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Managing Water in the West

Technical Memorandum TM-85-833000-2019-13

2018 Annual Report
Paradox Valley Seismic Network
Paradox Valley Unit, Colorado

U.S. Department of the Interior
Bureau of Reclamation

May 2019

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to 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.

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Seismology, Geomorphology, and Geophysics Group

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2018 Annual Report
Paradox Valley Seismic Network
Paradox Valley Unit, Colorado

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Peer Review Certification

This report has been reviewed and is believed to be in accordance with the service agreement and standards of the profession.

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1 Introduction

The Paradox Valley Seismic Network (PVSN) monitors earthquakes induced by injection operations at the Bureau of Reclamation's 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 2018. We provide project background information in section 2, including the history of PVU injection operations and details of the seismic network. In section 3, we present PVSN network operations during 2018, including maintenance of the seismic stations and data acquisition systems and annual network performance. The earthquake data recorded during 2018 are discussed in section 4 and compared to historical seismicity trends.

2 Project Background

2.1 Paradox Valley Unit

Reclamation's PVU, a component of the Colorado River Basin Salinity Control Project, intercepts salt brine that would otherwise flow into the Dolores River, a tributary of the Colorado River. PVU is located in western Montrose County approximately 90 km southwest of Grand Junction, CO and 16 km east of the Colorado-Utah border (Figure 2-1). The Dolores River flows from southwest to northeast across Paradox Valley (Figure 2-2), which was formed by the collapse of a salt-cored anticline (Figure 2-3). 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 located 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 2-2).

PVU Salinity Control Well No. 1 was completed in 1987 at 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 2-3). Based on interpretation of regional core and log data, 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 two 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 2-4.

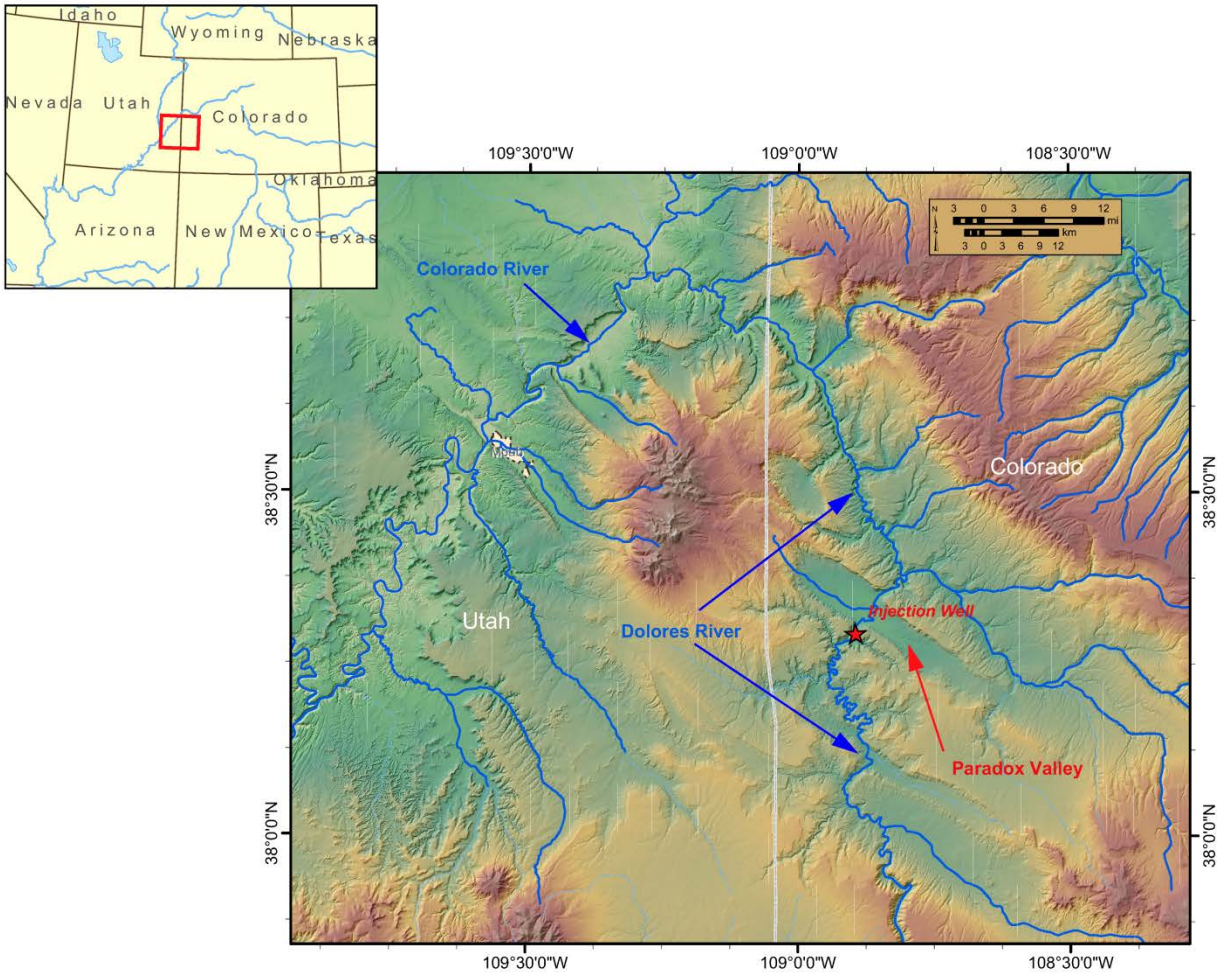


Figure 2-1. Location of the deep injection well at Reclamation's Paradox Valley Unit in western Colorado.

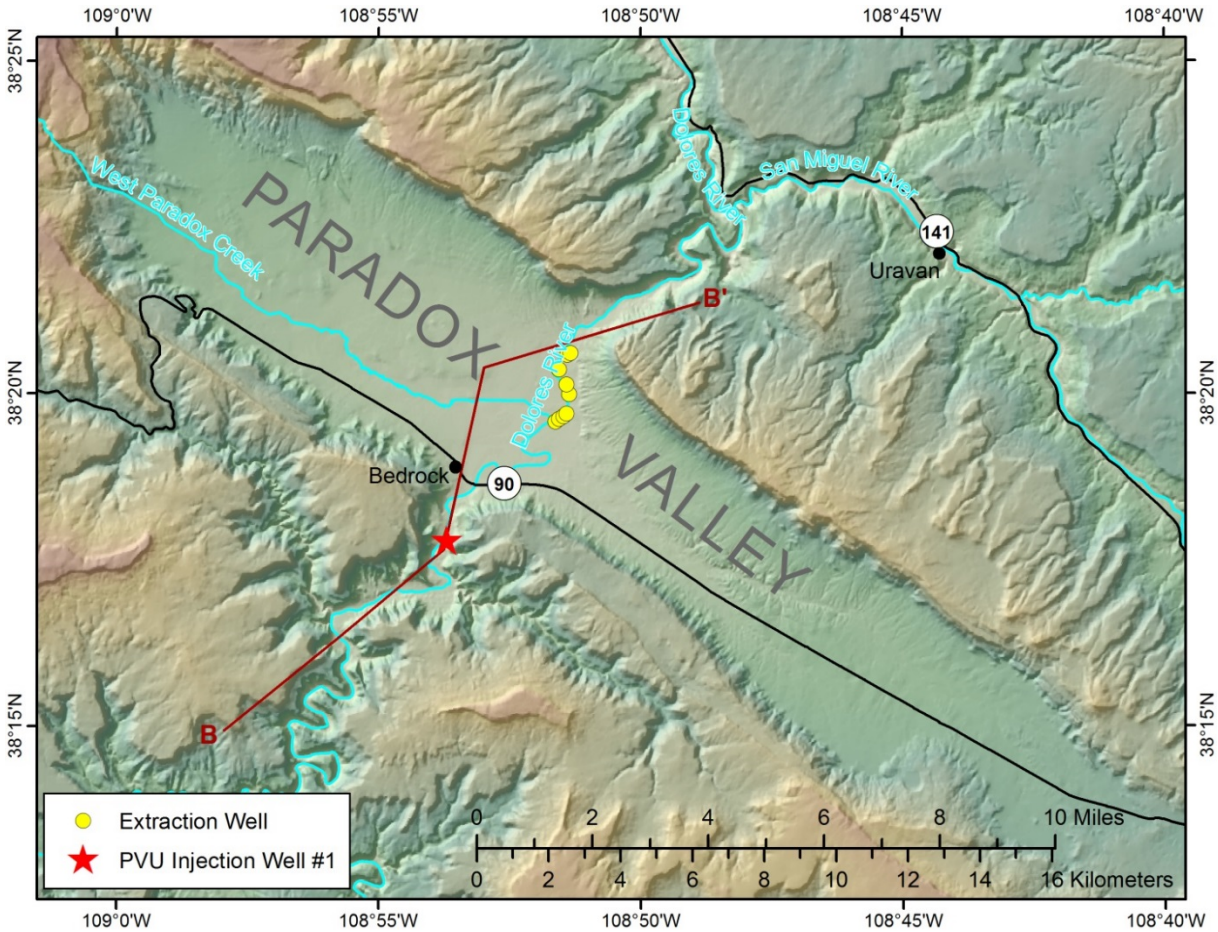


Figure 2-2. Location of the Paradox Valley Unit extraction wells (yellow circles) and injection well (red star). Cross section B-B´ is shown in Figure 2-3.

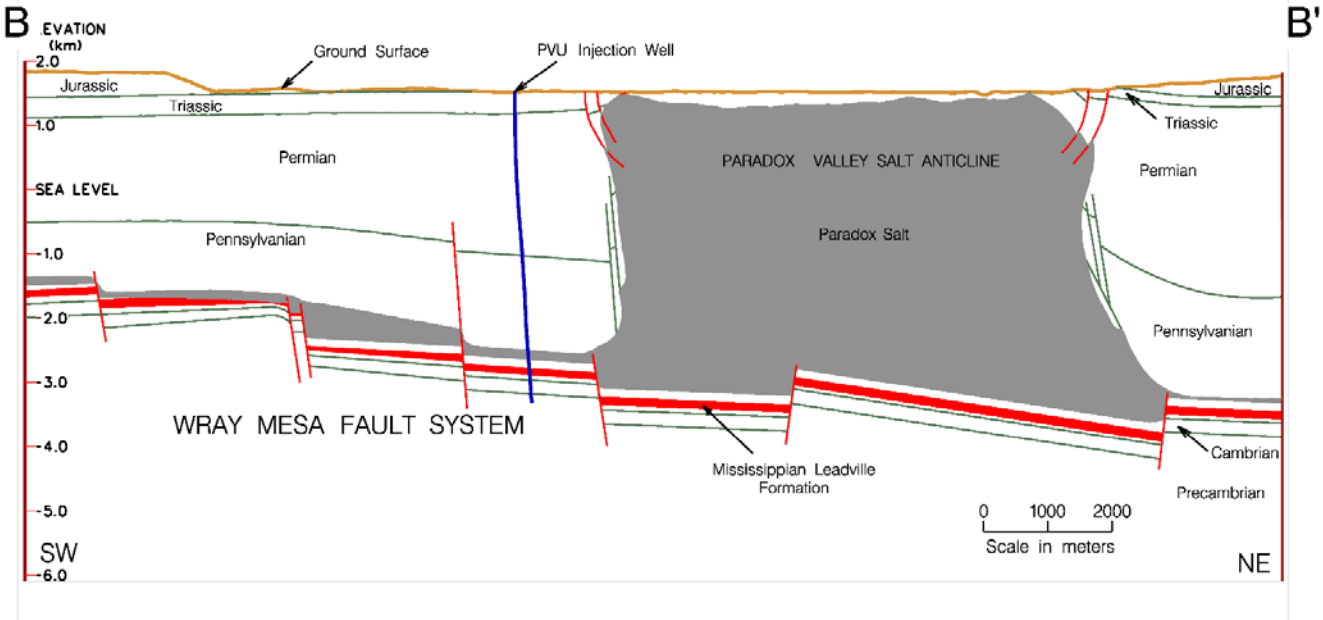


Figure 2-3. Vertical cross section roughly perpendicular to Paradox Valley, looking to the northwest. The location of the cross section is shown in Figure 2-2. Based on figure from Bremkamp and Harr (1988).

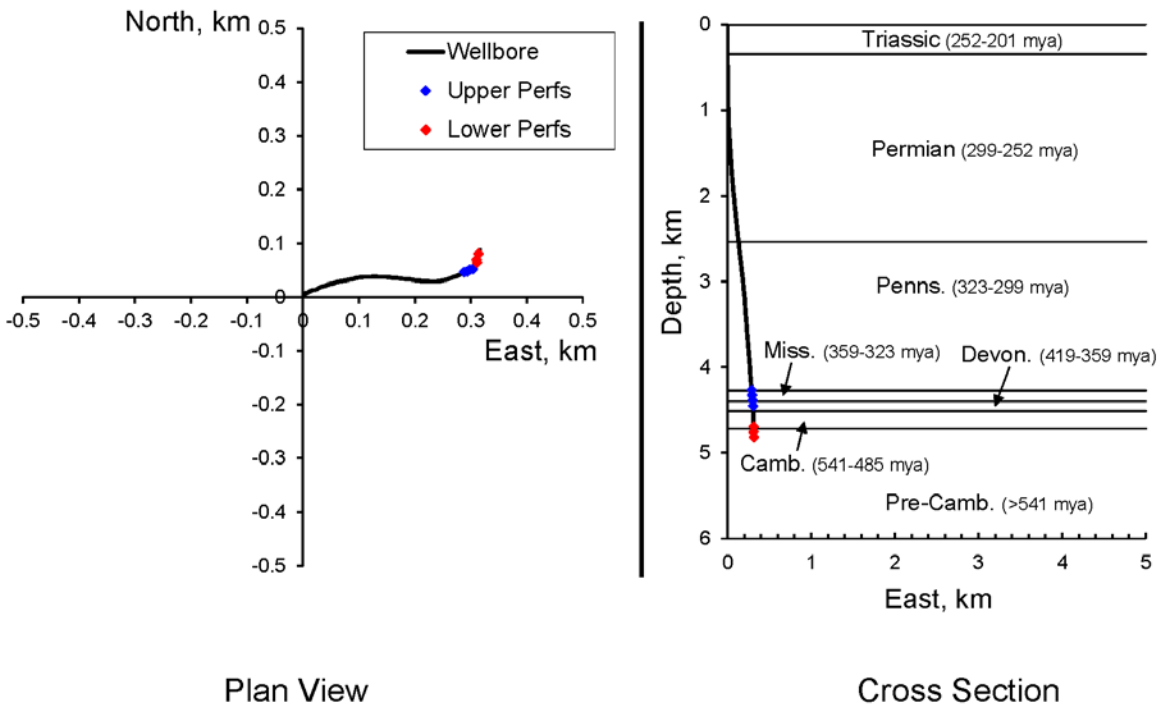


Figure 2-4: PVU injection well in plan view (left) and north-viewing vertical cross section (right). Figure includes the near-wellbore stratigraphy and locations of the upper and lower casing perforations. The ages of the geologic time periods are taken from the Geological Society of America Geologic Time Scale version 4.0 (Walker et al., 2013). The ages shown represent the entire span of any given geologic time period and do not necessarily represent the precise ages of the rocks present at the PVU injection well.

2.2 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. The purpose of these tests was to qualify for a Class V permit for deep disposal from the EPA. Near-continuous, long-term disposal of brine began in July 1996, after EPA granted the permit. Since long-term injection began, Reclamation has instituted and maintained five major changes in injection operations. Four of these changes were implemented to mitigate the potential for unacceptable seismicity, and one change was made to improve injection economics. Each change was maintained for a sufficient period to be considered a sustained injection “phase”. These injection phases are 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 2-5. The downhole pressures shown were computed from measured surface pressures using the density of the brine column in the wellbore.

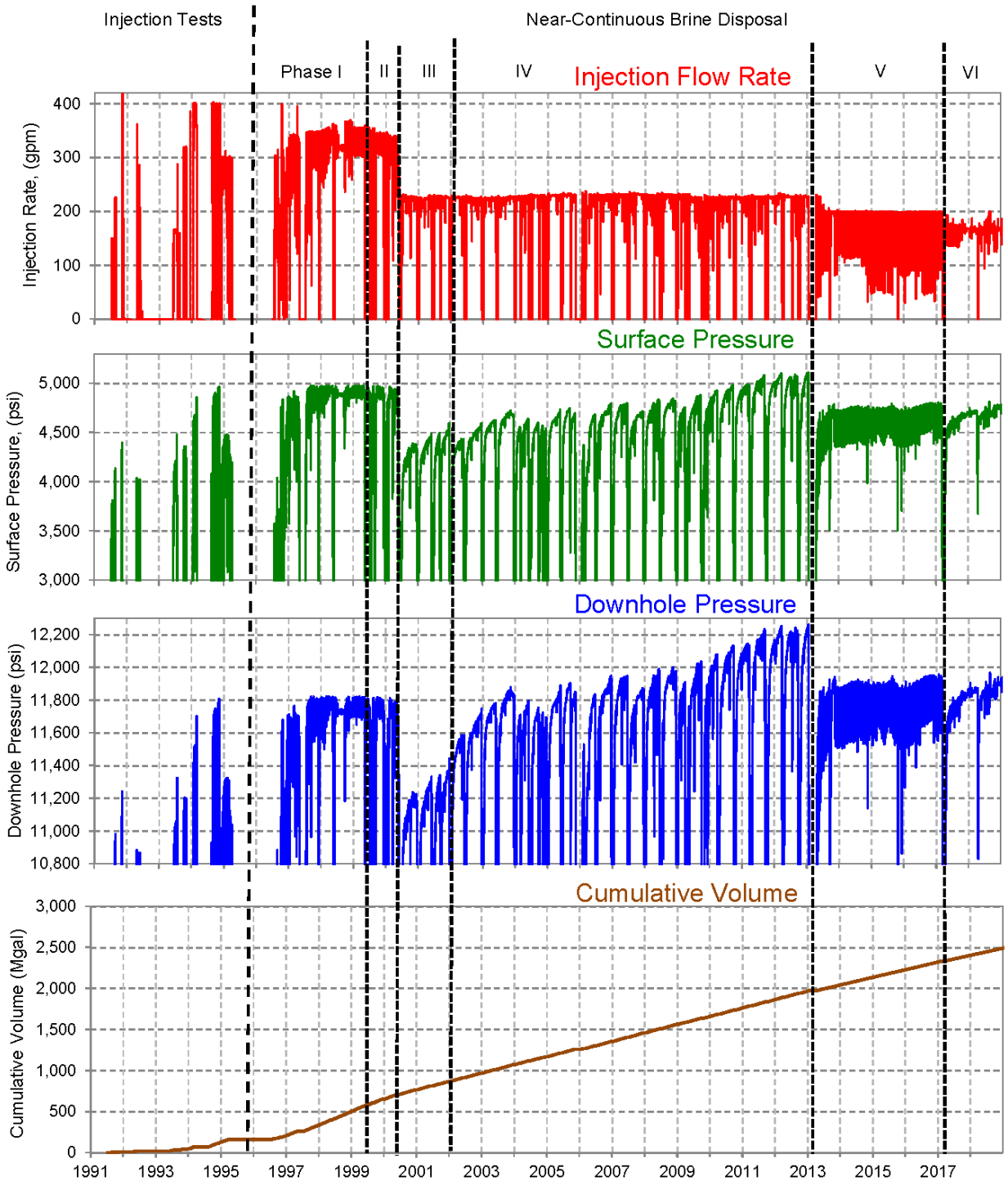


Figure 2-5: Daily average injection flow rate, daily average surface injection pressure, daily average downhole pressure at 4.3 km depth, and cumulative volume of brine injected during PVU injection operations. The downhole pressures are computed from the measured surface pressures using the density of the brine column in the well.

