau of Reclamation, 49 pp.

Envirocorp Services and Technology Inc., 1993, *Core Fluid Compatibility Test:* Report to the Bureau of Reclamation, 27 pp.

Gibbs, J. F., Healy, J. H., Raleigh, C. B., and Coakley, J., 1973, Seismicity in the Rangely, Colorado, Area: 1962-1970: *Bulletin of the Seismological Society of America*, v. 63, no. 5, p. 1557-1570.

Hsieh, P. A., and Bredehoeft, J. D., 1981, A reservoir analysis of the Denver earthquakes; a case of induced seismicity: *Journal of Geophysical Research. B*, v. 86, no. 2, p. 903-920.

Kharaka, Y. K., Ambats, G., Thordsen, J. J., and Davis, R. A., 1997, Deep well injection of brine from Paradox Valley, Colorado: Potential major precipitation problems remediated by nanofiltration: *Water Resources Research*, v. 33, no. 5, p. 1013-1020.

Mahrer, K., Ake, J., O'Connell, D., and Block, L., 2003, *2002 Status Report - Paradox Valley Seismic Network, Paradox Valley Project, Southwestern Colorado:* Technical Memorandum No. D8330-2003-009, Bureau of Reclamation, Technical Service Center, Denver, Colorado, 86 pp.

McKinley, R. M., 2001, *Comments on 19-Jun-2001 Mechanical Caliper Survey and 20-Jun-2001 Temperature Survey from Paradox Valley Injection Well #1*, 14 pp.

Nicholas, A., 2001, August 23rd Paradox Operations Meeting, Denver TSC, Internal Memorandum, Bureau of Reclamation,pp. 4.

Nicholson, C., and Wesson, R. L., 1990, *Earthquake Hazard Associated With Deep Well Injection - A Report to the U.S. Environmental Protection Agency:* Bulletin 1951, U.S. Geological Survey, 86 pp.

O'Connell, D. R. H., 2008, *Probabilistic Seismic Hazard Analysis, Hungry Horse Dam, Hungry Horse Project, Montana:* Technical Memorandum No. 86-68321-2008-12, Bureau of Reclamation, Technical Service Center, Denver, Colorado, 89 pp.

Petrotek, 2021, *PVU Injection Well #1 Evaluation 2021:* Report to the Bureau of Reclamation, 225 pp.

Raleigh, C. B., Healy, J. H., and Bredehoeft, J. D., 1976, An Experiment in Earthquake Control at Rangely, Colorado: *Science*, v. 191, no. 4233, p. 1230-1237.

Subsurface Technology, 2001, *Report of Operations:* Report to the Bureau of Reclamation, Houston, Texas, 24 pp.

Walker, J. D., Geissman, J. W., Bowring, S. A., and Babcock, L. E., 2013, The Geological Society of America Geologic Time Scale: *GSA Bulletin*, v. 125, no. 3-4, p. 259-272.

Wood, C. K., Block, L. V., King, V. M., and Yeck, W. L., 2016, *The ML 4.4 Earthquake of January 24, 2013, Near Paradox, Colorado, and Implications for Near-term Injection Operation*, Bureau of Reclamation, Denver, Colorado, 150 pp.

Appendix A

2021 Site Visit Reports

Paradox Valley Seismic Network
Site Visit Report

Site Visit Number: PVSN-2021-1
Prepared by: Justin Ball
Departure Date: May 3, 2021
Return Date: May 8, 2021
Personnel: Chris Wood, Justin Ball

Primary Purpose: Main priorities were to restore power at PV19, troubleshoot GPS power issue at PV12, complete the ground system installations at all three strong motion sites, and perform routine testing and battery replacement at 8 other stations.

Details:
Power was restored at PV19 by repairing the surge protection block (which had an open internal connection), replacing failed batteries and ProStar 30 solar power controller.

We attempted to reproduce the intermittent GPS power failure at PV12 by using freezer spray (to simulate the winter conditions that we believe caused the failure). We also disconnected and reconnected GPS power at the WAGO block, and weren't able to reproduce the failure mode on this trip. Further investigation will be necessary on future site visits.

At the three strong-motion stations (PVCC, PVEF, and PVPP), we completed the installation of improved grounding systems by connecting ground rods to new ground rails we installed inside the station enclosures. Additionally, we ran new grounding cables up the antenna masts and performed routine radio and antenna testing. All three stations were observed to be performing nominally after upgrades.

New batteries were installed at stations PV03, PV15, PV18, PV19, and PV20, along with routine testing of antennas and power systems at those stations as well as PV02, PV04, PV07, and PV13.

Seismometer vault inspections were performed at PV02 and PV18, both of which were found to be dry and in nominal condition. Seismometers at those sites were observed to remain level and properly oriented.

At the Hopkins Field site, we performed routine antenna and radio tests and replaced the radio power supply with an upgraded unit. The NetBotz environmental monitoring system's camera was configured and adjusted for an optimum viewing angle of the server rack and building entrance. Additionally, we inspected the backup generator, tested it, and recorded operational logs from its control unit. All systems at Hopkins Field were observed to be in good working order.

Summary of Work by Site:

Site	Preventive Maintenance					Comments
	Checked Power System	Replaced Batteries	Performed Antenna Test	Performed Wattmeter Test	Inspected Vault	
PV02	X		X		X	Opened vault, All OK
PV03	X	X	X			Replaced Batteries, All OK
PV04	X		X			All OK
PV07	X		X			All OK
PV12	X		X			Attempted to troubleshoot GPS issue, could not reproduce the problem. Reconnected WAGO block, tried freezer spay.
PV13	X		X			All OK.
PV15	X	X	X			Replaced batteries, All OK.
PV18	X	X	X		X	Replaced batteries, opened vault, All OK
PV19	X	X	X			No station power on arrival, batteries all bad, repaired surge block and replaced batteries and ProStar controller.
PV20	X	X	X			Replaced batteries, All OK.
PVCC	X		X			Completed ground system upgrades
PVEF	X		X			Completed ground system upgrades
PVPP	X		X			Completed ground system upgrades
Hopkins Field	X		X			Configured NetBotz camera and changed radio power supply