2.2.1 Phase I (July 22, 1996 – July 25, 1999)

During this initial phase of continuous injection, PVU injected at a nominal flow rate of 345 gpm (~1306 l/min), at about 4,950 psi (~34.1 MPa) average surface pressure. This corresponds 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 with each operating at 115 gpm. The surface pressure on occasion approached the wellhead pressure safety limit of 5,000 psi. This safety limit is based on the specifications of injection and wellhead equipment. It also corresponds to the maximum allowable surface injection pressure (MASIP) specified in the injection permit issued by EPA, which is specified to prevent breach of the geologic confining layer (the Paradox salt). When the surface pressure approached the MASIP, PVU would shut down one injection pump and sometimes two pumps, reducing the injection rate and allowing the pressure to drop a few hundred psi before returning to a three-pump operation. These shutdowns occurred frequently and lasted for minutes, hours, or a few days. This operational protocol resulted in fairly constant surface and downhole pressures (Figure 2-5). Maintenance shutdowns lasted for one to two weeks and, in mid-1997, a 71-day shutdown was needed to replace operations and maintenance contractors. The shutdowns resulted in an overall average injection rate for *Phase I* of roughly 300 gpm (1136 l/min), and the total of 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% fresh water.

2.2.2 Phase II (July 26, 1999 – June 22, 2000)

Following a local magnitude M_L 3.6 event in June, 1999, and a M_L 3.5 event in July, 1999, PVU altered the injection schedule to include a 20-day shutdown (i.e., a “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 from the wellbore) decreased during and following unscheduled maintenance shutdowns and during the shutdowns following the injection tests of 1991 through 1995. It was 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 flow rate was the same as during *Phase I*. One hundred and eighteen Mgal (0.4 x 10^9 liters) of fluid was injected during *Phase II*.

2.2.3 Phase III (June 23, 2000 – January 6, 2002)

Immediately following a M_L 4.3 earthquake on May 27, 2000, PVU injection was shut down for 28 days. During this shutdown period, Reclamation evaluated the existing injection strategy and its relationship to induced seismicity. The decision was made to reduce the injection flow rate in the expectation that this change would likely reduce the potential for inducing large-magnitude earthquakes. On June 23, 2000, PVU resumed injection 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*. One hundred and fifty-six Mgal (0.6 x 10^9 liters) of fluid was injected during this phase.

2.2.4 Phase IV (January 7, 2002 – April 16, 2013)

Beginning with continuous injection operations in 1996, PVU diluted the injectate to 70% PVB and 30% Dolores River fresh water. A geochemical study had predicted that if 100% PVB were injected, it would interact with connate fluids and the dolomitized Leadville Limestone at downhole (initial) temperatures and pressures, and that PVB would then precipitate calcium sulfate, which in turn would lead to restricted permeability (Kharaka, 1997). During October 2001, with the decreased injection rate discussed above, the injectate concentration question was reconsidered. Temperature logging in the injection interval recorded substantial near-wellbore cooling, indicating that if precipitation occurred, it would not be near the wellbore perforations where clogging would be a concern. Further analyses indicated that, if precipitation occurs, its maximum expected rate is ~8 tons of calcium sulfate per day. To put this amount into perspective, injecting at ~230 gpm and assuming a density of 9.86 lbs/gal (17% more dense than fresh water) results in a daily injection mass of ~1633 tons. The maximum expected precipitate is ~0.5% of the daily injection mass.

After considering this new information, the decision was made to begin injecting 100% PVB, in order to increase the amount of salt disposed of with the reduced injection rate initialized 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 same reduced injection rate as in *Phase III* (230 gpm) and biannual 20-day shutdowns were maintained. The volume of fluid injected during *Phase IV* was 1,110 Mgal (4.2×10^9 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 decade (mid-2000 to 2011). Hence, there was no need to frequently alter flow rates as was done during *Phases I* and *II*. Because of less frequent injection well shut-ins, the maximum surface and downhole pressures gradually increased during *Phases III* and *IV* (Figure 2-5). In addition, because of the increased density of the 100% PVB injected during *Phase IV* over the 70% PVB : 30% fresh water 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, the injection wellhead equipment was replaced with equipment having a higher pressure rating. Following this equipment upgrade, Reclamation applied to EPA for an increase in the MASIP. EPA granted an increase in the MASIP to 5350 psi when the injection permit was renewed in April, 2004.

2.2.5 Phase V (April 17, 2013 – March 11, 2017)

A M_L 4.4 induced earthquake occurred in the northern Paradox Valley area 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 could likely 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 reduce wellhead pressures, and forward modeling was used to evaluate the effect of different flow rates (Wood et al., 2016). In addition, the pressure-flow modeling

indicated that changing the injection well shut-in schedule to have shorter, more frequent shut-ins would result in a lower 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 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 acquisition 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) are tracked, and those hours are subtracted from the weekly scheduled 18-hour shut-in. 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 has been 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 (1.38×10^9 liters) of fluid were injected during this phase.

2.2.6 Phase VI (March 12, 2017 - present)

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 in response to ~1.5 years of increasing rates and magnitudes of PVU-induced earthquakes and the occurrence of a M_D 2.9 earthquake nearly 13 km from the injection well (on 3/12/17).

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 failures of the new 1.875" plungers forced reinstallation of larger plungers (one 2.125" plunger and one 2.000" plunger) in two of the three pumps. 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 pumps with the larger plungers. Weekly shutdown of the single pump with the 1.875" plunger continued. Injection is now continuous, with either one and two pumps running at any given time. The target daily injection volume is 242,000 gallons, corresponding to a target average injection rate of 168 gpm. Hence, the effective average flow rate remains the same as with the smaller plungers.

2.3 Seismic Monitoring

2.3.1 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 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; Raleigh et al., 1976; Hsieh and Bredehoeft, 1981; Nicholson and Wesson, 1990). 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. 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.

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 in order to provide better focal depth control and to allow for more sensitive event detection. Three vertical-component stations (PV12-PV14) were also 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 Hopkins Field, 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.

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 a factor of only about 1000, which corresponds to approximately two 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 3-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" (Guralp model CRM-6) modules 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 2-6.

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 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, respectively. The decision was made to decommission stations PV08 and PV09 because of site conditions resulting in poor seismic data quality. 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).

Upgrade of the PVSN seismic stations to broadband digital instrumentation was completed in late 2011. Consequently, Reclamation discontinued maintenance of the obsolete analog seismic stations. Four of those stations went permanently offline during 2011 (PV02, PV07, PV08, and PV15). 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 moved into a new building.

During 2018, we began replacing the Guralp model CMG-40TD broadband seismometers with Guralp 3ESPCDE seismometers, as the original broadband seismometers were reaching their expected end-of-life. In addition, 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 model 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.

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 (station name PVPP) was installed near the injection wellhead in 1997. A second strong-motion instrument was installed near the extraction facilities (PVEF) in 2003, and the third was installed in the nearby community of Paradox, Colorado (PVCC) in 2005. The strong-motion array is designed to measure ground motions from events that are large enough to be felt or cause damage, and which could saturate high-gain array stations closest to the epicenter.

The locations of the PVSN seismograph stations are shown in Figure 2-7. Details about the stations are provided in Table 2-1, including installation date, station type, and number of components. Table 2-2 lists the station location names.

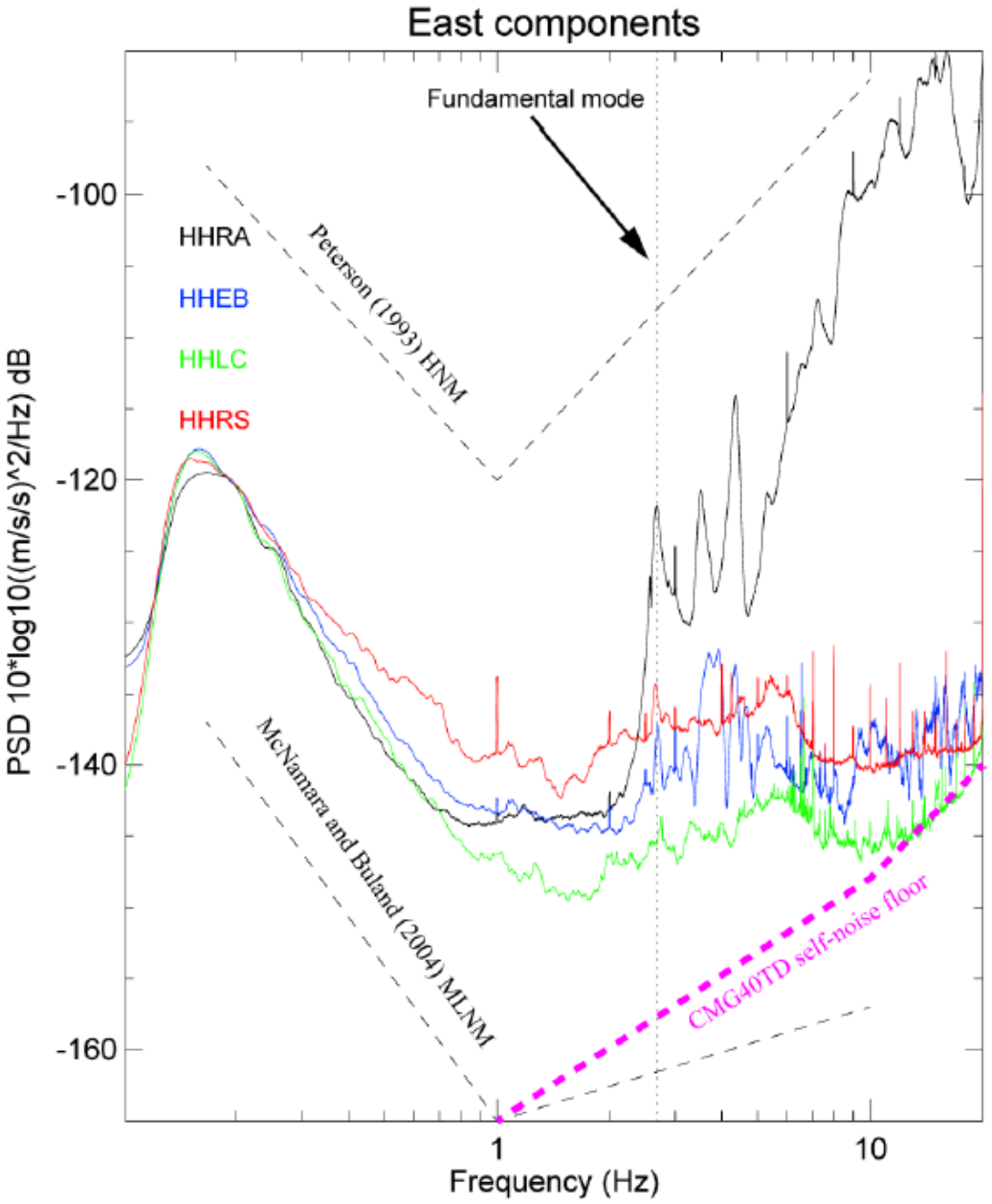


Figure 2-6: Stacked multi-taper acceleration power spectra from the east-west components of Guralp model CMG40TD seismometers installed at four first-generation stations (HHRA, HHEB, HHLC, and HHRS) near Hungry Horse Dam, Montana. Windows were 400 seconds in length, and represented ambient conditions (station HHRA was located close to 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 Paradox Valley to substantially reduce these crosstalk problems. Figure from O'Connell (2008).

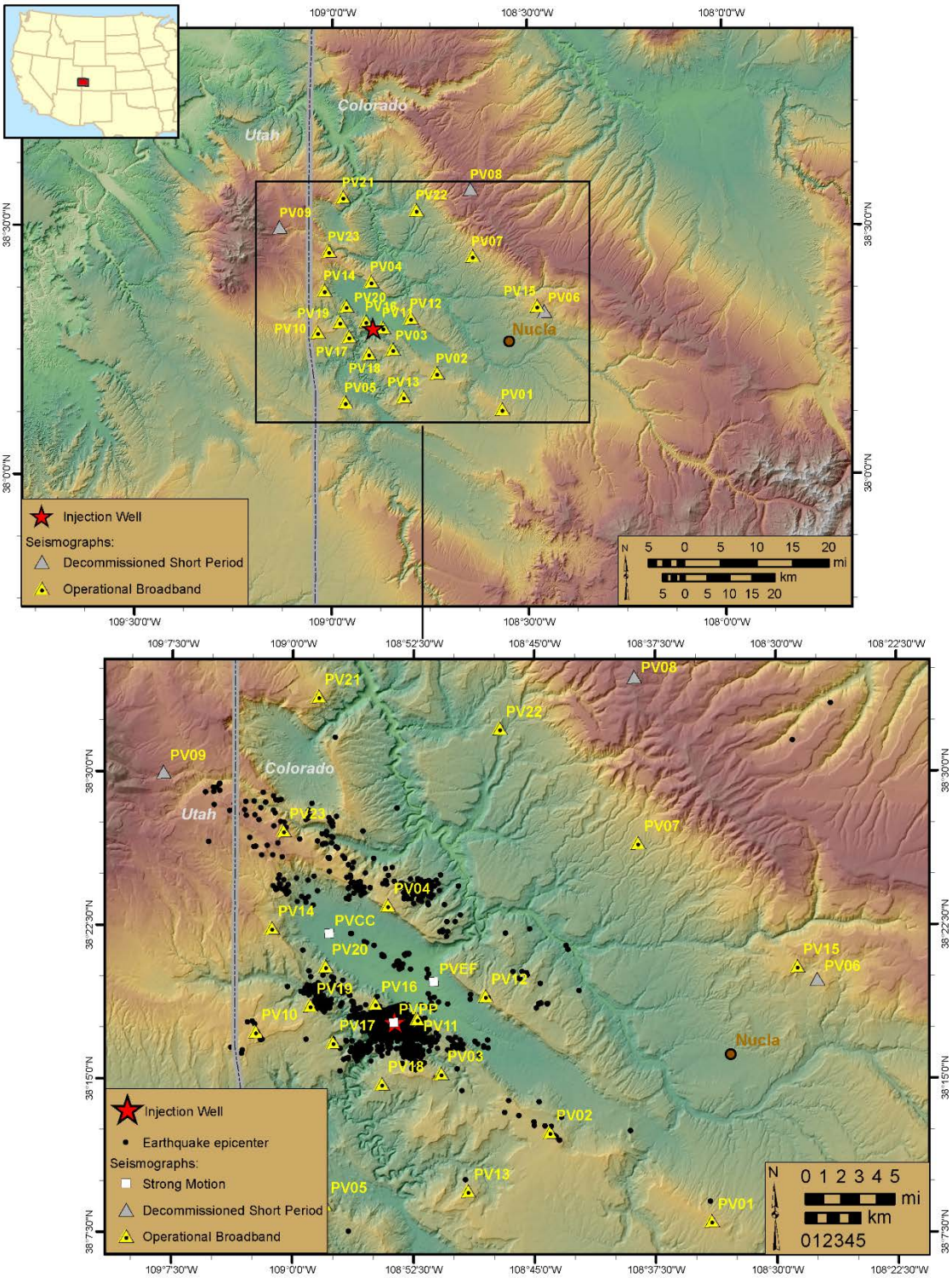


Figure 2-7: Locations of the PVSN seismic stations, PVU injection well, and epicenters of earthquakes ≤ 10 km deep. PVCC, PVEF, & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Stations PV08 and PV09 were decommissioned when the network was upgraded to broadband digital instrumentation.

Table 2-1: 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 broad-band	vertical triaxial
PV02	38.21	108.74	2177	5/83-8/27/11 10/08-present	short-period broad-band	vertical triaxial
PV03	38.25	108.85	1972	5/83-7/16/15 10/08-present	short-period broad-band	vertical triaxial
PV04	38.39	108.90	2176	5/83-6/06 5/07-present	short-period broad-band	vertical triaxial
PV05	38.15	108.97	2142	5/83-7/16/15 5/10-present	short-period broad-band	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 broad-band	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 broad-band	vertical triaxial
PV11	38.30	108.87	1882	12/89-10/13 10/08-present	short-period broad-band	triaxial triaxial
PV12	38.32	108.80	2092	12/89-7/05 11/05-present	short-period broad-band	vertical triaxial
PV13	38.16	108.82	2158	12/89-7/16/15 5/10-present	short-period broad-band	vertical triaxial
PV14	38.37	109.02	2234	12/89-4/02 6/07-present	short-period broad-band	vertical triaxial
PV15	38.34	108.48	2234	6/95-8/27/11 7/11-present	short-period broad-band	vertical triaxial
PV16	38.31	108.92	2025	7/99-7/16/15 5/10-present	short-period broad-band	vertical triaxial
PV17	38.28	108.96	1991	11/05-present	broad-band	triaxial
PV18	38.25	108.91	1999	7/11-present	broad-band	triaxial
PV19	38.31	108.98	2041	7/11-present	broad-band	triaxial
PV20	38.34	108.97	1852	7/11-present	broad-band	triaxial
PV21	38.56	108.97	2235	7/11-present	broad-band	triaxial
PV22	38.54	108.79	1925	7/11-present	broad-band	triaxial
PV23	38.45	109.01	2456	11/11-present	broad-band	triaxial
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 2-2: PVSN Telemetered Sites - Station Location Names

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

2.3.2 Induced Seismicity

More than 7,000 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. The majority of these events have depth estimates between approximately 2.5 and 6.5 km (relative to the ground surface elevation at the 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 2-8). The initial earthquakes were detected 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

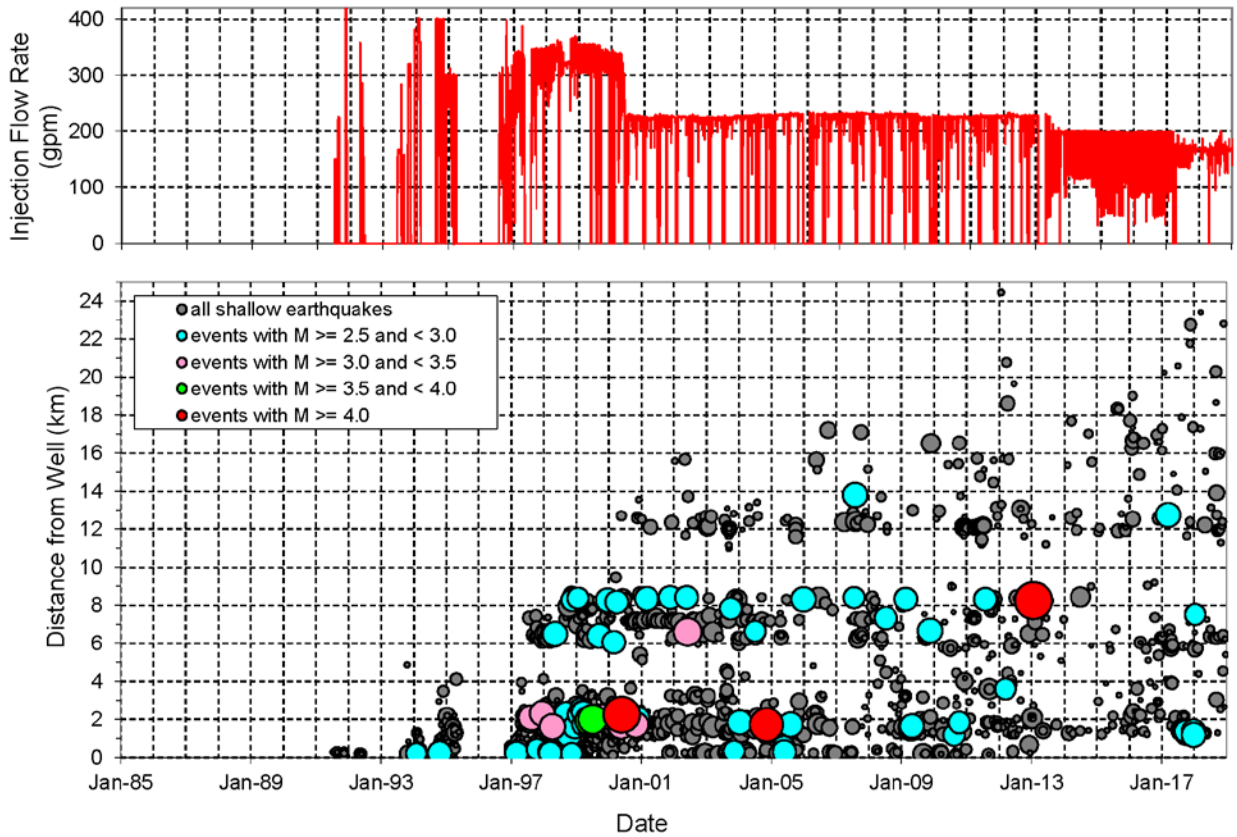


Figure 2-8: Lower plot: scatter plot of earthquakes having magnitude ≥ 0.5 and depth ≤ 10 km (relative to the ground surface elevation at the injection wellhead), plotted as a function of date and distance from the PVU injection well. Each circle represents a single earthquake, with the width of the circle scaled by the event magnitude. The magnitudes shown are duration magnitudes for earthquakes with M < 3.5 and local magnitudes for M ≥ 3.5. Upper plot: daily average injection flow rate.

of injection demonstrated in Figure 2-8 indicate that these earthquakes have been induced by PVU fluid injection.

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 2-9a). 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 2-9b). 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 2-9b). Several distinct clusters of earthquakes soon formed along the northern edges of the valley (Figure 2-9c). The earthquakes occurring in all of these groups are referred to as “northern valley events”. Following the formation of these clusters, the geographical expansion of induced seismicity greatly slowed for nearly a decade (Figure 2-9c, 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 2-9c), but the seismicity rate in this area markedly increased beginning in 2010 (Figure 2-9e). 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 2-9e). 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 2-9e, f, and g). Earthquakes likely related to PVU fluid injection are now occurring at distances up to 27 km northwest of the injection well and up to ~7 km outside the perimeter of the seismic network (Figure 2-9g). In addition, seismicity has occurred in several previously aseismic areas, including: toward the southeast to a distance of ~19 km from the injection well, east toward Uravan to a distance of ~17 km from the well, and west to a distance of ~14 km from the well (Figure 2-9e, f, g).

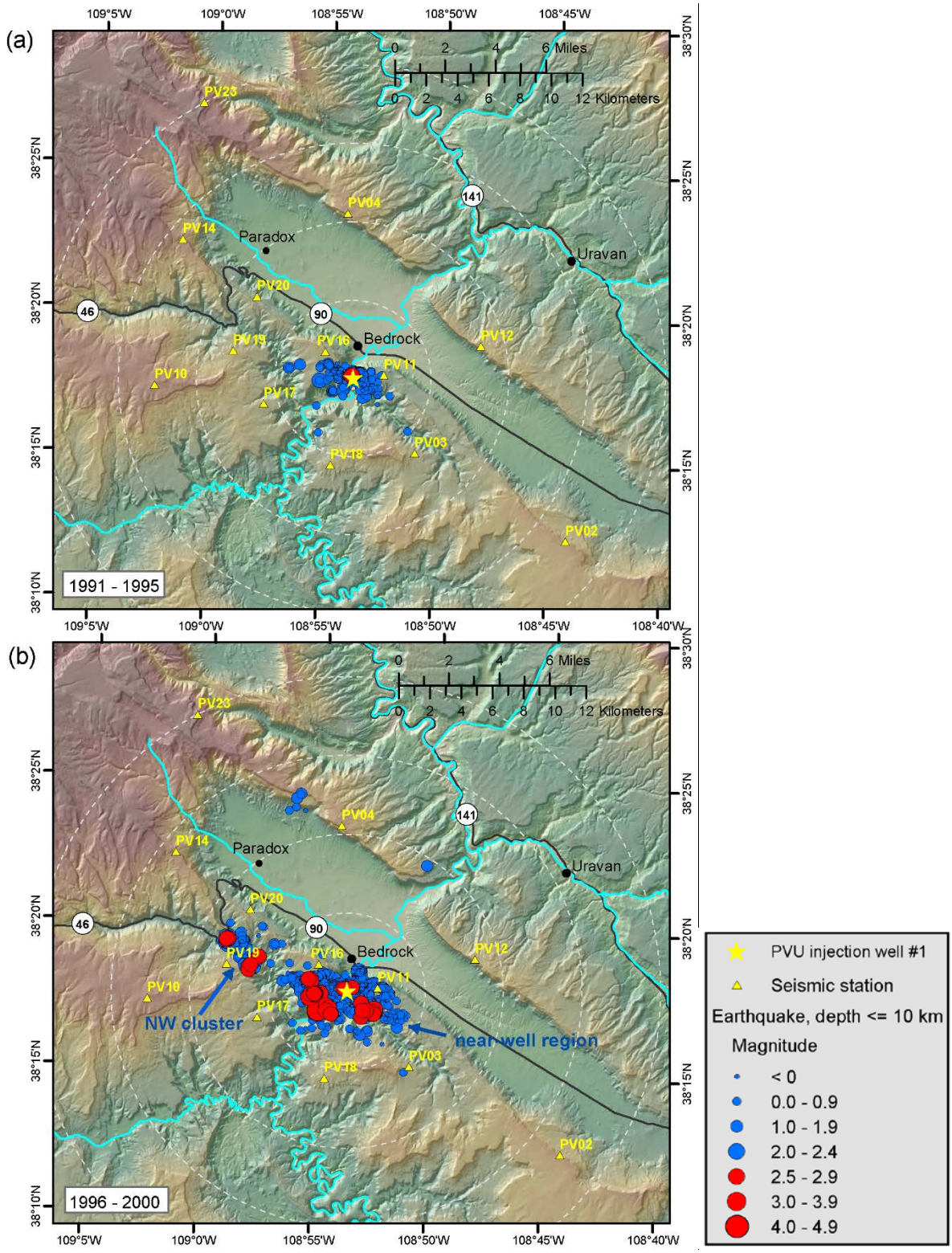


Figure 2-9: Maps showing the spatial distribution of shallow seismicity (depth ≤ 10 km) over time: (a) 1991-1995 (b) 1996-2000 (c) 2001-2004 (d) 2005-2008 (e) 2009-2012 (f) 2013-2016 (g) 2017-2018. Earthquake symbols are sized according to magnitude, and earthquakes with magnitudes ≥ 2.5 are shown in red. The dashed gray circles indicate radial distances of 5, 10, 15, and 20 km from the well.

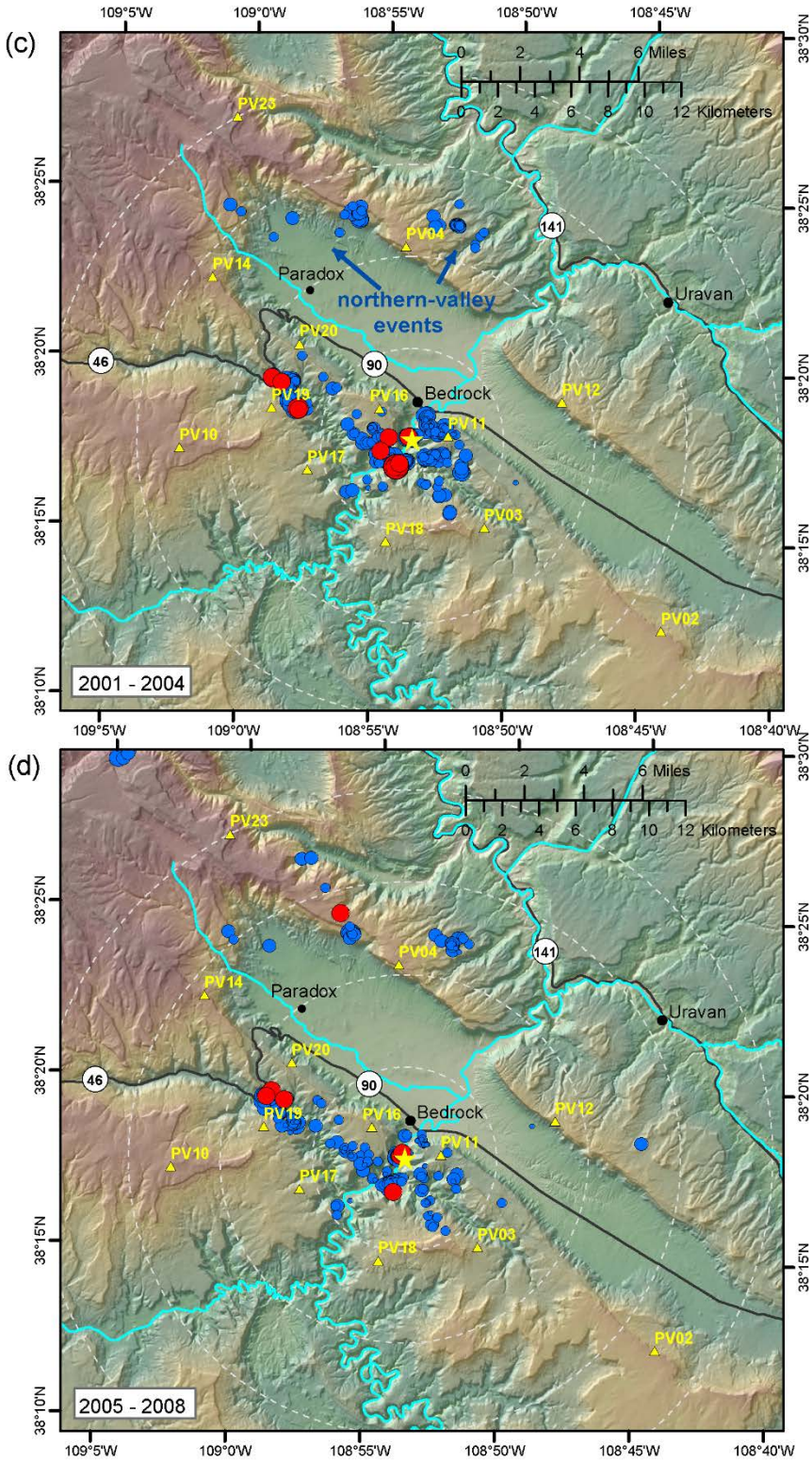


Figure 2-9, continued.

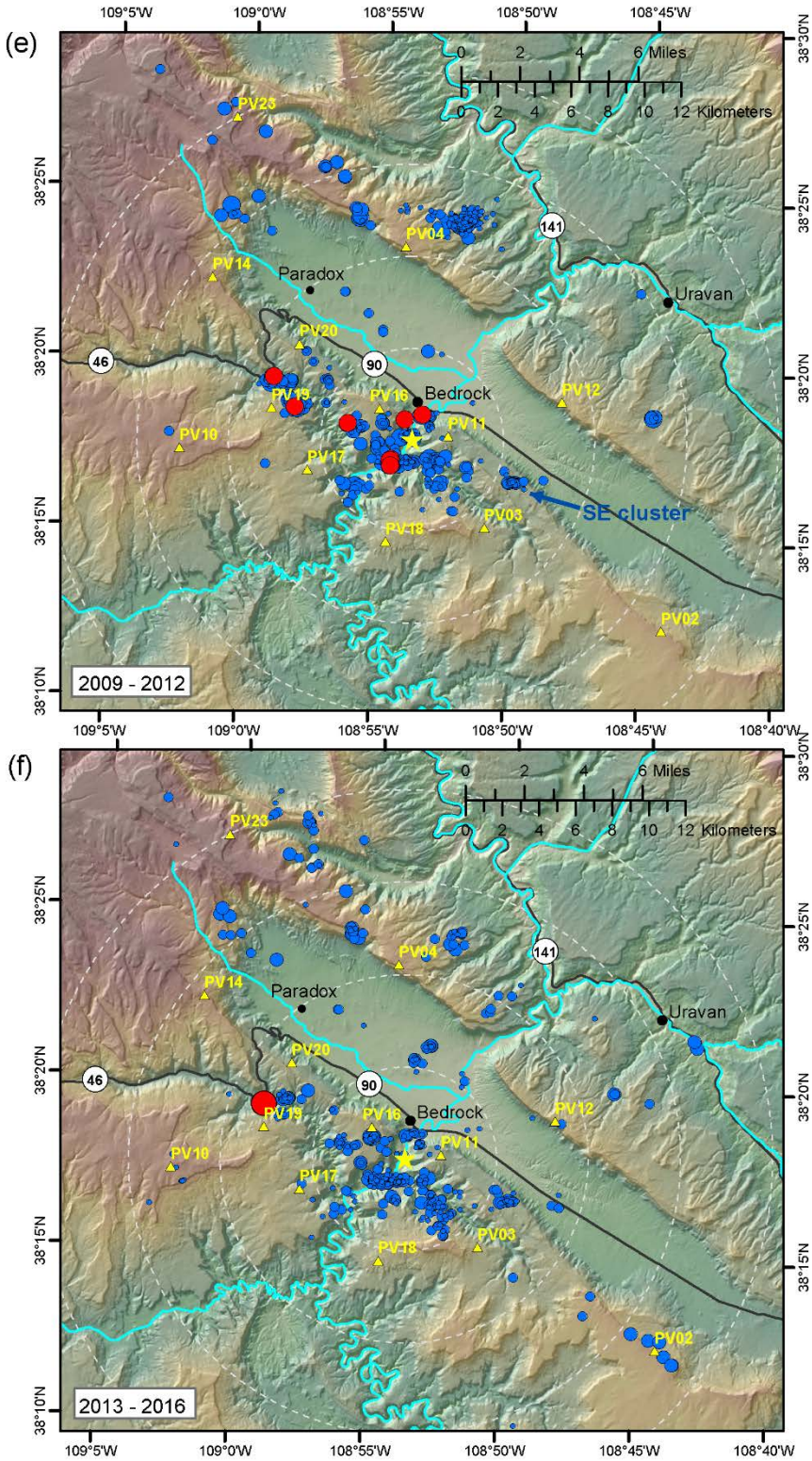


Figure 2-9, continued.

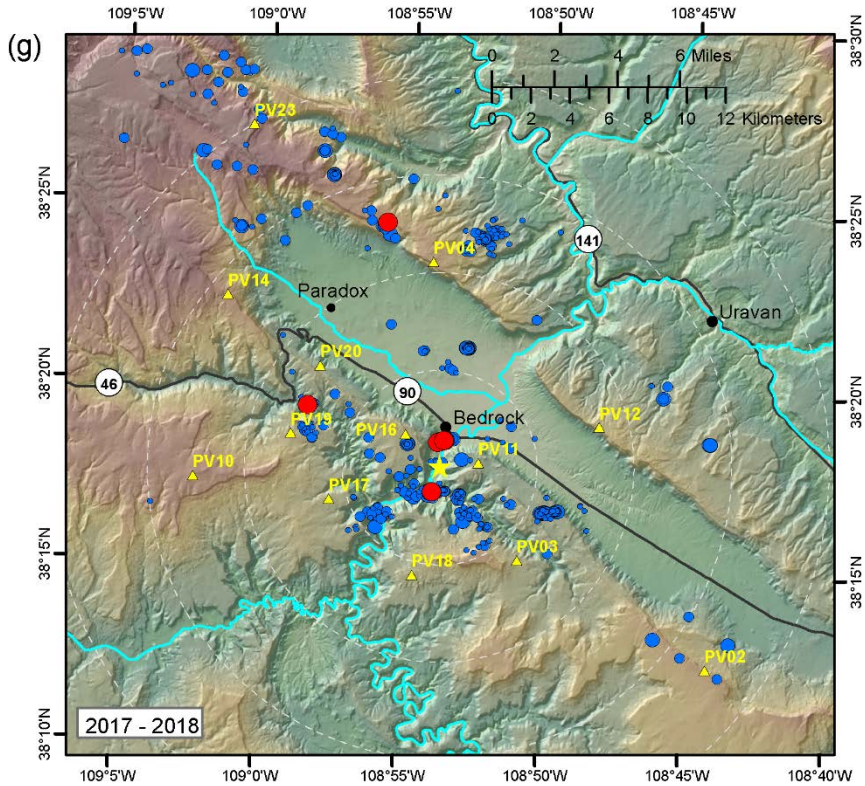


Figure 2-9, continued.