Abbreviations:

AP-1 – access point #1 antenna on the tower at the Hopkin's Field data communications center; receives radio data communications from individual stations PV01, PV07, and PV15

AP-2 – access point #2 antenna on the tower at the Hopkin's Field data communications center; receives radio data communications from radio repeater station PV02

AP-3 – access point #3 antenna on the tower at the Hopkin's Field data communications center; receives radio data communications from radio repeater stations PV04 and PV12

Chem rod – chemical ground rod that is part of the lightning protection grounding system at station PV02

DM24-BOB - seismic station electronics break-out-box located in enclosure; conditions power supply for the DM24 seismometer digitizer

GPS – refers to antenna that receives Global Positioning System satellite data to provide station timing

GPS-BOB - seismic station electronics break-out-box located in enclosure; serves as junction for dirty and clean power supplies and data communications

LVD - low-voltage disconnect

SPM – station power monitor

WAGO – refers to special tool needed for engaging (or disengaging) some electronics connections within station enclosure; manufactured by WAGO Corporation

Paradox Valley Seismic Network
Site Visit Report

Site Visit Number: PVSN-2021-2
Prepared by: Justin Schwarzer
Departure Date: 10/18/2021
Return Date: 10/20/2021
Personnel: Justin Schwarzer and Chris Wood

Purpose: PV19 was visited to troubleshoot the issues with the seismometer which had been offline since July 2021. GPS, DM24, and WAGO connections were tested, and no faults were found. A hard reset was performed on the seismometer; after reset seismometer returned to a functional state. A previously repaired WAGO surge protector was replaced with a new unit.

Standard radio and battery testing was performed at PV01, PV02, PV14, PV19. All standard testing was within acceptable ranges and no repairs or modifications were needed on this trip.

A gallon of water was added to the chemical ground rod at PV02.

PVCC was briefly visited. The interior of the fiberglass enclosure was found to be slightly flooded with water from recent rains getting in through enclosure doors. The water was removed, and the system's electrical connections were reviewed. Modifications to enclosure may be needed in future to ensure the site does not continue to flood.

The Hopkins Field server building was visited to make modifications to the NetBotz Wall Monitor 355 wiring in an attempt to reduce error messages. Standard radio testing was not performed this trip.

Appendix B

PVSN 2021 Local Earthquake Catalog

Table B-1: Local Earthquakes Recorded by PVSN During 2021

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]		Horizontal Distance from Injection Well (km)
						M_D	M_W	
1/1/21	12:03:57	38.2751	-108.9183	-3.1900	4.7	0.6	1.2	3.1
1/2/21	9:44:38	38.2774	-108.9185	-2.4910	4.0	0.8	1.4	3.0
1/2/21	11:37:21	38.2775	-108.9224	-1.3590	2.9	0.2	0.5	3.2
1/2/21	17:17:37	38.2695	-108.9055	1.8800	-0.4	1.2	1.4	3.1
1/3/21	3:02:22	38.2777	-108.9142	-2.5050	4.0	2.6	2.5	2.7
1/3/21	21:27:04	38.2778	-108.9143	-2.5190	4.0	-0.1	0.8	2.7
1/4/21	8:10:40	38.4713	-108.9773	-5.7900	7.3	-0.2	1.2	20.7
1/4/21	9:20:37	38.2781	-108.9142	-2.3550	3.9	-0.5		2.7
1/5/21	7:15:18	38.4675	-109.0310	-2.0800	3.6	-0.1		22.4
1/6/21	10:11:15	38.2781	-108.9138	-2.4300	4.0	-0.5	0.5	2.6
1/8/21	6:19:02	38.2852	-108.9006	-1.9810	3.5	0.0	0.6	1.4
1/8/21	8:46:48	38.2776	-108.9163	-2.5330	4.1	0.7	1.2	2.8
1/8/21	14:34:03	38.2761	-108.9181	-2.8780	4.4	2.3	2.0	3.0
1/9/21	3:38:39	38.4411	-108.9703	-4.0560	5.6	0.4		17.3
1/9/21	9:24:45	38.2730	-108.9420	-1.5700	3.1	-0.3	0.6	4.9
1/9/21	20:15:24	38.2766	-108.9208	-2.5190	4.0	0.5	1.2	3.2
1/12/21	0:22:25	38.2781	-108.9209	-1.3990	2.9	0.2	0.9	3.1
1/12/21	1:16:49	38.2822	-108.9073	-2.1840	3.7	-0.1	0.7	1.9
1/12/21	11:42:42	38.2768	-108.9178	-2.7110	4.2	1.4	1.5	3.0
1/15/21	23:37:10	38.2833	-108.9063	-1.9070	3.4	-0.5	0.5	1.8
1/16/21	16:53:00	38.2775	-108.9198	-2.4070	3.9	1.3	1.5	3.0
1/17/21	8:49:30	38.2849	-108.9010	-2.0350	3.6	-0.3		1.4
1/17/21	11:05:07	38.2837	-108.9021	-3.1870	4.7	-0.5	0.9	1.6
1/17/21	13:38:24	38.1902	-108.6937	-6.7000	8.2	0.7	1.0	21.2
1/18/21	20:45:04	38.2807	-108.9083	-2.2200	3.7	-0.6	0.3	2.1
1/22/21	10:52:08	38.2717	-108.9310	0.1900	1.3	-0.1	0.6	4.2
1/23/21	4:23:58	38.2853	-108.8999	-1.9600	3.5	0.2	1.0	1.3
1/23/21	10:25:33	38.2837	-108.9043	-1.9790	3.5	0.0	1.0	1.6
1/24/21	5:06:56	38.2851	-108.9007	-2.0060	3.5	0.3	1.0	1.4
1/24/21	15:21:55	38.2795	-108.8102	-2.8900	4.4	0.1	0.7	7.7
1/26/21	13:47:33	38.2578	-108.9400	1.8100	-0.3	0.4	1.1	5.8
1/27/21	3:05:43	38.2762	-108.9181	-2.8420	4.4	0.6	1.3	3.0
1/27/21	6:56:57	38.2855	-108.8978	-2.3220	3.8	0.4	1.1	1.3
1/31/21	2:55:49	38.2779	-108.9158	-2.4570	4.0	1.6	1.6	2.8
1/31/21	13:40:06	38.2837	-108.9045	-1.9460	3.5	-0.5		1.7
1/31/21	13:41:41	38.2836	-108.9044	-1.9700	3.5	0.0		1.7
2/1/21	13:28:42	38.2780	-108.9198	-2.2830	3.8	0.2	0.7	3.0
2/4/21	0:36:36	38.2840	-108.9038	-1.9500	3.5	-0.5		1.6
2/4/21	7:59:12	38.2765	-108.9165	-2.7980	4.3	-0.1	1.0	2.9
2/4/21	10:53:53	38.2773	-108.9161	-2.6100	4.1	-0.5		2.8