3 Network Operations during 2018

3.1 Network Maintenance and Upgrades

Five site visits were conducted during 2018. During these site visits, preventive and remedial maintenance was performed at the 20 broadband seismic stations and three strong motion stations and at the data communication center at Hopkins Field in Nucla, Colorado. 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, checking antenna azimuths, and inspecting seismometer vaults. Remedial maintenance included power-cycling a hung radio at station PV13 to restore data communication and power-cycling hung GPS antennas at stations PV16 and PV22 to restore station timing. At the data communication center at Hopkins Field, the arm for the omnidirectional antenna on the tower was lowered approximately 2-3 feet to increase the vertical separation between the omni antenna and the two yagi antennas mounted above it. Moreover, the AP-2 radio (for the PV02 radio repeater subnet) was replaced, a new KVM monitor/keyboard was installed, and batteries in the APC-3000 UPS unit were replaced while the old APC-1500 UPS unit was replaced with a new APC-3000 unit. Additional details of the maintenance activities performed during the 2018 site visits are included in the site visit reports in Appendix A.

In addition to maintenance activities described above, several PVSN upgrades were implemented in 2018. New Guralp model CMG-3ESP broadband seismometers were installed at stations PV02, PV10, PV18, PV20, and PV23, which improved the sensitivity and noise characteristics compared to the previously-installed Guralp model CMG-40T seismometers. The GPS antennas and station electronics break-out-boxes (DM24-BOBs and GPS-BOB circuit boards) were also replaced at these five stations for compatibility with the new seismometers. Another important upgrade was the addition of a GPS watchdog to the broadband station electronics. This upgrade was implemented to address the occasional loss of station timing due to GPS antennas ceasing to output serial data. The reason for this occasional loss of GPS data is not known but may be related to power fluctuations disrupting normal antenna function. Power-cycling the hung GPS antenna usually restores normal antenna function and station timing. The watchdog monitors GPS antenna serial data output and automatically power-cycles the GPS antenna if data output ceases. This upgrade was implemented at 18 of the 20 broadband seismic stations by replacing the circuit board in the GPS-BOB. Upgrades were completed at the data communication center in Nucla to enable remote monitoring and control of the local servers and other equipment from Reclamation’s office in Denver. These upgrades included the installation of two Ethernet-enabled power strips and the installation of a network interface card in the older UPS unit. In addition, the ability to control and monitor the radio data communication network was improved by purchasing vendor software (*Pulsenet*) and installing it on one of the servers in Nucla.

Obsolete GPS antennas were replaced at stations PV12 and PV14 in October 2018. These GPS antennas exhibited low voltage output, indicating that they were gradually failing. The broadband seismometers at these stations are more than 20 years old, and compatible GPS antennas can no longer be purchased from the vendor. To maintain station timing, custom-designed GPS antennas from *Matrix-5 Technologies, Inc.* were temporarily installed until the seismometers can be upgraded, which is anticipated for 2019. The timing provided by the Matrix-5 antennas is 1-sec early; this discrepancy is being corrected during data processing.

3.2 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 network communication hub at Hopkins Field, and the reliability of the data acquisition computer systems. The performance of each of these components is discussed below.

Only three of the 20 PVSN broadband seismic stations experienced GPS timing or other hardware failures in 2018 (Table 3-1). Stations PV16 and PV22 lacked GPS timing during part of 2018: station PV16 from June 3 to August 27 and station PV22 from February 19 to April 10. PVSN has experienced occasional loss of individual GPS station timing for several years, due to GPS antennas that temporarily stop transmitting data. As discussed in the previous section, a GPS watchdog feature was added to most of the PVSN broadband stations in 2018 to address this issue. Station PV13 was offline from early December 2017 until April 10, 2018 due to radio malfunction.

One station temporarily lost power during one or more nights in 2018. PV23 lost power multiple times in 2018 on the following dates and time (UTC): 1/7/18 12:15-15:27 (~ 3 hours), 1/10/18 13:00 – 1/11/18 16:07 (~27 hours), 1/21/18 7:00–17:40 (~ 10.5 hours), 2/11/18 13:30-15:17 (~ 2 hours), 2/13/18 13:45-18:47 (~5 hours), 2/14/18 8:45–17:47 (~ 9 hours), 2/15/18 2:45-15:02 (~ 12 hours), 2/16/18 13:15-15:17 (~ 2 hours), 2/24/18 3:00-15:17 (~ 12 hours), 3/19 from 4:30 to 14:46 UTC (~ 10 hours), 4/7 from approximately 6:15 to 16:17 UTC (~10 hours), and 4/8 from about 7:15 to 14:47 UTC (~7.5 hours). Diagnostic testing at this station during June 2018 suggested problems with both the solar panel regulator and one of the station batteries. The solar panel regular and all three station batteries were subsequently replaced.

Most stations experienced robust radio communications during 2018, which maintained the network's ability to continuously transmit seismic data, while a few stations experienced some data loss due to deteriorated radio communications. As already discussed, station PV13 was offline for more than three months because of a failed radio at that station. During this time, stations PV02 and PV05, which are on the same radio subnet as PV13, also experienced degraded radio data communications, resulting in average data loss of 2.5% for PV02 and ~7% for PV05. This can be observed as decreased station uptime in the plots presented in Figure 3-1. Data communication was markedly improved at all three stations after the April site visit (during which the transmitting radio at PV13 was rebooted and the receiving radio at Hopkins Field was replaced.) Other stations that experienced minor degraded radio communications during part of 2018 include PV10, PV20, and PV22. All of these stations are part of the PV12 radio subnet. They experienced ~3.5 – 5.0% data loss until August, when the yagi antenna at PV12 was upgraded and data communication substantially improved (Figure 3-1).

Table 3-1: Performance of PVSN seismic stations during 2018

Station	Performance
PV01	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV02	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV03	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV04	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV05	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV07	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV10	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV11	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV12	Online and functioning normally throughout the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub. Offline for approximately 57 hours during the week of October 23 due to difficulties related to the upgrade of its GPS antenna and station electronics. Time stamps are one second early since the installation of Matrix-5 antenna on October 21.
PV13	Offline for the months of January, February, March and up to April 10, 2018 due to radio malfunction. Online and functioning normally during the rest of the year. Other downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV14	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub. Time stamps are one second early since installation of Matrix-5 antenna on October 21.
PV15	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV16	Lost GPS timing on June 3rd at 19:49 UTC, which was restored during the August site visit, on 8/27 at 16:33 UTC. Online and functioning normally during the rest of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.

PV17	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV18	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV19	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV20	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV21	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub.
PV22	Online and functioning normally during most of the year. Downtime mainly due to onsite maintenance activities and a power outage by local utility company that led to server failures at the Nucla hub. Lost GPS timing on 2/19/18 at 19:25 (UTC), which was restored on April 10th at 19:47 UTC by power-cycling the GPS antenna.
PV23	Experienced power failures on the following dates and times (UTC): 1/7/18 12:15-15:27 (~ 3 hours), 1/10/18 13:00 – 1/11/18 16:07 (~27 hours), 1/21/18 7:00–17:40 (~ 10.5 hours), 2/11/18 13:30-15:17 (~ 2 hours), 2/13/18 13:45- 18:47 (~5 hours), 2/14/18 8:45–17:47 (~ 9 hours), 2/15/18 2:45-15:02 (~ 12 hours), 2/16/18 13:15-15:17 (~ 2 hours), 2/24/18 3:00-15:17 (~ 12 hours), 3/19 from 4:30 to 14:46 UTC (~ 10 hours), 4/7 from approximately 6:15 to 16:17 UTC (~10 hours), on 4/8 from about 7:15 to 14:47 UTC (~7.5 hours). At 9:11 UTC on April 20th, data communication from the station ceased, which was restored on April 26th.

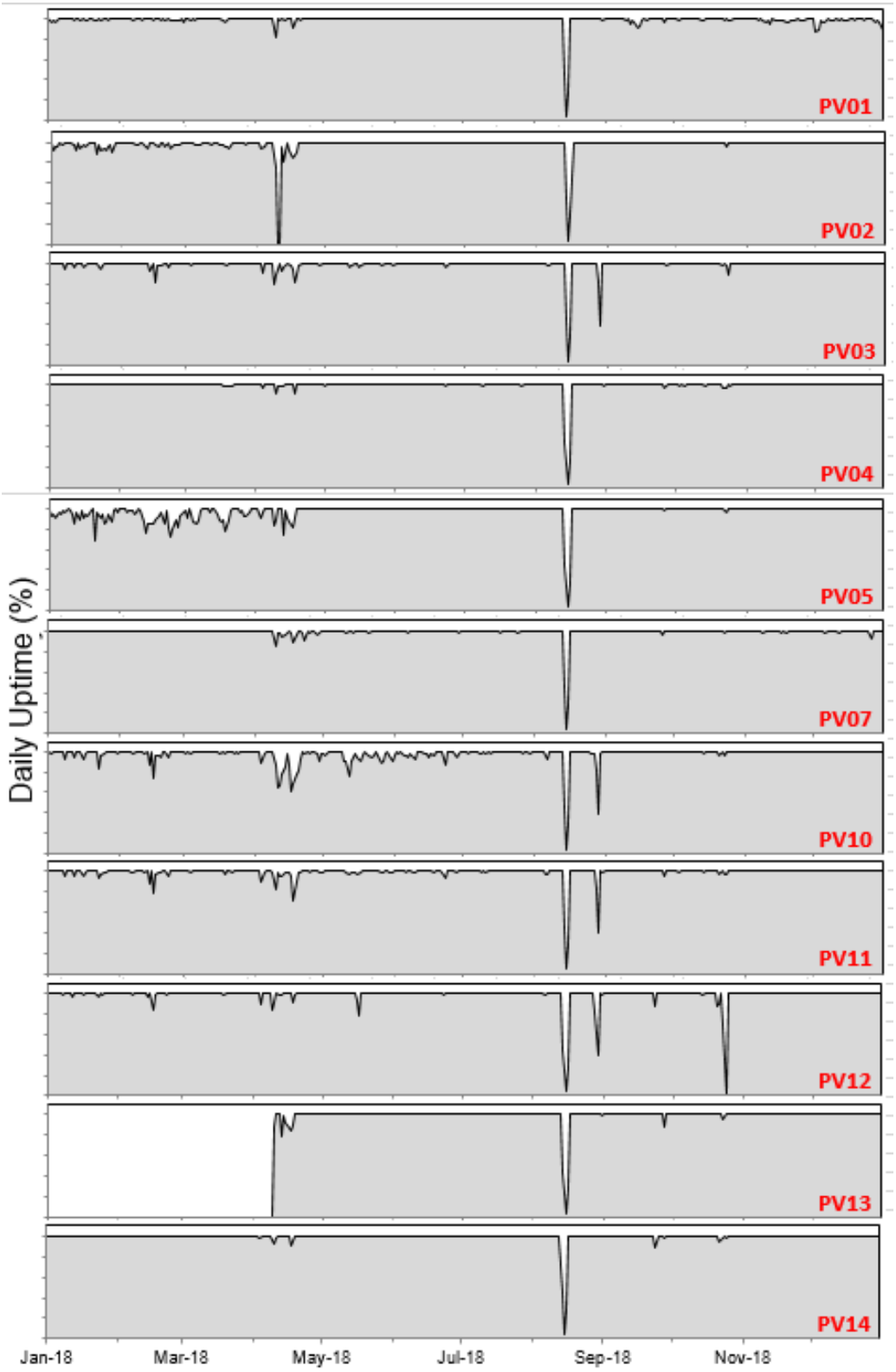


Figure 3-1: Daily uptime (%) for the PVSN seismic stations during 2018. The uptime values represent the percent of the day for which data from a given station were recorded. The vertical axes on the plots are scaled from 0 to 110%. Filled gray areas represent daily uptime, while dips in the filled volume show decreases in uptime (lack of data). Shaded blue areas indicate time periods with unreliable station timing.

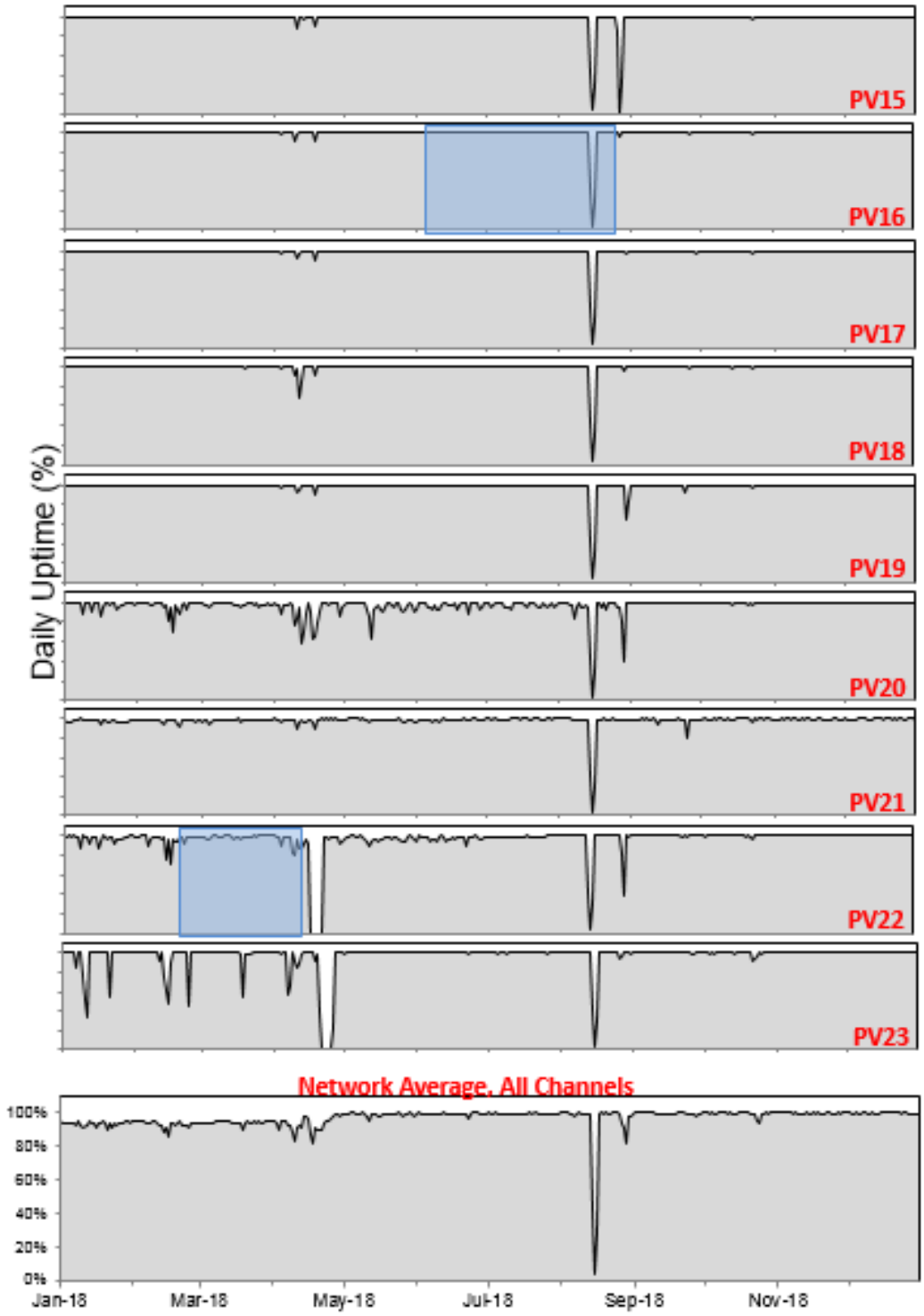


Figure 3-1, continued. The bottom plot shows the daily average performance for all PVSN channels.

The PVSN data acquisition computer systems were online and functioning normally during most of the year. Most data acquisition downtimes were short and due to planned maintenance or upgrade activities (Table 3-2). During the April visit, the network was offline on 4/10 from about 18:32 to 19:47 UTC (1 hour 15 min.) for patching of the *Scream* and *Earthworm* computer systems. PVSN was also offline on 4/18 from ~17:07 to 18:22 UTC (1 hour, 15 min.). This downtime was needed for reconfiguration of the radio data communications network. The network was also taken offline for approximately 17 minutes on October 23 (from ~14:01 to ~14:18 UTC) to accommodate preventive maintenance activities at Hopkins Field. In contrast to these short planned outages, a prolonged and unplanned downtime occurred during August, when PVSN was offline for approximately 55 hours (from 8/14 10:34 to 8/16 17:13 UTC). The downtime was due to a combination of an area-wide power outage in Nucla, failure of the backup generator at the PVSN communication hub at Hopkins Field, the remote *Earthworm* server in Nucla failing to reboot, and a *Scream* software bug associated with the unavailability of the local *Earthworm* server.

Considering data loss from hardware or power failures at individual seismic stations, radio communication data drop-outs, and PVSN downtimes, the 2018 annual uptimes for the PVSN telemetered high-gain seismic stations ranged from 72% to 99%, with 19 of the 20 stations having uptimes ≥ 96% (Figure 3-2; Table 3-3). 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. In 2018, PVSN was offline for nearly 58 hours, or 2.4 days. This corresponds to an annual PVSN uptime of 99.3% (Table 3-4).

Table 3-2: Times when PVSN was down or degraded in 2018

Time Period (UTC)	Reason
4/10 ~ 18:32 to 19:47 UTC (1 hour 15 min.)	Patching of the *Scream* and *Earthworm* computer systems.
4/18 ~17:07 to 18:22 UTC (1 hour, 15 min.)	Reconfiguration of the radio data communications network.
8/14 10:34 to 8/16 17:13 UTC (55 hours)	Downtime was due to a combination of an area-wide power outage in Nucla, failure of the backup generator at Hopkins Field, failure of the *Earthworm* server at Hopkins Field to reboot, and a bug in the *Scream* software
10/23 ~14:01 to ~14:18 UTC (17 min.)	Downtime to accommodate preventive maintenance activities at Hopkins Field.

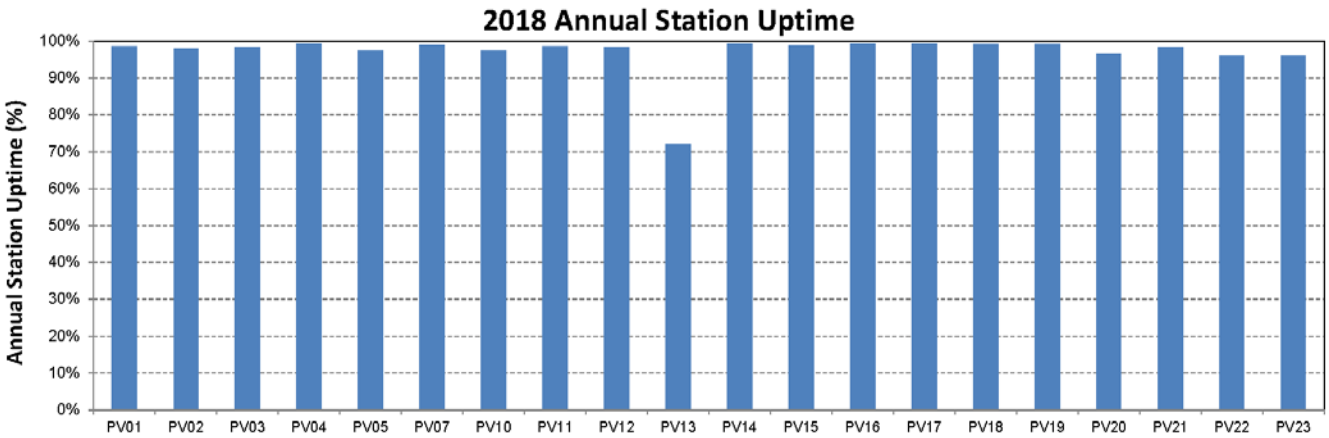


Figure 3-2. Graph of annual (2018) uptime for each PVSN telemetered high-gain seismic station.