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]		Horizontal Distance from Injection Well (km)
						M_D	M_W	
2/4/21	15:01:39	38.2772	-108.9213	-2.4400	4.0	1.5	1.5	3.1
2/9/21	6:27:39	38.2778	-108.9144	-2.5270	4.1	0.3	1.0	2.7
2/10/21	5:56:31	38.2794	-108.9065	-2.5510	4.1	0.0	0.8	2.2
2/11/21	10:04:13	38.2772	-108.9148	-2.7030	4.2	-0.2	0.5	2.8
2/11/21	12:58:42	38.2784	-108.9188	-1.4650	3.0	-0.2		2.9
2/13/21	22:17:39	38.2830	-108.9041	-2.2530	3.8	0.0	1.1	1.7
2/14/21	5:34:57	38.3993	-108.8852	-3.8510	5.4	1.0	1.8	11.4
2/15/21	0:39:50	38.3996	-108.8856	-3.8670	5.4	1.0	1.4	11.5
2/15/21	1:43:42	38.3997	-108.8857	-3.7540	5.3	0.3	1.0	11.5
2/17/21	22:05:23	38.2781	-108.9156	-2.4170	3.9	-0.3	0.4	2.7
2/19/21	11:29:51	38.3625	-108.8302	-12.1700	13.7	-0.5		9.3
2/20/21	16:41:13	38.2840	-108.9036	-1.9600	3.5	-0.3		1.6
2/21/21	10:32:18	38.2837	-108.9122	-2.4100	3.9	-0.4	0.6	2.1
2/21/21	10:48:28	38.2829	-108.9057	-2.0130	3.5	1.2	1.5	1.8
2/21/21	11:23:36	38.2829	-108.9057	-1.9910	3.5	-0.5		1.8
2/21/21	11:28:30	38.2828	-108.9062	-2.0110	3.5	-0.7		1.8
2/21/21	11:46:28	38.2828	-108.9059	-2.0380	3.6	-0.2	1.0	1.8
2/21/21	22:38:33	38.2835	-108.9047	-1.9890	3.5	-0.5		1.7
2/23/21	8:40:05	38.2782	-108.9181	-2.2500	3.8	0.0	0.8	2.9
2/25/21	15:34:31	38.2697	-108.8658	-1.3140	2.8	-0.5		3.9
2/28/21	8:41:02	38.2765	-108.9263	-1.4250	2.9	-0.4		3.5
3/1/21	7:07:39	38.2849	-108.9017	-1.9850	3.5	0.4	0.9	1.4
3/1/21	12:29:33	38.2826	-108.9040	-2.3220	3.8	-0.4		1.7
3/1/21	17:56:19	38.2764	-108.9230	-2.5420	4.1	1.1	1.4	3.3
3/2/21	18:10:43	38.2767	-108.9231	-2.5140	4.0	-0.1	0.9	3.3
3/5/21	4:53:59	38.2774	-108.8308	-2.3260	3.9	1.3	1.4	6.0
3/5/21	12:21:03	38.2831	-108.9055	-1.9800	3.5	-0.6		1.8
3/7/21	18:39:05	38.2750	-108.9231	-2.9000	4.4	0.8	1.4	3.4
3/9/21	16:00:59	38.2767	-108.9230	-2.5320	4.1	-0.3	0.9	3.3
3/10/21	21:43:21	38.3887	-108.9748	-2.3700	3.9	0.6	1.4	12.4
3/12/21	15:30:57	38.2838	-108.8994	-2.4470	4.0	0.1	0.8	1.5
3/13/21	8:11:50	38.2775	-108.9149	-2.6640	4.2	-0.1		2.7
3/14/21	21:20:58	38.2756	-108.9329	-1.1910	2.7	0.4	1.2	4.0
3/15/21	15:21:45	38.2847	-108.8949	-2.2730	3.8	0.8	1.2	1.3
3/16/21	7:16:13	38.2755	-108.9331	-1.1810	2.7	0.1	0.7	4.1
3/16/21	7:29:28	38.2755	-108.9331	-1.1910	2.7	-0.1		4.1
3/16/21	7:31:28	38.2752	-108.9337	-1.3600	2.9	-0.7		4.1
3/16/21	7:31:59	38.2754	-108.9331	-1.1850	2.7	-0.6		4.1
3/17/21	2:02:35	38.2826	-108.9063	-2.0470	3.6	-0.1		1.8
3/17/21	9:03:10	38.2860	-108.8986	-1.9340	3.5	-0.4		1.2
3/17/21	19:15:40	38.2843	-108.9028	-1.9710	3.5	-0.4		1.5

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]		Horizontal Distance from Injection Well (km)
						M_D	M_W	
3/21/21	11:18:59	38.2852	-108.9078	-2.1660	3.7	1.0	1.0	1.7
3/22/21	4:25:55	38.2697	-108.8661	-1.2930	2.8	-0.3		3.9
3/22/21	8:18:45	38.2861	-108.8980	-1.9900	3.5	0.1		1.2
3/22/21	9:25:18	38.2697	-108.8661	-1.2880	2.8	0.0	0.9	3.9
3/22/21	9:25:32	38.2696	-108.8660	-1.2930	2.8	-1.1		3.9
3/23/21	1:32:20	38.2698	-108.8661	-1.3000	2.8	-0.6		3.9
3/25/21	5:01:48	38.2780	-108.9215	-2.1500	3.7	-0.4	0.6	3.1
3/25/21	6:05:44	38.3143	-108.9624	-1.2380	2.8	0.3	0.8	6.2
3/26/21	9:26:48	38.2738	-108.8822	-0.8200	2.3	0.6	1.1	2.8
3/26/21	10:01:09	38.2762	-108.9317	-1.2330	2.8	1.0	1.5	3.9
3/26/21	10:18:08	38.2756	-108.9317	-1.2670	2.8	-0.5	0.6	4.0
3/26/21	10:18:23	38.2757	-108.9317	-1.2680	2.8	-1.1		4.0
3/27/21	15:47:21	38.2693	-108.8696	-0.9310	2.5	-0.6		3.8
3/27/21	19:44:21	38.2773	-108.8310	-2.3110	3.8	0.6	1.3	6.0
3/29/21	0:22:47	38.2784	-108.9187	-1.4540	3.0	0.2	0.9	2.9
3/30/21	7:49:05	38.2869	-108.9038	-1.6580	3.2	-0.2		1.3
4/2/21	1:44:50	38.2857	-108.8997	-1.9630	3.5	-0.6		1.3
4/3/21	16:30:13	38.2828	-108.9059	-1.9420	3.5	-0.1		1.8
4/5/21	8:14:44	38.2814	-108.8960	-2.7520	4.3	-1.0		1.7
4/8/21	5:40:27	38.2860	-108.8982	-1.9830	3.5	0.3	0.9	1.2
4/9/21	5:44:39	38.2832	-108.9072	-1.7500	3.3	-0.7		1.8
4/10/21	11:09:42	38.3521	-108.7342	-3.8590	5.4	0.2		15.4
4/10/21	11:25:56	38.3521	-108.7341	-3.8690	5.4	0.4		15.4
4/10/21	17:40:48	38.3521	-108.7343	-3.8810	5.4	-0.5		15.3
4/10/21	17:42:37	38.3513	-108.7008	-5.8700	7.4	-0.5		18.0
4/10/21	18:11:58	38.3521	-108.7338	-3.8670	5.4	-0.2		15.4
4/10/21	18:13:20	38.3521	-108.7339	-3.8630	5.4	0.3		15.4
4/10/21	18:13:37	38.3520	-108.7344	-3.8660	5.4	-0.4		15.3
4/10/21	19:49:32	38.3521	-108.7344	-3.8650	5.4	0.9	1.5	15.3
4/10/21	19:51:27	38.3520	-108.7345	-3.8730	5.4	-0.1		15.3
4/10/21	23:53:14	38.3521	-108.7345	-3.8530	5.4	-0.1		15.3
4/11/21	0:13:45	38.3521	-108.7344	-3.8710	5.4	0.7		15.3
4/11/21	0:14:33	38.3521	-108.7343	-3.8610	5.4	0.1		15.3
4/11/21	0:16:32	38.3521	-108.7345	-3.8640	5.4	0.0		15.3
4/11/21	0:38:35	38.3521	-108.7344	-3.8690	5.4	1.0	1.5	15.3
4/11/21	7:54:35	38.3521	-108.7346	-3.8690	5.4	1.4	1.5	15.3
4/11/21	7:58:19	38.3521	-108.7343	-3.8720	5.4	0.3		15.3
4/11/21	7:58:36	38.3521	-108.7342	-3.8770	5.4	-0.2		15.4
4/11/21	8:11:54	38.3521	-108.7347	-3.8560	5.4	0.7		15.3
4/11/21	8:55:42	38.3520	-108.7342	-3.8620	5.4	-0.1	0.5	15.3
4/11/21	8:56:21	38.3521	-108.7341	-3.8630	5.4	0.5		15.4