Table 3-3: Annual PVSN station uptime in 2018.

Station	Annual Station Uptime in 2018
PV01	98%
PV02	98%
PV03	98%
PV04	99%
PV05	97%
PV07	99%
PV10	97%
PV11	99%
PV12	98%
PV13	72%
PV14	99%
PV15	99%
PV16	99%
PV17	99%
PV18	99%
PV19	99%
PV20	97%
PV21	98%
PV22	96%
PV23	96%

Table 3-4: Annual PVSN uptimes

Year	Annual Number of Days with Monitoring Absent or 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%

**not tabulated in 2001

[1] includes 40.5 hours of downtime in September 2014 when network was operating but event detection was severely degraded due to malfunctioning of the data acquisition software

[2] includes 50% rating for 12 days in February and 5 days in December when network was operating but monitoring was substantially degraded due to absence of data from 8-12 stations simultaneously.

[3] includes 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.

4 Seismic Data Recorded in 2018

4.1 Annual Summary

Two hundred and fifty-five earthquakes were recorded within or near the perimeter of PVSN during 2018. The map in Figure 4-1 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 recorded during 2018 are classified into four categories based on their depths (relative to the ground surface elevation of 1.524 km above msl at the injection well) and distances from the injection well:

1. Shallow near-well: depth ≤ 10 km, distance from 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 injection well

The earthquakes are color-coded using these categories in the map presented in Figure 4-1. The numbers and magnitudes of the earthquakes recorded during 2018 in each of the location categories are summarized in Table 4-1. The 2018 local earthquake catalog is included in Appendix B.

All but six of the 255 local earthquakes recorded during 2018 have depths ≤ 10 km. Of these relatively shallow earthquakes, 83 occurred within 5 km of the injection well, 41 occurred at distances between 5 and 10 km from the well, and 125 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 these earthquakes as being induced by PVU brine injection.

One shallow earthquake with duration magnitude (M_D) ≥ 2.5 occurred during 2018. This magnitude threshold is significant because it is the approximate minimum magnitude for human detection of earthquakes in the Paradox Valley area. The M_D 2.5+ induced earthquake occurred 7.5 km northwest of the injection well (Figure 4-2). It occurred on January 12th and had a magnitude of M_D 2.5.

The six deep events recorded during 2018 occurred northeast of Paradox Valley. One earthquake occurred 15.2 km east of the injection well, and the other five earthquakes occurred in a tight cluster 18 km east-northeast of the well (Figure 4-1, purple circles).The single event 15.2 km from the well has an estimated depth of 11.3 km, relative to the ground surface elevation at the injection well, and a magnitude of M_D 0.4. The five events in the cluster 18 km from the well have depths of 10.2-10.3 km and magnitudes of M_D 0.8 (2 events), M_D 1.6, M_D 1.9, and M_D 2.3. No earthquakes were detected within ~10 km of these six events in 23 years of seismic monitoring prior to 2007. Since the onset of seismicity in this area in 2007, earthquakes have been recorded within ~10 km of these earthquakes nearly every year, and the general rate of seismicity in this area has increased. Most earthquakes in this area have depths between 6.3 and 11.3 km, with the deeper earthquakes, such as the 2018 events, generally occurring farther east (Figure 4-1, purple and white circles). The lack of seismicity in this area prior to 2007 and its continued occurrence and generally increasing rate since then suggest that these earthquakes are related to PVU fluid injection.

The local earthquakes recorded by PVSN during 2018 are plotted as a function of date, earthquake magnitude, and location category in Figure 4-3. The rate of shallow near-well and intermediate-range

seismicity was fairly consistent through most of the year, while the rate of distant seismicity displays a much greater temporal variation. The rate of distant seismicity was highest between mid-August and November. Most of this activity occurred near the northwest end of Paradox Valley (Figure 4-1, yellow circles). A swarm of distant seismicity occurred during late September and early October. That swarm corresponds to events occurring in a cluster ~12 km north-northeast of the injection well, just northeast of seismic station PV04 (Figure 4-1).

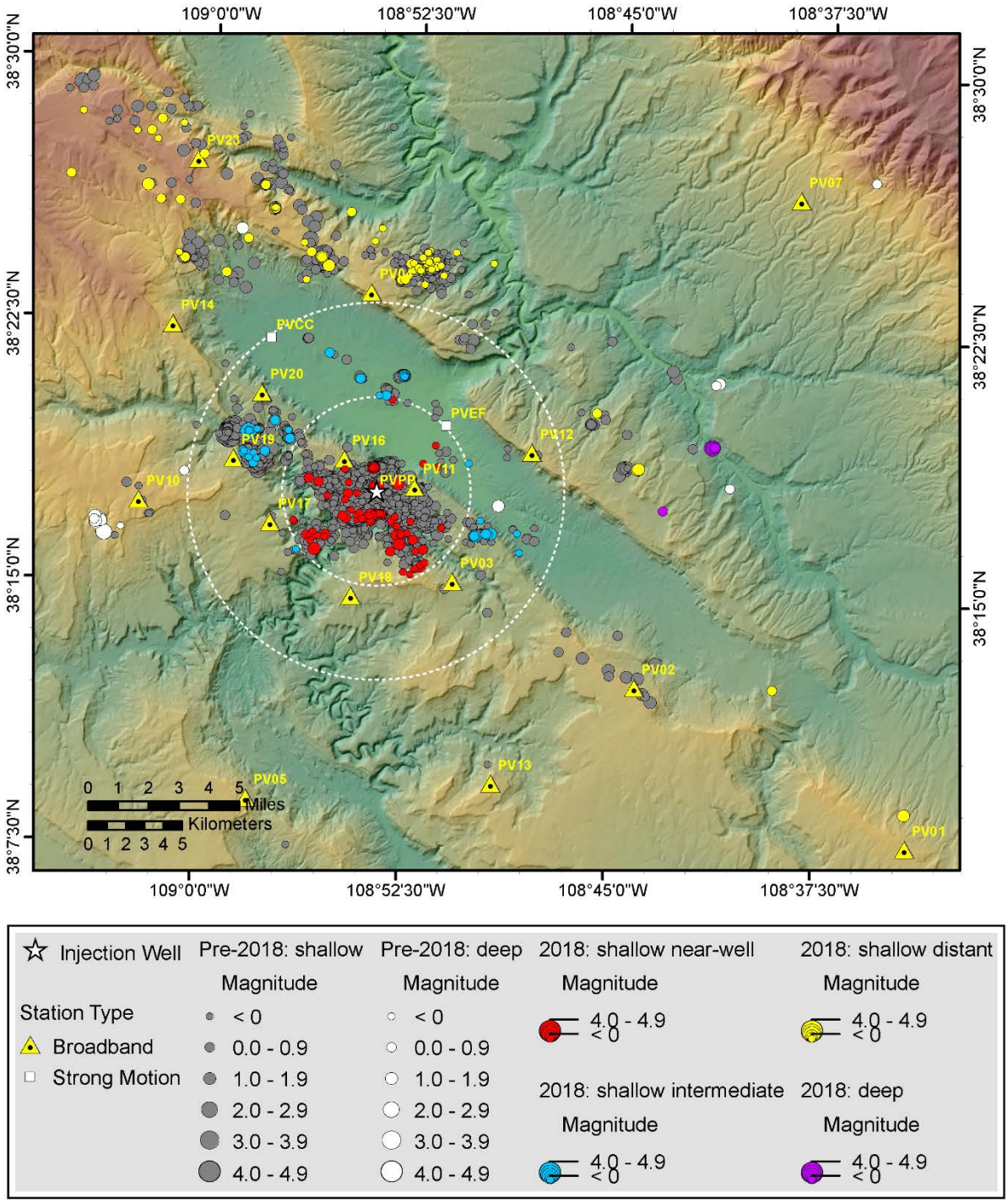


Figure 4-1: Locations of local earthquakes recorded by PVSN during 2018 (colored circles) and previous years (gray and white circles). The events that occurred during 2018 are color-coded using the event location categories described in the text. Events identified as "shallow" have depths ≤ 10 km (relative 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.

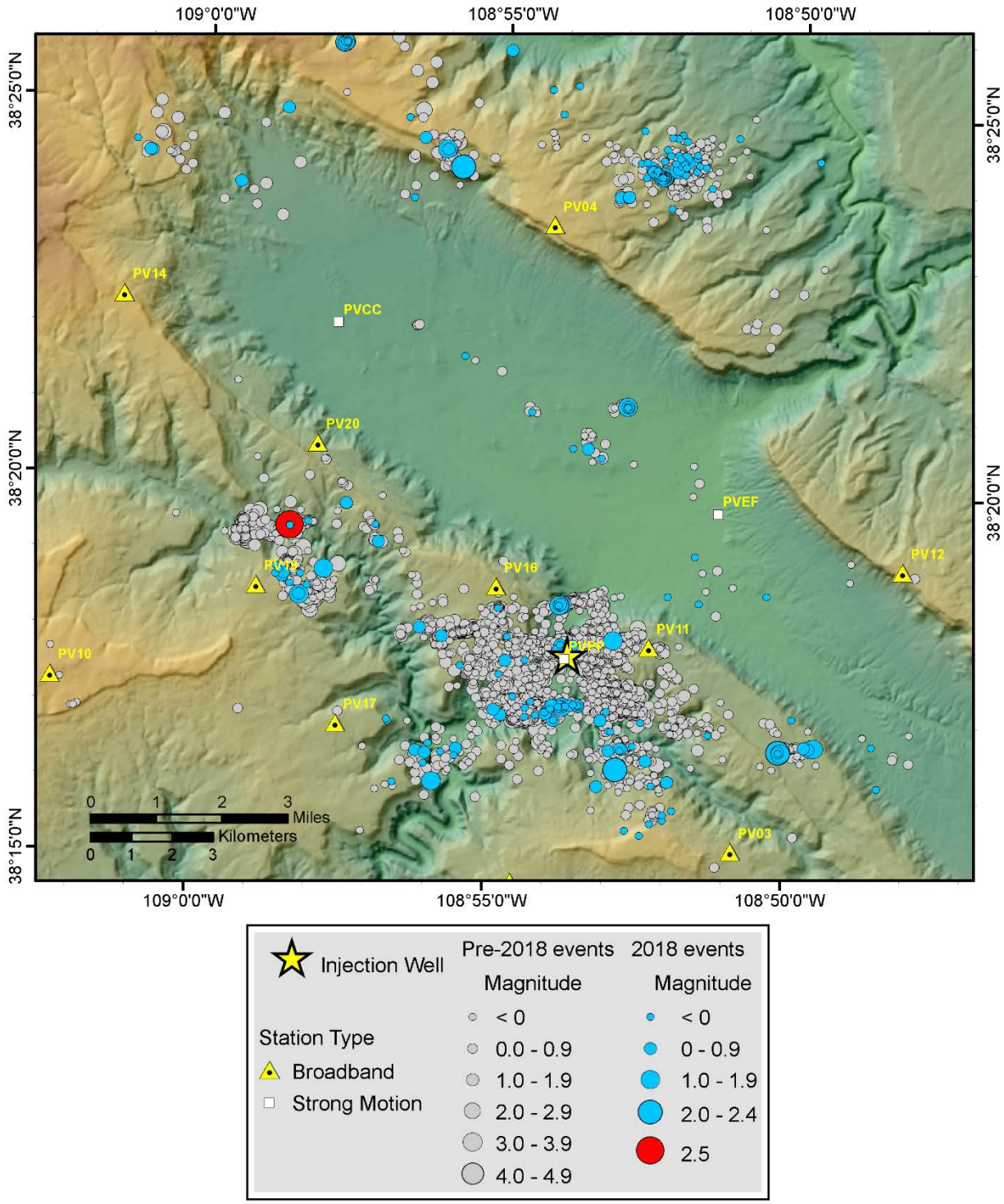


Figure 4-2: Earthquakes recorded in 2018 by magnitude. The one event in 2018 with $M_D \geq 2.5$ is shown in red; those with smaller magnitudes are shown in blue. The epicenters of earthquakes recorded prior to 2018 are shown in gray for reference. Events with depths ≤ 10 km (relative to the ground surface elevation at the injection well) are included.

Table 4-1: Summary of earthquakes recorded during 2018 by event location category

Location Category	Depth	Distance from well	Number of Earthquakes	Number of Earthquakes with $M_D \geq 0.5$	Magnitude Range
shallow near-well	≤ 10 km	0 to 5 km	83	14	-0.9 – 1.7
shallow intermediate		> 5 to 10 km	41	13	-0.7 – 2.5
shallow distant		> 10 km	125	30	-1.2 – 1.8
TOTAL SHALLOW			**249**	**57**	**-1.2 – 2.5**
deep	> 10 km	all distances, within or near perimeter of PVSN	6	5	0.4 – 2.3
TOTAL			**255**	**62**	**-1.2 – 2.5**

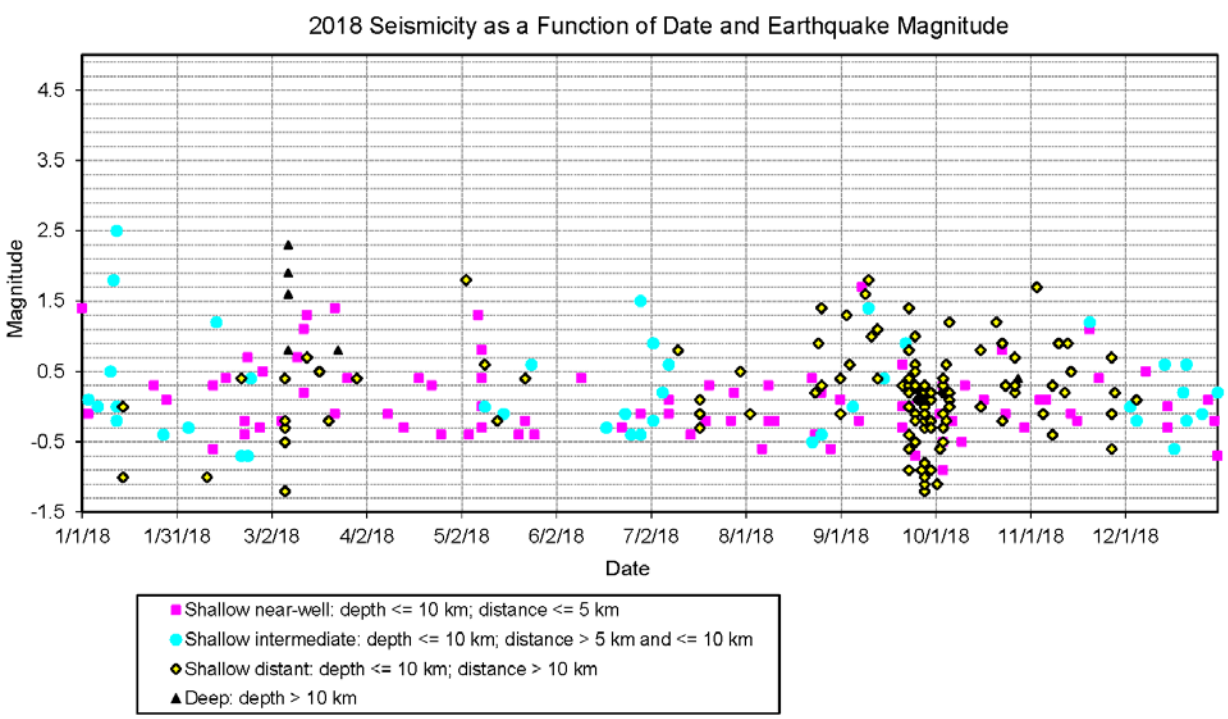


Figure 4-3: Earthquakes recorded by PVSN during 2018 plotted as a function of date, magnitude, and event location category.

4.2 Shallow Earthquakes

4.2.1 Seismicity near the Injection Well

The hypocenters of the earthquakes that occurred in 2018 within 7 to 9 km of the injection well are compared to those from previous years in the map in Figure 4-4 and in the vertical cross sections presented in Figure 4-5. In these figures, the earthquakes that occurred during 2018 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 the waveform data were not of sufficient quantity or quality to include these events in the relative location. As seen in the map and cross sections, the earthquakes induced within ~7-9 km of the injection well during 2018 occurred in areas of previous seismic activity.

The one M_D 2.5 local earthquake that occurred during 2018 is represented by the blue diamond in Figure 4-4 and Figure 4-5. This earthquake occurred on January 12th 7.5 km northwest of the injection well, at a depth of 3.8 km (relative to the ground surface elevation at the injection wellhead). This earthquakes appears to have occurred on the same fault that failed during the January 2013 local magnitude M_L 4.4 (moment magnitude 4.0) earthquake. Its epicenter lies on the interpreted fault lineation of the January 2013 earthquake (Figure 4-4). Its focal mechanism, indicating a fault plane striking N84°E and dipping 86° SE, is consistent with the focal mechanism of the January 2013 earthquake (Block et al., 2014).

4.2.2 Distant Earthquakes

During 2018, 125 earthquakes with computed depths ≤ 10 km were detected at distances greater than 10 km from the injection well. One hundred and nineteen of these earthquakes occurred at or near the northern end of Paradox Valley, where seismicity has been detected every year since 2000. For comparison, 59 events occurred in this northern-valley region in 2017 and 29 in 2016. Historically, the annual number of northern-valley events has varied widely, ranging from 2 to 557 events per year since 2000. The northern-valley earthquakes recorded during 2018 range in magnitude from M_D -1.2 to M_D 1.8. Twenty-five of these earthquakes have $M_D \geq 0.5$ (compared to 12 such events in 2017) and eight earthquakes have $M_D \geq 1.0$ (compared to four in 2017).