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]		Horizontal Distance from Injection Well (km)
						M_D	M_W	
4/12/21	6:30:26	38.2857	-108.8979	-1.9540	3.5	-0.2		1.2
4/15/21	9:04:53	38.4064	-108.9349	-4.3180	5.8	0.1	1.0	12.7
4/16/21	8:40:08	38.2779	-108.9202	-2.3100	3.8	-0.9		3.0
4/16/21	18:04:59	38.2778	-108.9203	-2.3230	3.8	1.3	1.5	3.0
4/16/21	23:25:08	38.2771	-108.8652	-1.0630	2.6	0.0	0.9	3.4
4/17/21	7:28:31	38.2825	-108.9057	-2.2780	3.8	-0.3		1.8
4/17/21	7:49:00	38.2765	-108.9228	-2.5910	4.1	0.3	1.0	3.3
4/20/21	18:57:27	38.3142	-108.9625	-1.2310	2.8	-0.6	0.8	6.2
4/21/21	9:46:18	38.2742	-108.7995	-2.4000	3.9	-0.3		8.7
4/21/21	9:46:47	38.2742	-108.8005	-2.5200	4.0	-0.9		8.6
4/22/21	2:23:38	38.2847	-108.9026	-1.8610	3.4	-0.6		1.5
4/23/21	2:26:33	38.2746	-108.9209	-3.1610	4.7	-0.7		3.3
4/23/21	15:53:37	38.3143	-108.9623	-1.2250	2.7	-0.6		6.2
4/24/21	13:30:57	38.4043	-109.0143	-4.0900	5.6	-0.2	1.0	15.9
4/29/21	10:26:55	38.2810	-108.9107	-1.8370	3.4	0.8	1.2	2.2
4/29/21	16:27:22	38.4062	-108.9348	-4.3170	5.8	0.8	1.4	12.7
4/30/21	0:07:06	38.2856	-108.9004	-1.9410	3.5	-0.6		1.3
5/1/21	7:30:23	38.2835	-108.9040	-2.0520	3.6	2.5	2.2	1.7
5/1/21	7:46:23	38.2832	-108.9049	-2.0180	3.5	-0.7		1.7
5/1/21	9:04:03	38.2832	-108.9049	-1.9920	3.5	-0.4		1.7
5/1/21	11:10:46	38.2830	-108.9048	-2.0800	3.6	0.9	1.2	1.7
5/1/21	11:23:52	38.2836	-108.9046	-1.9490	3.5	-0.2		1.7
5/1/21	11:26:18	38.2833	-108.9046	-2.0200	3.5	1.0	1.1	1.7
5/1/21	11:56:29	38.2819	-108.9080	-2.0140	3.5	-0.2		2.0
5/1/21	12:36:22	38.2832	-108.9048	-2.0240	3.5	1.3	1.4	1.7
5/1/21	12:52:35	38.2831	-108.9049	-2.0260	3.6	0.2		1.7
5/1/21	12:54:23	38.3107	-108.7373	-7.7930	9.3	1.7	1.6	13.9
5/1/21	13:42:16	38.2831	-108.9042	-2.0860	3.6	-0.1	0.8	1.7
5/1/21	16:57:27	38.2763	-108.9173	-2.8760	4.4	-0.7	0.7	3.0
5/1/21	19:12:14	38.2839	-108.9038	-1.9600	3.5	-0.6		1.6
5/2/21	4:07:11	38.2752	-108.9353	-0.6600	2.2	0.5	0.9	4.3
5/2/21	14:37:16	38.2818	-108.9080	-2.0190	3.5	-0.1	0.9	2.0
5/2/21	14:38:23	38.2818	-108.9080	-2.0220	3.5	-0.5		2.0
5/2/21	21:09:08	38.2818	-108.9081	-2.0130	3.5	-0.3		2.0
5/2/21	21:37:20	38.2779	-108.9145	-2.5150	4.0	0.8	1.3	2.7
5/3/21	17:47:21	38.2828	-108.9057	-2.0440	3.6	-0.4		1.8
5/3/21	18:18:42	38.3220	-108.6980	-8.3670	9.9	0.0		17.5
5/3/21	23:24:42	38.2435	-108.8668	0.0700	1.5	-0.4		6.4
5/4/21	1:45:48	38.2813	-108.9072	-2.0070	3.5	-0.6		2.0
5/4/21	8:57:32	38.3220	-108.6976	-8.3300	9.9	1.4	1.5	17.5
5/7/21	0:57:35	38.2836	-108.9036	-2.0690	3.6	-0.4		1.6

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]		Horizontal Distance from Injection Well (km)
						M_D	M_W	
5/8/21	9:26:38	38.2763	-108.9172	-2.8540	4.4	1.8	1.7	3.0
5/19/21	5:44:11	38.2772	-108.9219	-2.4230	3.9	-0.1	0.8	3.2
5/22/21	10:34:30	38.2787	-108.9214	-3.0640	4.6	0.4	1.0	3.0
5/25/21	8:19:02	38.4106	-108.9338	-5.1990	6.7	1.1	1.3	13.1
5/25/21	23:26:09	38.2777	-108.9204	-2.3590	3.9	0.0	0.9	3.1
5/27/21	18:26:01	38.2760	-108.9166	-3.0220	4.5	-0.7	0.9	3.0
5/28/21	19:09:17	38.2695	-109.0570	-0.3700	1.9	-0.5		14.5
5/29/21	12:19:38	38.2834	-108.9048	-1.9640	3.5	1.0	1.1	1.7
6/2/21	20:27:14	38.2856	-108.9000	-1.9680	3.5	-0.6		1.3
6/6/21	12:05:17	38.2761	-108.9318	-1.2100	2.7	0.3	1.0	3.9
6/6/21	12:17:40	38.2761	-108.9317	-1.2000	2.7	-0.1		3.9
6/6/21	22:18:37	38.2761	-108.9316	-1.2030	2.7	-0.6		3.9
6/10/21	4:57:06	38.2840	-108.9038	-1.9290	3.5	-0.5		1.6
6/10/21	9:33:31	38.2648	-108.9455	-0.5400	2.1	-0.6	0.6	5.6
6/11/21	16:35:48	38.2812	-108.9094	-2.2070	3.7	-0.3		2.1
6/11/21	18:23:27	38.2810	-108.9094	-2.1750	3.7	-0.4		2.1
6/12/21	4:03:37	38.2766	-108.9231	-2.5210	4.0	0.4	1.0	3.3
6/12/21	18:45:29	38.2648	-108.8732	-0.7200	2.2	-0.7		4.0
6/15/21	15:14:01	38.2768	-108.9228	-2.4950	4.0	0.3	1.1	3.3
6/18/21	6:39:47	38.2831	-108.9038	-2.1190	3.6	-0.7		1.7
6/18/21	13:04:20	38.2825	-108.9055	-2.3050	3.8	0.0	0.7	1.8
6/19/21	15:16:44	38.2842	-108.8990	-2.4500	4.0	1.0	1.2	1.4
6/21/21	8:33:35	38.2830	-108.9043	-2.1210	3.6	-0.5		1.7
6/21/21	11:40:12	38.2768	-108.9212	-2.4500	4.0	0.5	1.1	3.2
6/21/21	13:47:44	38.3047	-108.9225	-3.0120	4.5	-0.6		2.6
6/22/21	4:54:35	38.2628	-108.8725	0.6100	0.9	0.3	0.6	4.2
6/25/21	4:42:43	38.2820	-108.9072	-2.1040	3.6	2.2	1.9	1.9
6/25/21	5:32:11	38.2821	-108.9072	-2.0810	3.6	-0.8		1.9
6/26/21	8:50:40	38.2771	-108.9219	-2.4380	4.0	-0.1	0.6	3.2
6/28/21	9:05:07	38.2798	-108.9003	-2.6770	4.2	1.9	1.7	1.9
6/30/21	3:44:38	38.2861	-108.8949	-2.0060	3.5	-0.5		1.2
6/30/21	8:27:30	38.2817	-108.9074	-1.9950	3.5	0.6	1.0	2.0
6/30/21	22:49:56	38.2764	-108.9310	-1.2220	2.7	-0.6	0.5	3.9
7/1/21	10:50:28	38.2764	-108.9311	-1.2390	2.8	0.1		3.9
7/2/21	5:48:27	38.2785	-108.9189	-1.4590	3.0	0.4	0.8	2.9
7/2/21	10:44:32	38.2765	-108.9181	-2.7290	4.3	-0.4		3.0
7/3/21	12:55:51	38.2822	-108.9070	-2.0620	3.6	-0.6		1.9
7/4/21	6:26:29	38.2817	-108.9065	-2.0630	3.6	1.1	1.2	1.9
7/6/21	1:02:04	38.2815	-108.9068	-2.0260	3.6	-0.1	0.8	2.0
7/6/21	20:49:26	38.2713	-109.0568	-10.3000	11.8	0.6	1.3	14.4
7/8/21	8:10:32	38.2797	-108.9212	-2.6880	4.2	-0.1	0.8	3.0