The seismicity in the northern-valley area is expanding to the northwest, with 12 earthquakes occurring beyond the northwest perimeter of the Paradox Valley Seismic Network during 2018 (Figure 4-1). Uncertainties in the computed locations and depths of earthquakes greatly increase when they occur outside the perimeter of the seismic network. Earthquakes are already occurring up to roughly 7 km outside the northwest 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 addition to the continued distant seismicity at the northern end of Paradox Valley, shallow earthquakes occurred at large distances from the injection well at several other azimuths during 2018. Four shallow distant earthquakes occurred east of Paradox Valley and south of the Dolores River, one at a distance of 12.4 km from the well and three co-located 13.9 km from the well (Figure 4-1, yellow circles). The magnitudes of these events range from M_D 0.9 to M_D 1.8, and their depth estimates range

from 6.3 to 9.3 km. (As discussed in section 4.1, six likely-induced earthquakes with depths slightly deeper than the 10-km cut-off criterion also occurred in this area during 2018.) Earthquakes have occurred in this area since 2007, and rates have generally increased over time.

Two shallow distant earthquakes occurred southeast of the injection well during 2018. These events occurred at distances of 23.5 and 32.8 km from the well (Figure 4-1, yellow circles). The magnitude of the closer event is M_D 0.2, and its depth estimate is 7.3 km (relative to the PVU injection wellhead). The farther event has a magnitude of M_D 1.6 and a depth estimate of 4.6 km. No seismicity had been detected within 6 km of either of these earthquakes in the preceding 33 years of PVSN seismic monitoring.

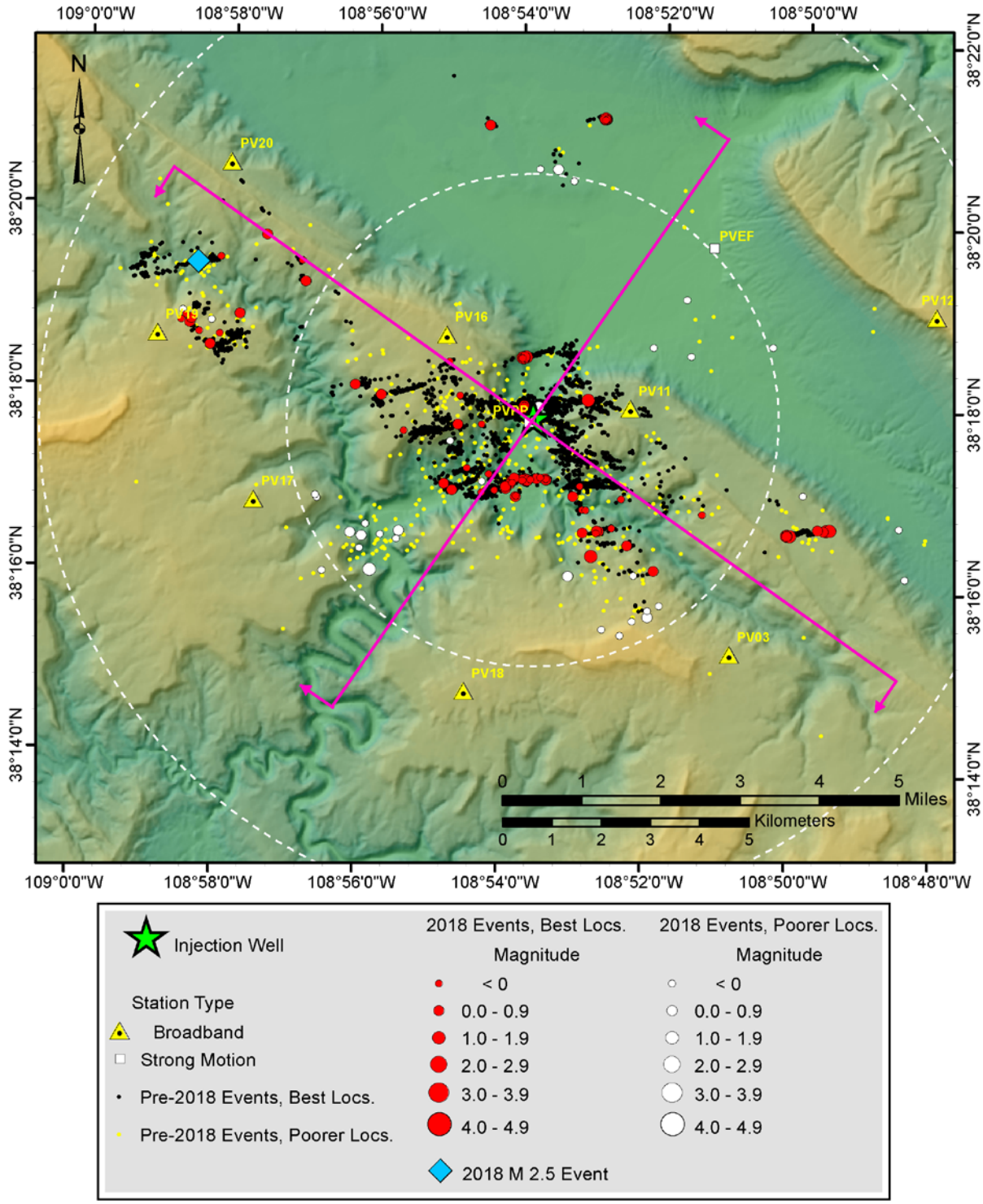
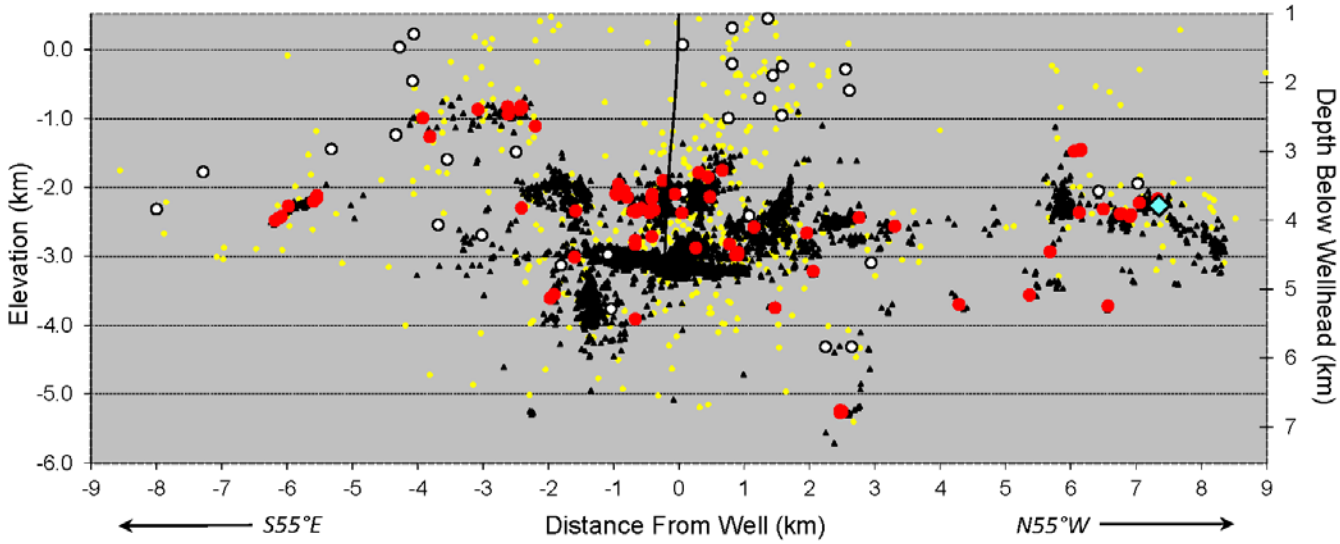


Figure 4-4: Map showing the epicenters of shallow earthquakes (≤ 10 km depth) in the vicinity of the injection well in 2018, compared to the locations of previously-induced events. The white dashed circles indicate radial distances of 5 and 10 km from the injection well. The magenta lines indicate the orientations of the cross sections presented in Figure 4-5.

(a) Cross section parallel to Paradox Valley, looking to the southwest



(b) Cross section perpendicular to Paradox Valley, looking to the northwest

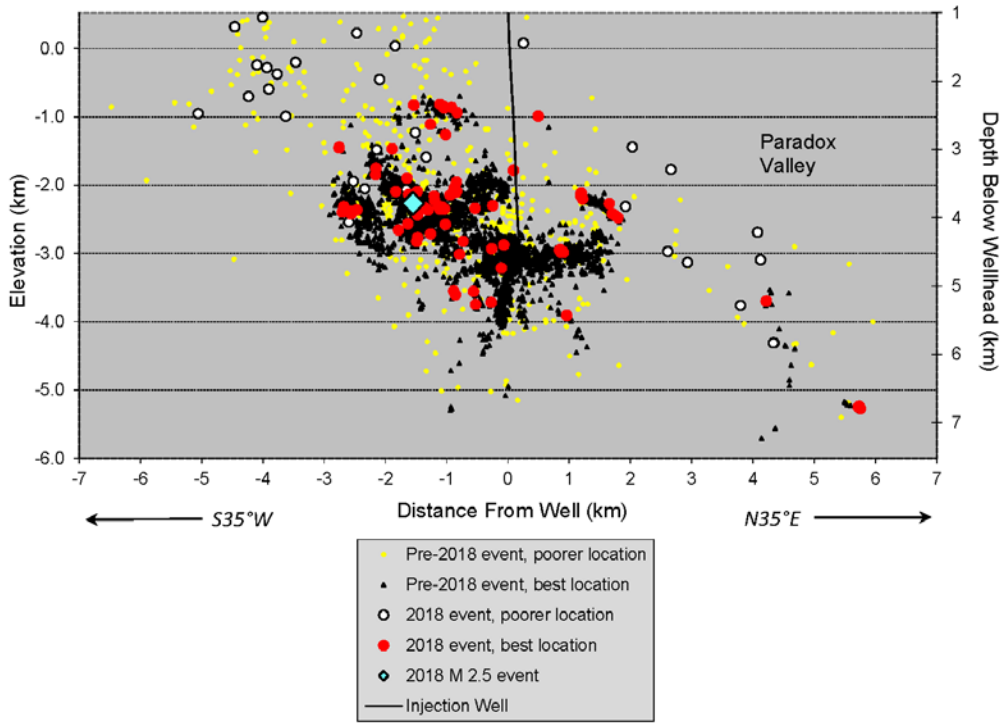


Figure 4-5: Vertical cross sections showing the hypocenters of earthquakes occurring within approximately 7-9 km of the injection well in 2018, compared to the locations of previously-induced events: (a) section parallel to Paradox Valley (b) section perpendicular to Paradox Valley. The orientations of the cross sections are indicated by the magenta lines in Figure 4-4.

4.2.3 Comparison to 2017 Seismicity

The number of shallow earthquakes observed within 10 km of the injection well decreased markedly in 2018 compared to 2017, while the number of earthquakes > 10 km from the well substantially increased (Table 4-2). During 2018, 83 earthquakes were detected within 5 km of the injection well, compared to 194 in 2017, a decrease of 57%. A slightly smaller percent decrease was observed in the 5-10 km distance range, with the number of earthquakes decreasing from 75 in 2017 to 41 in 2018, a decrease of 45%. At distances > 10 km, the number of shallow earthquakes increased from 68 in 2017 to 125 in 2018, an increase of ~84%.

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 nominal magnitude completeness threshold). These values are presented in Table 4-3. Substantial decreases in seismicity rates are still observed within 10 km of the well, while a large increase is observed for distance > 10 km: 69% decrease for the 0-5 km distance range, 32% decrease for the 5-10 km distance range, and 67% increase for distance > 10 km.

Table 4-2: Number of earthquakes with depth ≤ 10 km recorded in 2017 and 2018, as a function of distance from the injection well. These counts include all shallow events recorded, regardless of magnitude.

Distance Range (km)	Number of Events Recorded in 2017	Number of Events Recorded in 2018	Percent Change
0 to 5	194	83	-57.2%
> 5 to 10	75	41	-45.3%
> 10	68	125	83.8%

Table 4-3: Number of earthquakes with depth ≤ 10 km and magnitude ≥ M_D 0.5 recorded in 2017 and 2018, as a function of distance from the injection well.

Distance Range (km)	Number of Events Recorded in 2017	Number of Events Recorded in 2018	Percent Change
0 to 5	45	14	-68.9%
> 5 to 10	19	13	-31.6%
> 10	18	30	66.7%

The numbers of earthquakes recorded during 2017 and 2018 are plotted as a function of magnitude in Figure 4-6. Individual histograms are shown for earthquakes within 5 km of the injection well, for those at distances of 5 to 10 km from the well, and for events > 10 km from the well. These radial distances are indicated by the white dashed circles on the map in Figure 4-4. Normalized cumulative magnitude-frequency plots of the same data are presented in Figure 4-7. For the 0-5 km distance range, seismicity rates were lower for all magnitudes in 2018 compared to 2017 (upper plot in Figure 4-6). In addition, the maximum earthquake magnitude decreased from M_D 2.9 in 2017 to M_D 1.7 in 2018. For the 5-10 km distance range, seismicity rates were lower for most magnitudes in 2018 compared to 2017 (middle plot in Figure 4-6). In contrast, the rate of earthquakes between M_D 2.0 and M_D 2.5 increased slightly. The maximum earthquake magnitude for this distance range increased from M_D 1.8 in 2017 to M_D 2.5 in 2018. For earthquakes occurring more than 10 km from the injection well, seismicity rates increased for most magnitudes in 2018 compared to 2017 (lower plot in Figure 4-6) . In contrast, the rate of

earthquakes between M_D 2.5 and M_D 3.0 decreased slightly. The maximum earthquake magnitude for this distance range decreased from M_D 2.9 in 2017 to M_D 1.8 in 2018. For all distance ranges, the normalized cumulative histograms are similar in 2017 and 2018, indicating no substantial change in event detection capability or ratio of smaller- to larger-magnitude events (Figure 4-7).

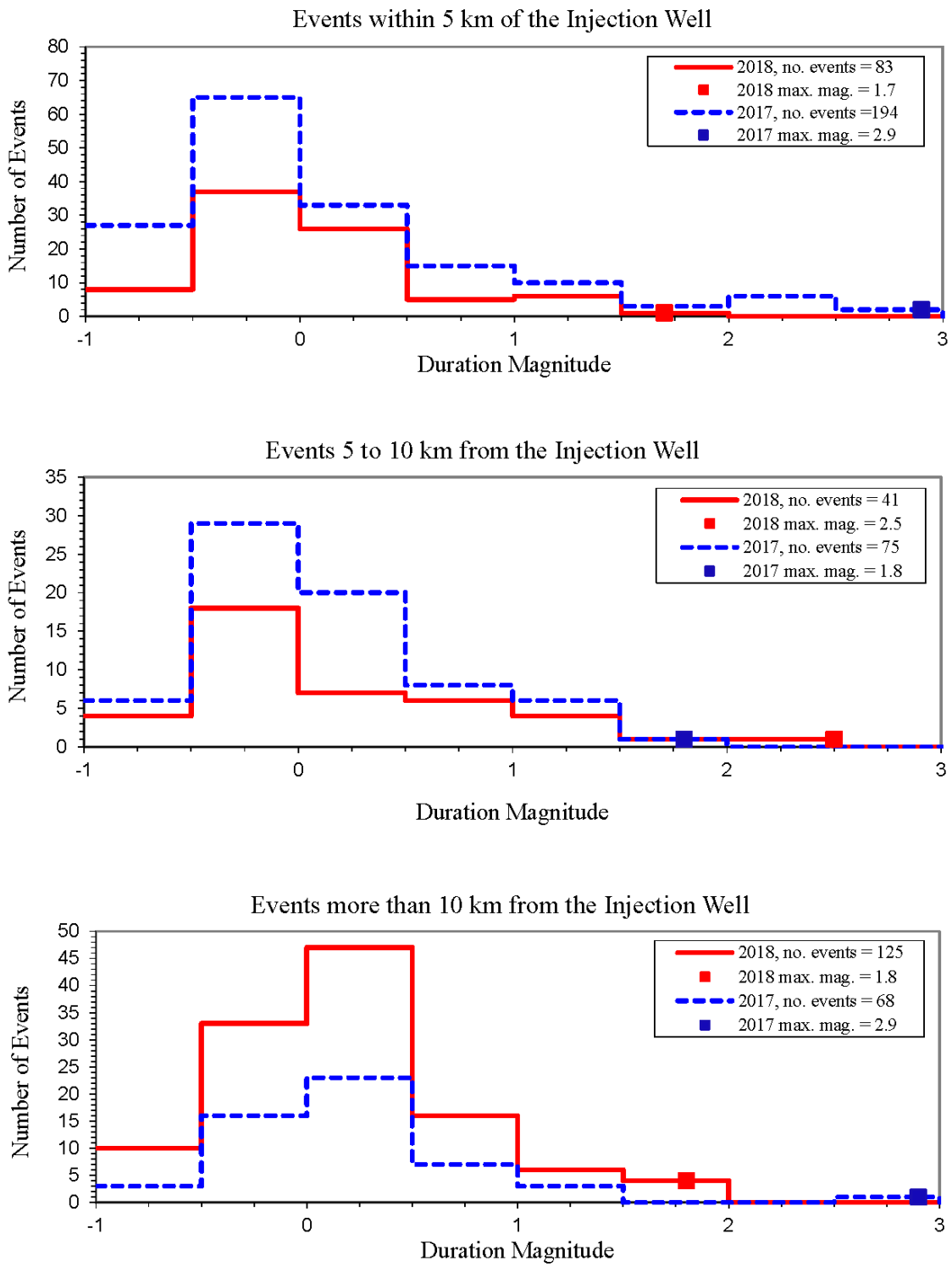


Figure 4-6: Magnitude histograms of events within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and more than 10 km from the well (bottom) during 2018 (solid red lines) and 2017 (dashed blue lines). The squares indicate the maximum earthquake magnitude for a given distance range and year.