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]		Horizontal Distance from Injection Well (km)
						M_D	M_W	
7/9/21	4:33:57	38.2782	-108.9221	-2.1190	3.6	-0.6		3.1
7/11/21	4:00:28	38.2859	-108.8992	-1.9590	3.5	0.0	0.8	1.2
7/13/21	3:18:15	38.2797	-108.9211	-2.6870	4.2	-0.7	0.7	3.0
7/15/21	17:47:58	38.2856	-108.8996	-1.9060	3.4	-0.5		1.3
7/16/21	6:42:38	38.2859	-108.8982	-1.9590	3.5	0.3	0.8	1.2
7/16/21	7:33:27	38.2782	-108.9221	-2.1230	3.6	-0.5		3.1
7/17/21	16:46:20	38.2844	-108.9028	-2.0070	3.5	-0.3		1.5
7/17/21	20:26:23	38.3144	-108.9625	-1.2280	2.8	-0.1	0.9	6.2
7/18/21	15:56:28	38.2796	-108.9212	-2.6800	4.2	0.2	1.0	3.0
7/19/21	8:02:42	38.2785	-108.9188	-1.4660	3.0	0.9	1.3	2.9
7/19/21	8:36:23	38.2785	-108.9189	-1.4430	3.0	-0.6		2.9
7/20/21	6:48:56	38.2781	-108.9217	-2.1310	3.7	0.1	0.8	3.1
7/22/21	16:31:06	38.2828	-108.8941	-2.8100	4.3	-0.4		1.5
7/22/21	17:15:36	38.2780	-108.9185	-2.3400	3.9	-0.5	0.6	2.9
7/23/21	18:37:40	38.2842	-108.9029	-1.9490	3.5	0.0	0.8	1.5
8/2/21	8:44:49	38.2786	-108.9186	-1.4770	3.0	1.4		2.9
8/2/21	8:45:54	38.2763	-108.9193	-1.6500	3.2	-1.2		3.1
8/2/21	10:36:38	38.2813	-108.9118	-1.3700	2.9	0.1	0.7	2.2
8/4/21	6:50:26	38.2838	-108.9041	-1.9190	3.4	-0.4		1.6
8/4/21	6:50:38	38.2842	-108.9045	-1.7620	3.3	-1.0		1.6
8/4/21	11:05:41	38.2838	-108.9040	-1.9420	3.5	-0.4		1.6
8/5/21	9:18:17	38.4042	-108.8693	-4.5370	6.1	0.1	0.8	12.2
8/5/21	23:57:41	38.2737	-108.9362	-0.4300	2.0	-0.1	0.6	4.4
8/9/21	1:01:53	38.2868	-108.8951	-2.0830	3.6	-0.2	0.8	1.1
8/9/21	23:32:48	38.2815	-108.9125	-1.8300	3.4	-1.1		2.3
8/11/21	7:46:15	38.2783	-108.9221	-2.0860	3.6	-0.7		3.1
8/12/21	11:21:42	38.2837	-108.9042	-1.9440	3.5	-0.3		1.6
8/12/21	14:30:01	38.2837	-108.9041	-1.9300	3.5	-0.5		1.6
8/12/21	17:14:26	38.2776	-108.9217	-2.3680	3.9	-0.8		3.1
8/13/21	20:31:54	38.3996	-108.8672	-4.4130	5.9	-0.3		11.7
8/14/21	6:53:14	38.2761	-108.9312	-1.1630	2.7	-0.7		3.9
8/15/21	6:34:52	38.2856	-108.8969	-2.0640	3.6	-0.4	0.6	1.2
8/15/21	11:32:25	38.2857	-108.8971	-2.0190	3.5	-0.6		1.2
8/16/21	4:24:23	38.4452	-109.0362	-4.7000	6.2	0.7	1.1	20.6
8/18/21	14:44:19	38.5213	-109.0095	-11.2800	12.8	0.2		26.9
8/20/21	4:18:20	38.2783	-108.9203	-1.3950	2.9	-0.2	0.6	3.0
8/21/21	0:01:35	38.2819	-108.9080	-2.0380	3.6	-0.6		2.0
8/21/21	2:45:33	38.2819	-108.9079	-2.0460	3.6	2.6	2.2	2.0
8/21/21	2:49:39	38.2820	-108.9077	-2.0120	3.5	-0.6		2.0
8/21/21	7:00:53	38.2820	-108.9078	-1.9920	3.5	-0.5		2.0
8/21/21	7:33:49	38.2818	-108.9082	-2.0510	3.6	1.7		2.0