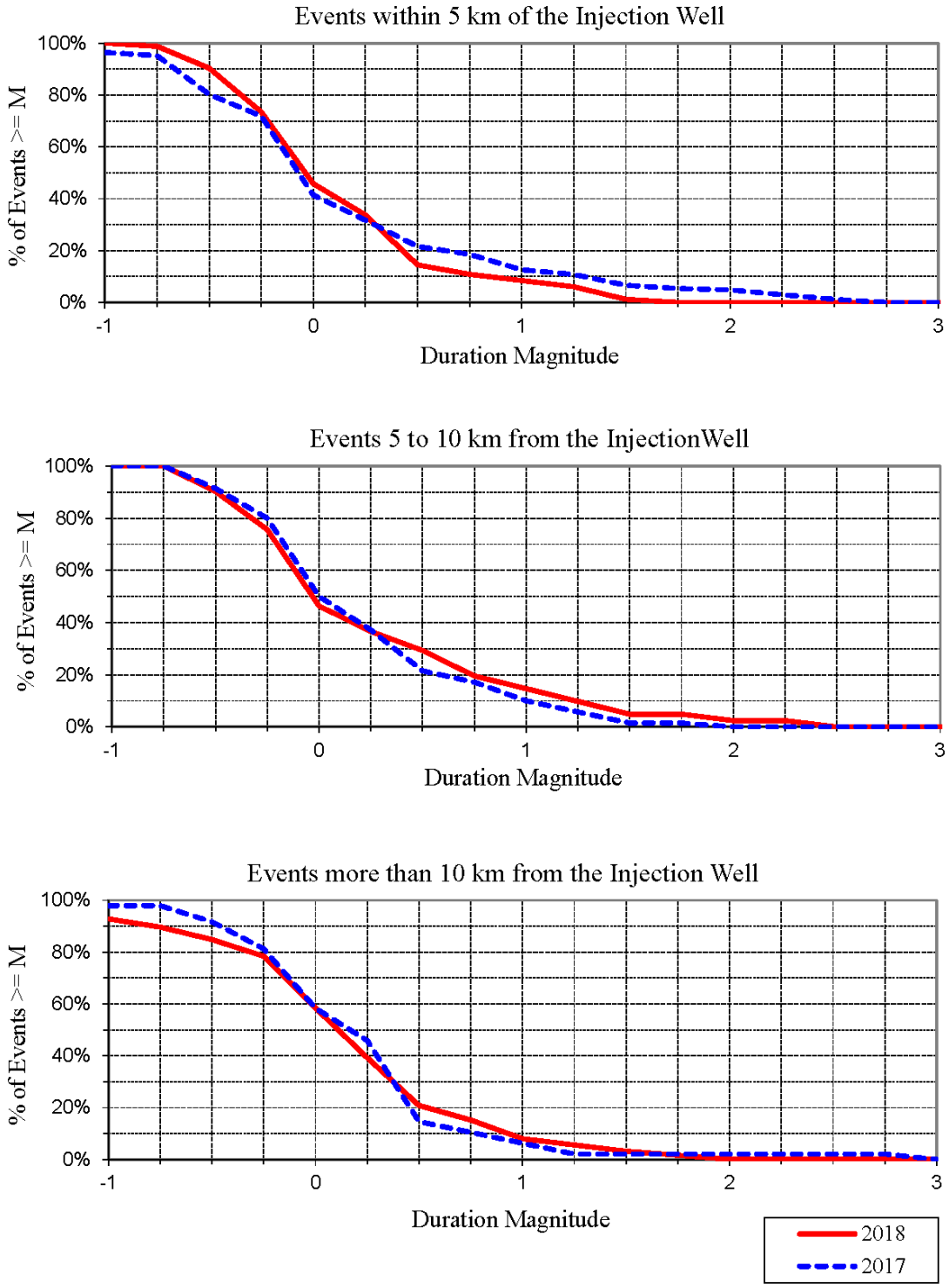


Figure 4-7: Cumulative magnitude-frequency plots of events within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and more than 10 km from the well (bottom) during 2018 (solid red lines) and 2017 (dashed blue lines).

4.3 Historical Seismicity Trends

The rates and magnitudes of earthquakes that occurred during 2018 are compared to the historical seismicity trends in three plots described below. Only events with $M_D \geq 0.5$ (M 0.5+) are included in these plots, since the detection capability for earthquakes with magnitudes less than this threshold has varied considerably over the history of PVSN. First, the bubble plots in Figure 4-8 show the historical occurrence of shallow seismicity (depth ≤ 10 km) as a function of date and earthquake magnitude during long-term injection at PVU (1996-2018). 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 downhole injection pressures, averaged over varying lengths of time, are included in Figure 4-8 for reference. In order to better observe the trends in recent years, similar plots that only include data from 2010-2018 are presented in Figure 4-9. Lastly, we show the annual seismicity rates for 2010-2018, for the different distances from the well, in Figure 4-10.

These plots show that both the seismicity rate and maximum earthquake magnitude for the near-well area (within 5 km of the well) were relatively low in 2018, compared to historical levels. Figure 4-8b and Figure 4-9b indicate that no near-well earthquakes with magnitude $\geq M_D$ 2.0 occurred during 2018 and that the absence of M_D 2.0+ near-well events only occurred during four (2007-08, 2014-15) of the previous 21 full years of PVU fluid injection (1997-2017).
The 2018 annual rate of near-well M 0.5+ events was 69% lower than the 2017 rate and 46% lower than the 2016 rate (Figure 4-10a). It was 43% lower than the average rate for the preceding eight years (2010-2017).

Both the seismicity rate and maximum earthquake magnitude observed at distances of 5 to 10 km from the injection well in 2018 were typical compared to historical trends. Figure 4-8c and Figure 4-9c indicate that the maximum earthquake magnitude in this distance range was between M_D 2.5 and M_D 3.0 in 2018 and that the maximum earthquake magnitude was also in this range during 12 of the previous 21 full years of fluid injection. The seismicity rate in this distance range during 2018 was 32% lower than the 2017 rate but only 7% lower than the 2016 rate and 4% lower than the average rate experienced during the preceding eight years (2010-2017) (Figure 4-10b).

The annual rate of distant M 0.5+ events, those occurring more than 10 km from the injection well, has been increasing steadily since 2013 (Figure 4-10c). The 2018 rate was 67% higher than the 2017 rate and 114% higher than the 2016 rate. The annual rate still remains modest compared to peak historical rates, which at times were very high due to intense swarms of activity lasting days to weeks. The maximum magnitude of the distant shallow induced earthquakes in 2018, M_D 1.8, was neither unusually large nor unusually small (Figure 4-8d).

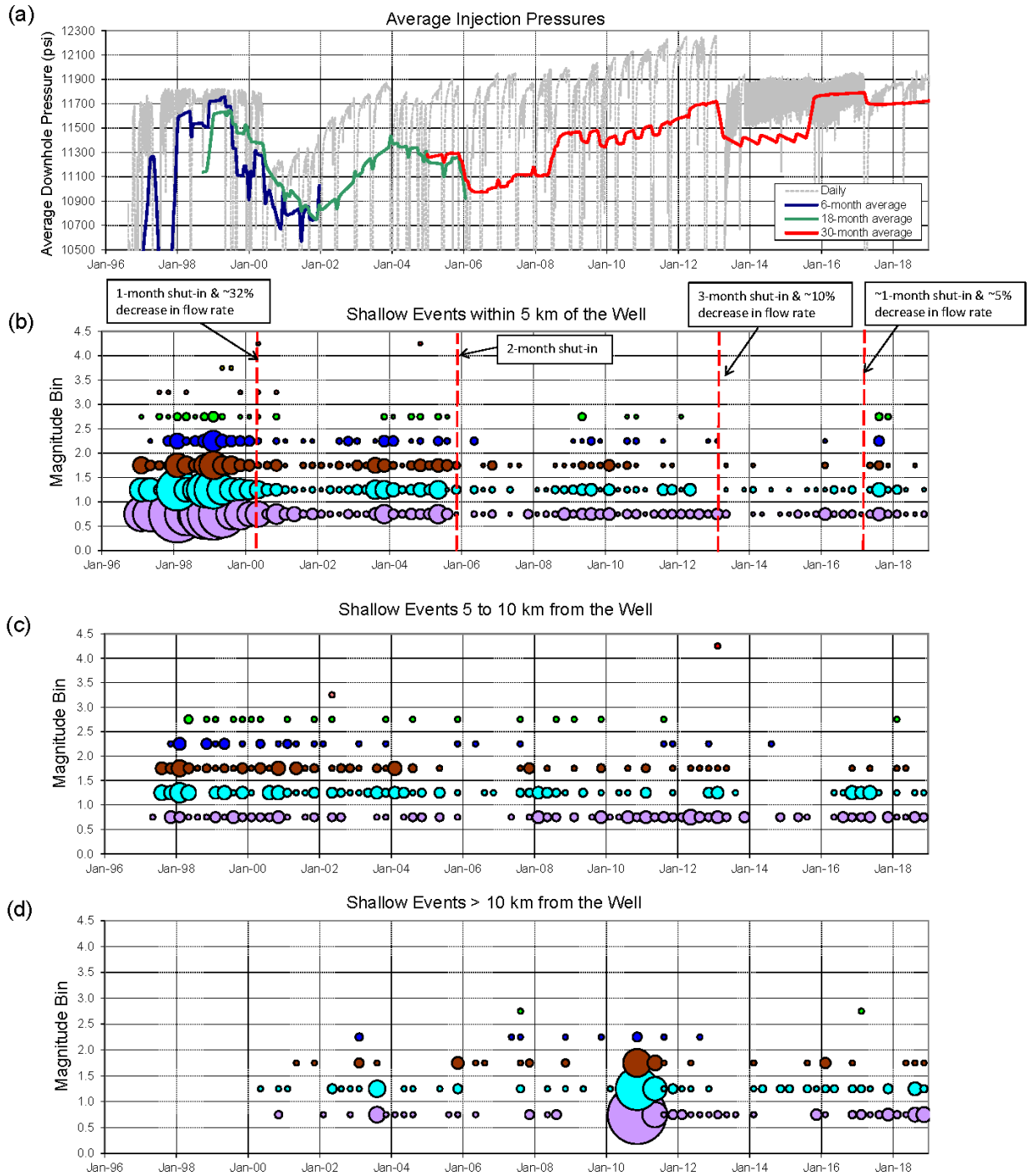


Figure 4-8: Injection well downhole pressure data averaged over daily, 6-month, 18-month, and 30-month time periods (a) and occurrence of shallow seismicity (depth ≤ 10 km) as a function of date and magnitude: within 5 km of the injection well (b), at distances of 5 to 10 km from the well (c), and more than 10 km from the well (d). 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.

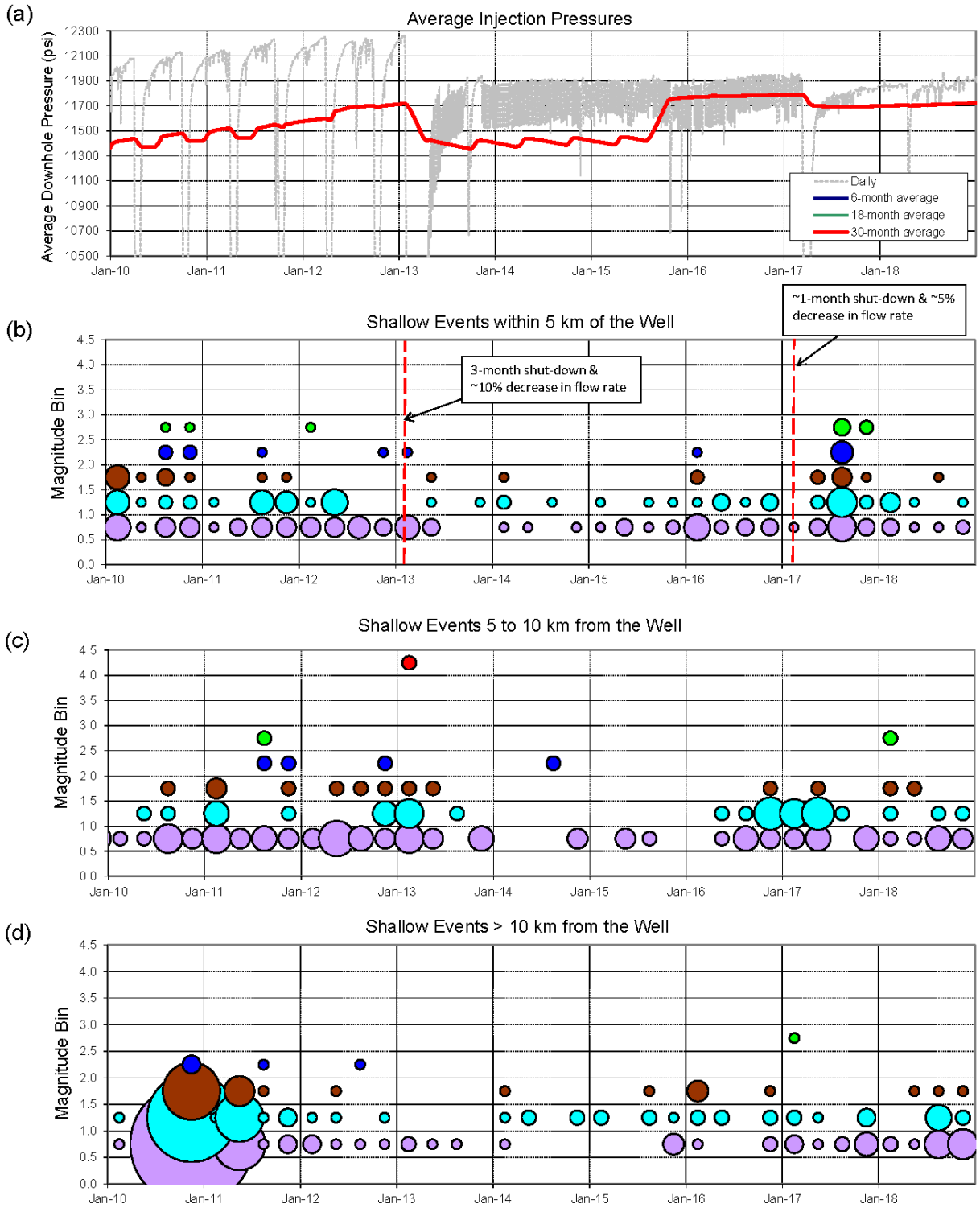


Figure 4-9: Same as Figure 4-8, but only showing data from 2010-2018.

Figure 4-10: Annual number of shallow earthquakes (depth ≤ 10 km) with $M_D \geq 0.5$: within 5 km of the injection well (a), 5 to 10 km from the well (b), and more than 10 km from the well (c). Data from 2010 to 2018 are shown. High counts in 2010 and 2011 for events more than 10 km from the well are clipped.

5 Conclusions

The Paradox Valley Seismic Network performed well during 2018. The uptime of the network was 99.3%, the second highest network uptime since 2012. Uptimes for the individual telemetered high-gain seismic stations ranged from 72% to 99%, with 19 of the 20 stations having uptimes ≥ 96%.

Annual rates of induced earthquakes within 10 km of the injection well decreased substantially in 2018 compared to the previous year, while the rate of distant induced earthquakes increased. The rate of shallow (depth ≤10 km) M_D 0.5+ events within 5 km of the well was 69% lower in 2018 than in 2017. The rate of shallow M_D 0.5+ earthquakes between 5 and 10 km from the well decreased 32% compared to the previous year. In contrast, the annual rate of distant M 0.5+ events, those more than 10 km from the injection well, has been increasing steadily since 2013. The 2018 rate was 67% higher than the 2017 rate and 114% higher than the 2016 rate.

The number of large induced earthquakes decreased substantially in 2018 compared to 2017. Only one earthquake with magnitude ≥ M_D 2.5 occurred during 2018, compared to six such events in 2017. This magnitude threshold is significant because it is the approximate minimum magnitude for human detection of earthquakes in the Paradox Valley area. In addition, the maximum earthquake magnitude decreased from M_D 2.9 in 2017 to M_D 2.5 in 2018.

The 2018 M_D 2.5 induced earthquake occurred 7.5 km northwest of the injection well on January 12th. Based on its location and focal mechanism, this earthquakes appears to have occurred on the same fault that failed during the January 2013 local magnitude M_L 4.4 (moment magnitude 4.0) earthquake.

The geographical extent of the induced seismicity is continuing to expand. Earthquakes potentially related to PVU fluid injection are now occurring at distances up to ~33 km from the well. In addition, the induced seismicity is expanding beyond the northwest perimeter of the seismic network. Since the accuracy of computed locations and depths of earthquakes occurring outside the network is relatively low, our ability to accurately monitor the continued expansion of the seismicity in this direction with the current network configuration will be poor.

6 References

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Appendix A

2018 Site Visit Reports

Paradox Valley Seismic Network
Site Visit Report

Site Visit Number: PVSN-2018-1
Prepared by: Lisa Block and Glenda Besana-Ostman
Departure Date: 4/08/2018
Return Date: 4/14/2018
Personnel: Chris Wood, Justin Schwarzer, Glenda Besana-Ostman, Lisa Block

Primary Purpose: To perform preventive maintenance at the telemetered broadband seismic stations and Hopkins Field data communication center and to install new seismometers at five stations.

Details:
New Guralp CMG-3ESP broadband seismometers were installed at stations PV02, PV10, PV18, PV20, and PV23. These seismometers have improved sensitivity and noise characteristics compared to the previously-installed Guralp CMG-40T seismometers. At each of these sites, the GPS antennas, DM24-BOBs, and GPS-BOB circuit boards were also replaced with upgraded units. These new components were required for compatibility with the new seismometers.

In addition to the routine preventive maintenance work performed at the data communication center at Hopkins Field, the arm for the omnidirectional antenna on the tower there was lowered approximately 2-3 feet. This was done to increase the vertical separation between the omni antenna and the two yagi antennas mounted on the tower above it. In addition, the radio for the AP-2 radio (for the PV02 radio repeater subnet) was replaced because the previous radio had low power output. A new KVM monitor/keyboard was also installed. Batteries in the APC-3000 UPS unit were replaced, and the old APC-1500 UPS unit was replaced with a new APC-3000 unit.

All three strong motion sites were also visited during this trip.

Work by Site:

Site	Preventive Maintenance					Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault	
PV02	X		X	X	X	Replaced seismometer, GPS antenna, DM24-BOB, & GPS-BOB circuit board. Moved omni antenna arm to different tower face. Put in stakes for PV05 and PV 13 azimuths. Needs WAGO screwdriver, new GPS antenna bracket, and solar panel angle adjusted ~10°.
PV03	X		X	X		Replaced bolt-style radio-polyphaser jumper cable with crimped-style cable. Needs WAGO screwdriver. Still has LVD circuits on battery fuse block.
PV04	X		X	X		Replaced DM24-BOB because TX light was not blinking (although BOB was otherwise functioning). Vault needs glass plate.
PV05	X		X	X		
PV10	X		X	X	X	Replaced seismometer, GPS antenna, DM24-BOB, & GPS-BOB circuit board. Needs WAGO screwdriver and new GPS antenna bracket.
PV11	X		X	X	X	Replaced bolt-style radio-polyphaser jumper cable with crimped-style cable. Seismometer vault was wet. Needs WAGO screwdriver.
PV12	X		X	X	X	Moved omni antenna arm to different tower face. Spline ball bracket needs repair or replacement. Still has LVD circuits on battery fuse block. Battery voltages (wired) on secondary enclosure larger than expected (~0.4 V). Floating battery voltages on secondary enclosure not measured (because there are no fuses that can be easily removed). Re-test batteries during next visit.
PV13						Power-cycled hung radio to restore data communications.
PV14						Retrieved SPM. (Data downloaded later.) Put more dirt on vault, which was partially exposed.