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]		Horizontal Distance from Injection Well (km)
						M_D	M_W	
8/21/21	12:05:42	38.2819	-108.9076	-2.0460	3.6	-0.4		2.0
8/21/21	13:37:42	38.2819	-108.9077	-2.0450	3.6	-0.7		2.0
8/23/21	3:13:35	38.2607	-108.9857	0.3200	1.2	-0.3		8.9
8/24/21	6:28:59	38.2810	-108.9079	-2.0160	3.5	-0.2	0.6	2.1
8/24/21	12:31:24	38.2722	-108.8897	-0.7600	2.3	-0.2	0.5	2.7
8/26/21	7:45:49	38.2773	-108.8312	-2.3000	3.8	0.1	0.5	6.0
8/28/21	11:35:48	38.1991	-108.7257	-4.2910	5.8	0.2	0.4	18.3
8/28/21	15:44:10	38.1991	-108.7256	-4.3020	5.8	0.2		18.4
8/29/21	1:15:22	38.2874	-108.9256	-2.0780	3.6	0.1	1.0	2.9
8/30/21	2:20:02	38.2783	-108.9201	-1.4140	2.9	0.1	0.6	3.0
8/30/21	20:17:56	38.1958	-108.7213	-7.2400	8.8	-0.3		18.9
8/31/21	6:56:50	38.2763	-108.9173	-2.8670	4.4	1.4	1.3	3.0
8/31/21	7:34:33	38.2763	-108.9175	-2.8840	4.4	2.0	1.8	3.0
8/31/21	13:10:53	38.1990	-108.7257	-4.2960	5.8	0.0		18.3
9/1/21	1:38:47	38.2847	-108.8956	-2.2630	3.8	1.2	1.2	1.3
9/2/21	4:22:08	38.1989	-108.7257	-4.2870	5.8	1.0		18.4
9/2/21	12:55:03	38.2841	-108.9032	-1.9310	3.5	0.1	0.8	1.6
9/4/21	11:04:43	38.4410	-108.9701	-4.0470	5.6	1.2	1.1	17.3
9/4/21	12:00:50	38.2743	-108.9360	0.0700	1.5	1.6	1.6	4.4
9/4/21	12:33:27	38.2763	-108.9313	-1.2070	2.7	1.1	1.3	3.9
9/4/21	12:35:17	38.2763	-108.9313	-1.2000	2.7	-0.2		3.9
9/4/21	14:12:00	38.2837	-108.9045	-1.9300	3.5	-0.3		1.7
9/5/21	3:26:26	38.2766	-108.9230	-2.5010	4.0	1.7	1.6	3.3
9/5/21	9:42:43	38.2763	-108.9316	-1.2050	2.7	0.2	1.0	3.9
9/6/21	3:09:46	38.2766	-108.9232	-2.5070	4.0	1.3		3.3
9/6/21	14:07:18	38.1991	-108.7255	-4.3140	5.8	-0.1		18.4
9/6/21	17:10:02	38.2842	-108.9031	-1.9170	3.4	-0.6		1.5
9/6/21	21:02:50	38.1992	-108.7259	-4.2840	5.8	-0.3	0.8	18.3
9/7/21	5:33:44	38.2816	-108.9085	-2.0990	3.6	-0.7		2.0
9/7/21	16:09:37	38.2840	-108.9035	-1.9100	3.4	-0.5		1.6
9/7/21	17:02:26	38.2776	-108.9219	-2.3170	3.8	-0.6	0.7	3.2
9/7/21	21:42:36	38.2862	-108.8983	-2.0830	3.6	0.0	0.8	1.2
9/10/21	1:41:51	38.3433	-108.8858	-3.8000	5.3	-0.2		5.3
9/10/21	10:12:39	38.2846	-108.9032	-2.9570	4.5	-0.5		1.5
9/10/21	15:15:45	38.1992	-108.7257	-4.2890	5.8	0.0		18.3
9/12/21	21:03:05	38.2772	-108.9220	-2.4360	4.0	-0.6		3.2
9/15/21	3:43:31	38.2763	-108.9174	-2.9140	4.4	-0.2	0.8	3.0
9/18/21	15:41:53	38.1993	-108.7258	-4.2670	5.8	1.1	1.0	18.3
9/18/21	15:48:31	38.1993	-108.7256	-4.2820	5.8	0.0		18.3
9/19/21	10:52:49	38.2758	-108.9176	-3.0460	4.6	0.0		3.0
9/19/21	13:15:45	38.2768	-108.9229	-2.4800	4.0	2.3	2.2	3.3

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]		Horizontal Distance from Injection Well (km)
						M_D	M_W	
9/30/21	4:24:56	38.2747	-108.9170	-2.3400	3.9	-1.2		3.1
10/1/21	13:12:52	38.2796	-108.9133	-1.5310	3.1	-0.1	0.7	2.5
10/1/21	13:14:22	38.2780	-108.9115	-1.5200	3.0	-0.7		2.5
10/5/21	12:08:35	38.2779	-108.9213	-2.2130	3.7	0.0	0.9	3.1
10/5/21	17:06:56	38.2856	-108.8994	-1.8940	3.4	-0.6		1.3
10/5/21	17:30:57	38.2778	-108.9214	-2.2190	3.7	0.1	0.9	3.1
10/6/21	19:11:11	38.2845	-108.8923	-2.1980	3.7	-0.7		1.4
10/7/21	5:23:40	38.2863	-108.8972	-2.0870	3.6	-1.2		1.2
10/8/21	4:22:11	38.2778	-108.9215	-2.2220	3.7	0.6	1.1	3.1
10/9/21	4:30:02	38.2851	-108.8937	-1.8740	3.4	0.0	1.1	1.3
10/10/21	2:28:36	38.1992	-108.7258	-4.2760	5.8	1.1	1.2	18.3
10/10/21	2:29:01	38.1993	-108.7259	-4.2630	5.8	0.5	1.2	18.3
10/10/21	3:10:41	38.2840	-108.9042	-1.9130	3.4	-0.5		1.6
10/10/21	4:17:06	38.1992	-108.7258	-4.2850	5.8	0.0		18.3
10/10/21	7:10:30	38.2778	-108.9214	-2.2230	3.7	0.0	0.9	3.1
10/11/21	9:03:04	38.1993	-108.7260	-4.2650	5.8	0.7	0.8	18.3
10/15/21	15:23:54	38.2838	-108.9044	-1.9360	3.5	0.0		1.6
10/16/21	12:57:57	38.2777	-108.9211	-2.2730	3.8	-0.3	0.9	3.1
10/16/21	14:01:34	38.2777	-108.9211	-2.2610	3.8	-0.4	0.9	3.1
10/16/21	19:22:15	38.2777	-108.9210	-2.2610	3.8	0.2	0.9	3.1
10/19/21	7:08:42	38.2840	-108.9036	-1.9030	3.4	-0.4		1.6
10/22/21	1:34:44	38.2818	-108.9043	-2.2980	3.8	0.0	1.0	1.8
10/23/21	6:52:04	38.2755	-108.9244	-2.7840	4.3	-0.7		3.5
10/24/21	5:06:03	38.2860	-108.8989	-1.9590	3.5	-0.5		1.2
10/24/21	19:27:32	38.2778	-108.9202	-2.3270	3.9	0.0	1.0	3.0
10/27/21	7:26:02	38.2822	-108.9072	-2.1590	3.7	-0.5		1.9
10/28/21	10:45:10	38.2775	-108.9216	-2.3740	3.9	-0.4		3.1
10/28/21	12:01:38	38.2838	-108.9041	-1.9480	3.5	0.0		1.6
10/30/21	5:32:17	38.2777	-108.9199	-2.3680	3.9	0.3	0.9	3.0
10/30/21	20:05:22	38.2830	-108.9038	-2.2660	3.8	-0.1		1.7
11/3/21	11:36:18	38.3907	-109.0188	-6.3500	7.9	1.1	1.2	15.0
11/3/21	23:39:44	38.2829	-108.8950	-2.6700	4.2	-0.4		1.5
11/3/21	23:47:01	38.3113	-108.7319	-7.8970	9.4	1.5	1.7	14.4
11/5/21	3:56:24	38.2812	-108.9107	-1.8220	3.3	-0.7		2.2
11/5/21	6:36:12	38.3978	-108.8958	-0.2800	1.8	1.2	1.5	11.2
11/5/21	6:45:40	38.4043	-108.9063	-0.0800	1.6	0.1	0.6	12.0
11/6/21	5:18:17	38.2779	-108.9217	-2.2080	3.7	0.4	1.0	3.1
11/6/21	5:19:03	38.2779	-108.9217	-2.2050	3.7	-0.3		3.1
11/15/21	5:54:22	38.2626	-108.8705	-0.9080	2.4	-0.2	0.8	4.3
11/20/21	9:17:27	38.2770	-108.9230	-2.4490	4.0	0.0	0.9	3.3
11/21/21	10:33:04	38.2761	-108.9182	-2.8650	4.4	1.9	1.8	3.0

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]		Horizontal Distance from Injection Well (km)
						M_D	M_W	
11/21/21	14:08:57	38.2830	-108.9040	-2.2500	3.8	0.0	1.0	1.7
11/21/21	14:09:13	38.2830	-108.9041	-2.2280	3.8	-0.8		1.7
11/22/21	1:07:48	38.3425	-108.8869	-4.2990	5.8	1.7	1.6	5.2
11/22/21	11:12:19	38.2851	-108.9010	-1.9200	3.4	-0.4		1.4
11/22/21	11:12:36	38.2867	-108.9017	-2.1900	3.7	-1.3		1.2
11/22/21	23:43:00	38.4041	-109.0150	-3.9200	5.4	0.3	0.9	15.9
11/25/21	21:34:12	38.2817	-108.9078	-2.0600	3.6	-0.5		2.0
11/27/21	2:05:15	38.2572	-108.8733	-0.3200	1.8	-0.1	0.6	4.8
11/28/21	9:14:20	38.2771	-108.9215	-2.4490	4.0	1.9	1.7	3.2
11/29/21	9:01:09	38.2773	-108.9212	-2.4370	4.0	-0.3		3.1
12/2/21	13:28:44	38.2834	-108.9060	-1.9550	3.5	-0.7		1.8
12/2/21	13:41:16	38.2833	-108.9059	-1.9430	3.5	-0.6		1.7
12/2/21	20:00:48	38.2834	-108.9059	-1.9330	3.5	0.6	1.1	1.7
12/5/21	12:35:31	38.3143	-108.9621	-1.2330	2.8	0.4		6.2
12/8/21	10:01:01	38.2835	-108.9065	-1.7500	3.3	-0.9		1.8
12/9/21	3:09:31	38.3525	-108.6942	-7.6840	9.2	1.5	1.7	18.6
12/11/21	6:24:30	38.3402	-108.8921	-5.0440	6.6	0.7	1.2	4.9
12/12/21	1:33:37	38.4411	-108.9696	-4.0570	5.6	1.1	1.4	17.3
12/12/21	18:39:57	38.2695	-109.0500	-0.7000	2.2	-0.3		13.9
12/13/21	4:08:15	38.2853	-108.9004	-1.9630	3.5	0.1		1.3
12/14/21	14:53:13	38.2825	-108.9207	-2.1800	3.7	-0.7		2.7
12/17/21	0:53:09	38.2854	-108.9002	-1.9630	3.5	-0.4		1.3
12/17/21	0:53:40	38.2855	-108.9005	-1.9290	3.5	-0.7		1.3
12/17/21	22:30:01	38.2820	-108.9080	-2.0640	3.6	0.1		2.0
12/18/21	9:12:01	38.2653	-108.8692	-1.0110	2.5	-0.5	0.7	4.1
12/20/21	21:43:09	38.2771	-108.9230	-2.4380	4.0	-0.4		3.3
12/22/21	9:08:07	38.2829	-108.9054	-2.1840	3.7	-0.4		1.8
12/26/21	6:44:44	38.2732	-108.9280	-0.3500	1.9	-0.4	0.8	3.9
12/27/21	7:09:24	38.3111	-108.7319	-7.9480	9.5	0.2		14.4

[1] Date and time listed are in Coordinated Universal Time, UTC (Mountain Standard Time = UTC – 7 hours; Mountain Daylight Savings Time = UTC – 6 hours)
[2] Elevation is given with respect to mean sea level.
[3] Depth is referenced to the surveyed ground surface elevation at the injection wellhead, 1.524 km.
[4] M_D = duration magnitude; M_W = moment magnitude. All magnitudes computed using only PVSN data.