Site	Preventive Maintenance					Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault	
PV18	X		X	X	X	Replaced seismometer, GPS antenna, DM24-BOB, & GPS-BOB circuit board. Replaced bolt-style radio-polyphaser jumper cable with crimped-style cable. Needs new GPS antenna bracket. Still has LVD circuits on battery fuse block.
PV20	X		X	X	X	Replaced seismometer, GPS antenna, DM24-BOB, & GPS-BOB circuit board. Replaced bolt-style radio-polyphaser jumper cable with crimped-style cable. Installed SPM (from PV14). Needs new GPS antenna bracket. Road needs trees trimmed.
PV22	X		X			Replaced GPS-BOB circuit board with revised version (E1) having watchdog feature. Upon replacing board and power-cycling GPS antenna, station timing was restored. Had to walk to station because of closed road. Could not test radios because forgot smartcard for laptop.
PV23	X		X	X	X	Replaced seismometer, GPS antenna, DM24-BOB, & GPS-BOB circuit board. Replaced damaged GPS-BOB ribbon cable. Downloaded SPM data. Needs new GPS antenna bracket.
Hopkins Field		X	X	X		The arm for the omni AP-1 antenna was lowered 2-3 feet, and the antenna was replaced. The AP-2 radio was replaced because the previous radio had low power output. A new KVM monitor/keyboard was installed. Batteries in the APC-3000 UPS unit were replaced, and the old APC-1500 UPS unit was replaced with a new APC-3000 unit. The serial connector on the KVM switch is loose or damaged and needs repair. Need extra shelf on rail or wall for radio maintenance testing and maybe longer jumper cables for the test meter that would reach the shelf.
PVCC, PVEF, PVPP						Checked seismometers and phone modem communications

Abbreviations:

AP-1 – access point #1 antenna on the tower at the Hopkins 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 Hopkins Field data communications center; receives radio data communications from radio repeater station PV02

AP-3 – access point #3 antenna on the tower at the Hopkins 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

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-2018-2
Prepared by: Lisa Block
Departure Date: 4/26/2018
Return Date: 4/27/2018
Personnel: Chris Wood

Primary Purpose: To modify the DM24-BOB at station PV23 and bring the station back online and to diagnose and try to resolve the issue of repeated station power failures.

Details:
The revised DM24-BOB that was installed at this station during upgrade of the seismometer on April 11th prevented the seismometer from rebooting following a station power interruption on April 20th. During this site visit, the DM24-BOB was modified to allow the seismometer to reboot following station power cycling. In addition, the three batteries and the solar regulator at this station were replaced to try to resolve the repeated station power failures.

The SPM data at stations PV23 and PV20 were also downloaded during this site visit. The SPM at PV23, which was recording faulty solar panel voltage values, was replaced.

Work by Site:

Site	Preventive Maintenance					Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault	
PV20						Downloaded SPM data. Modified DM24-BOB (snipped lead to stiffening capacitor) to allow seismometer to reboot following station power cycling.
PV23	X	X				Modified DM24-BOB (snipped lead to stiffening capacitor) to allow seismometer to reboot following station power cycling. Replaced all three batteries. Replaced solar regulator (Prostar). Downloaded SPM data. Replaced SPM with different unit so previous SPM could be returned to Denver for repair. Installed new GPS antenna bracket.

Abbreviations:

AP-1 – access point #1 antenna on the tower at the Hopkins 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 Hopkins Field data communications center; receives radio data communications from radio repeater station PV02

AP-3 – access point #3 antenna on the tower at the Hopkins 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

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-2018-3
Prepared by: Lisa Block and Chris Wood
Departure Date: 8/26/2018
Return Date: 8/31/2018
Personnel: Chris Wood and Lisa Block

Primary Purposes: Restore GPS timing at station PV16; perform standard preventive maintenance at several broadband seismic stations; install new station electronics; and install ethernet-enabled power strips at the Hopkins Field communication center so that servers and other equipment can be controlled remotely from Denver.

Details:

The revised station electronics (GPS-BOB circuit boards) installed during this site visit have a watchdog feature that monitors serial data output from the GPS antenna and power-cycles the antenna if output ceases. This feature was added to address the occasional loss of GPS station timing that has occurred during the last few years. The reason for occasional loss of GPS timing is not known but may be related to power fluctuations disrupting normal antenna function. Power-cycling the antenna usually restores normal antenna function and station timing.

Current and voltage measurements were also made at several of the seismic stations, to determine the power consumption of individual station components. These measurements are being compiled in a separate spreadsheet. Additional measurements, which will be made during future site visits, are needed to better understand component power consumption and to evaluate the amount of variation in power consumption between stations. Hence, this work is ongoing, and details of the measurements are not provided here.

Some follow-up work was performed at seismic stations where new seismometers were installed in April. The capacitors in the DM24-BOBs installed at stations PV02, PV10, and PV18 were disconnected, because it was determined that they are unnecessary and that they prevent the new seismometers from rebooting after the station experiences a power interruption. (This change was made at stations PV20 and PV23 during a previous site visit.) New GPS antenna brackets were installed at stations PV02 and PV10, to provide a better mount for the new GPS antennas installed last Spring.

Work by Site:

Site	Preventive Maintenance					Installed New GPS-BOB board	Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault		
PV02						X	Installed GPS antenna bracket. Snipped capacitor lead in DM24-BOB. Retrieved GPS-BOB board that needs component moved for easier installation. Made current measurements. Needs WAGO screwdriver and solar panel angle adjusted ~10°. Still has LVD circuits on battery fuse blocks.
PV03							Made current measurements. Needs WAGO screwdriver. Still has LVD circuits on battery fuse block.
PV10	X					X	Installed GPS antenna bracket. Snipped capacitor lead in DM24-BOB. Retrieved GPS-BOB board that needs component moved for easier installation. Made current measurements. Needs WAGO screwdriver.
PV12	X		X	X			Replaced 12-element Yagi antenna with 18-element antenna to improve RSSI for subnet. Replaced omni antenna. Repaired spline ball bracket. Made current measurements. Still has LVD circuits on battery fuse block.
PV15	X		X	X		X	Replaced GPS antenna because of occasional clock sync errors. Staked antenna azimuth and adjusted azimuth 8 degrees. Made current measurements.

Site	Preventive Maintenance					Installed New GPS-BOB board	Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault		
PV16	X		X	X		X	Replaced bolt-style radio-polyphaser jumper cable with crimped-style cable. Replaced corroded battery eyelet. Antenna test results were marginal. Take spare cables and antenna on next visit. Needs new polyphaser grounding wire.
PV17	X		X	X		X	Made current measurements. Needs plastic bag for logbook.
PV18						X	Snipped capacitor lead in DM24-BOB. Retrieved GPS-BOB board that needs component moved for easier installation. Made current measurements. Still has LVD circuits on battery fuse block.
PV19	X		X	X	X	X	Replaced seismometer with one removed from PV20 in April, 2018. Previous seismometer had excessive 1-Hz noise. Replaced GPS antenna because of occasional clock sync errors. Staked antenna azimuth and adjusted azimuth 4 degrees. Made current measurements. GPS antenna has been repeatedly rebooting since site visit. Replace GPS antenna and GPS-BOB board during next trip. Need to reprogram seismometer in Scream as T4R70.
PV20						X	Retrieved GPS-BOB board that needs component moved for easier installation. Downloaded SPM data and retrieved SPM.
PV23	X					X	Retrieved GPS-BOB board that needs component moved for easier installation. Downloaded SPM data. Replaced thermostat for fan. Made current measurements.

Site	Preventive Maintenance					Installed New GPS-BOB board	Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault		
Hopkins Field							Installed Ethernet-enabled power strips and rewired rack. Programmed second UPS. Made list of needed supplies. Needs cables labeled, generator log checked, new rack-mounted shelf installed, and KVM video connector repaired. Need security camera and new (enclosed) cabinet.

Abbreviations:

AP-1 – access point #1 antenna on the tower at the Hopkins 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 Hopkins Field data communications center; receives radio data communications from radio repeater station PV02

AP-3 – access point #3 antenna on the tower at the Hopkins 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

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-2018-4
Prepared by: Justin Ball and Chris Wood
Departure Date: 9/16/2018
Return Date: 9/21/2018
Personnel: Chris Wood and Justin Ball

Primary Purposes: Upgrade the GPS-BOB printed circuit board at 12 sites, replace deteriorating batteries at PV07, perform scheduled preventative maintenance, and at Hopkins Field, check the generator operation and install a network card in a UPS to allow for remote monitoring.

Details:
The revised station electronics (GPS-BOB printed circuit boards) installed during this site visit and our prior visit in August 2018 have a watchdog feature that monitors serial data output from the GPS antenna and power-cycles the antenna if output ceases. This feature was added to address the occasional loss of GPS station timing that has occurred during the last few years. The reason for occasional loss of GPS timing is not known but may be related to voltage fluctuations from the solar panels disrupting normal antenna function. Power-cycling the antenna usually restores normal antenna function and station timing.

Current and voltage measurements were also made at several of the seismic stations, to determine the power consumption of individual station components. These measurements are being compiled in a separate spreadsheet. Additional measurements, which will be made during future site visits, are needed to better understand component power consumption and to evaluate the amount of variation in power consumption between stations. Hence, this work is ongoing, and details of the measurements are not provided here.

During this trip we also replaced several radio telemetry antennas/cables at sites where the routine antenna impedance-match measurements we performed indicated deterioration of transmission line components.

Work by Site:

Site	Preventive Maintenance					Installed New GPS-BOB board	Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault		
PV01	X		X	X		X	Installed new GPS-BOB board and made current measurements, performed scheduled antenna and radio tests.
PV03	X		X	X		X	Installed new GPS-BOB board and made current measurements, performed scheduled antenna tests. Station still needs WAGO screwdriver. Still has LVD circuits on battery fuse block.
PV04	X		X			X	Installed new GPS-BOB board and made current measurements, performed scheduled antenna tests. Need to move Yagi to top of tower, remount spline ball, eliminate splice in braided grounding cable and install fuse blocks in aux. battery enclosure on future site visit.
PV05	X		X			X	Installed new GPS-BOB board and made current measurements, performed scheduled antenna tests. Measured battery voltage to be ~0.5 V lower on rightmost battery than the other two. Will need to replace all batteries on next site visit.
PV07	X	X	X	X		X	Installed new GPS-BOB board and made current measurements, performed scheduled antenna tests. Replaced all batteries and cleaned wildfire ash out of electronics enclosure.

Site	Preventive Maintenance					Installed New GPS-BOB board	Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault		
PV11	X		X	X		X	Installed new GPS-BOB board and made current measurements, performed scheduled antenna and radio tests. Battery tests indicated that the batteries at their end-of-life and need to be replaced before winter. An apparently defective but unused PolyPhaser also needs to be replaced. Site is missing WAGO driver. Antenna azimuth measured at 74 degrees, need to reorient to nominal azimuth of 71 degrees next time someone climbs this tower.
PV12	X					X*	Attempted to install new GPS-BOB board and subsequently found that the new board did not work with the old-style mushroom antenna presently installed at PV12. After extensive testing of logic levels and current draw of various combinations of old and new BOB boards and GPS antennas, we determined the best course of action was to leave the old GPS BOB and antenna in place for the time being.
PV13	X		X	X		X	Installed new GPS-BOB board and made current measurements, performed scheduled radio and antenna tests. Discovered unusual frequency dependence of antenna/cable impedance-match. Although all antenna measurements remained within acceptable tolerances we decided the best course of action will be to troubleshoot the unusual response on a subsequent trip when more time is available for

Site	Preventive Maintenance					Installed New GPS-BOB board	Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault		
							testing. Despite swapping the Yagi antenna, 2 polyphasers and 2 different antenna cables at PV13, we were unable to improve the antenna/cable impedance-match response significantly; therefore, we left the original antenna cable in place, connected to the new Yagi antenna.
PV14	X		X	X	X	X	Replaced GPS-BOB board, performed current measurements, and inspected seismometer vault. Subsequent failure of the GPS antenna to sync with the DM24 indicated that the old GPS antenna was too weak to drive the new GPS-BOB board. During a second visit to the station, logic level measurements were made with various combinations of old and new GPS BOB and GPS antennas in attempt to resolve persistent sync issues. As a temporary workaround, the original GPS-BOB board was reinstalled, pending delivery of upgraded GPS antennas from Matrix-5.
PV19						X	Installed new GPS-BOB board and new CMG-ELP antenna, performed current measurements, added missing ground connection to GPS BOB enclosure.

Site	Preventive Maintenance					Installed New GPS-BOB board	Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault		
PV21	X		X	X		X	Installed new GPS-BOB board, performed current measurements and scheduled antenna/radio tests. Determined antenna cable needed to be replaced, installed new Yagi antenna along with the new antenna cable. Removed metal conduit that had enclosed old antenna cable after discovering it was full of standing water.
PV22	X		X	X		X	Replaced GPS-BOB board and performed current measurements and scheduled antenna and radio tests. While still within acceptable tolerances, antenna measurements indicated that the Yagi and/or cables may need to be replaced on next site visit.
Hopkins Field							Installed a network interface card in the one UPS that did not have one (which was installed in April, 2018). This will allow for remote monitoring and diagnostics needed for more reliable preventive maintenance. Inspected the backup generator and recovered its digital event logs to troubleshoot the cause of its failure to provide backup power during the outage which occurred in August. Generator logfiles report low-coolant condition, but visual inspection of coolant levels in overflow tank and radiator body indicates a fault in the coolant level sensor. Generator air filter appeared to be due for replacement, battery terminals exhibited substantial corrosion, but crankcase oil level was ok.

Site	Preventive Maintenance					Installed New GPS-BOB board	Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault		
							Need to get a tech out to perform yearly maintenance and probably replace the coolant sensor. Equipment rack still needs some cables labeled, new rack-mounted shelf installed, and KVM video connector repaired. Need security camera and new (enclosed) cabinet. Outdoor high-pressure sodium light bulb needs replacement with RAB part number LHPS70, 70W HPS or similar.

Abbreviations:

AP-1 – access point #1 antenna on the tower at the Hopkins 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 Hopkins Field data communications center; receives radio data communications from radio repeater station PV02

AP-3 – access point #3 antenna on the tower at the Hopkins 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

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-2018-5
Prepared by: Glenda Besana-Ostman and Lisa Block
Departure Date: 10/21/2018
Return Date: 10/26/2018
Personnel: Lisa Block and Glenda Besana-Ostman

Primary Purpose:
To perform preventive maintenance at the telemetered broadband seismic stations and Hopkins Field data communication center, to replace GPS antennas and install new GPS bob boards and chips for firmware upgrade.

Details:
New Matrix-5 antennas were installed at stations PV12 and PV14. Upgraded GPS bob boards were installed at PV03, PV12, and PV14. The chips on the GPS bob boards were replaced at PV04 and PV23. The replacement of antennas, boards, and chips should provide continuous and more reliable timing for the seismic data at these particular stations. Batteries were replaced at PV11 based on low voltage measurements during the previous site visit.

At Hopkins Field, the AP-1, AP-2, and AP-3 antennas and cables were checked and verified to be good. The status of the generator was inspected, and a new rack shelf was installed on the uppermost portion of the rack.

Work by Site:

Site	Preventive Maintenance					Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault	
PV02	X		X			Checked ProStar PS-30 status, solar panel open circuit voltage, voltages of all 6 batteries both open and closed-circuits, and measured antenna statuses for yagi and omni antennas, as well as currents (mA) for all loads except the fan. Needs WAGO screwdriver and solar panel angle adjusted ~10°.
PV03	X					Replaced LVD fuses with auto fuses on battery WAGO blocks. Installed new GPS bob board w/ new firmware. Measured floating battery voltages. Needs WAGO screwdriver.
PV04						Tested output voltage levels of Guralp mushroom GPS antenna – were good. Replaced chip on GPS bob board to upgrade firmware. Needs dimension measurement of topmost portion of tower to attach/relocate yagi antenna. Vault needs glass plate.
PV11	X	X				Checked power system, measured battery voltage levels before and after battery replacement. Needs WAGO screwdriver.
PV12						Removed Guralp mushroom GPS antenna and replaced with Matrix-5 antenna s/n 001. Replaced GPS bob board with board having watchdog feature and newest firmware. Installed jumper 2 to disable GPS antenna reboots (because reboot of Matrix-5 GPS antenna causes old MK-2 seismometers to reboot). Issues related to power, repeated reboots and garbled messages observed; resolved by fixing power connections. Still has LVD circuits.

Site	Preventive Maintenance					Comments
	Checked Power System	Replaced Batteries	Tested Antennas and cables	Tested Radio(s)	Inspected Vault	
PV14	X					Installed SPM. Measured floating battery voltages and old mushroom antenna current. Installed Matrix-5 antenna s/n 002 and GPS bob board with new firmware with jumper 3 to disable reboots. Needs new vault.
PV23	X					Replaced chip on GPS bob board (upgraded firmware) and ribbon cable. Downloaded SPM data and erased memory. Inspected seismometer vault area for possible damage or land movement- found none.
Hopkins Field			X			The antennas for AP-1, AP-2, and AP-3 radios were tested. All measurements are indicative of good status. A new rack shelf was installed to be used to hold equipment for future testing. Display on generator indicated 10/22/18 as last inspection date. Generator needs new battery. The serial connector on the KVM switch is loose or damaged and needs repair. A smaller ladder may be required to access jumper cables on the wall. A shelf on the north wall near the radios may be useful for antenna testing. Labels on cables and connections should be redone.
Naturita Storage						Installed new shelves (on wheels) and re-organized equipment. Updated antenna inventory (see ipad notes).

Abbreviations:

AP-1 – access point #1 antenna on the tower at the Hopkins 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 Hopkins Field data communications center; receives radio data communications from radio repeater station PV02

AP-3 – access point #3 antenna on the tower at the Hopkins 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

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

Appendix B

PVSN 2018 Local Earthquake Catalog

Table B-1: Local earthquakes recorded by PVSN during 2018

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
1/1/18	14:13:34	38.3077	-108.8972	-3.0	4.5	1.4	1.2
1/3/18	10:59:13	38.2600	-108.8705	-0.5	2.0	-0.1	4.6
1/3/18	13:51:51	38.2767	-108.8353	-2.1	3.6	0.1	5.7
1/6/18	0:18:36	38.2766	-108.8352	-2.1	3.7	0.0	5.7
1/10/18	11:22:52	38.3284	-108.9583	-3.7	5.2	0.5	6.6
1/11/18	14:28:57	38.2766	-108.8352	-2.2	3.7	1.8	5.7
1/12/18	7:30:01	38.3230	-108.9740	-2.3	3.8	2.5	7.5
1/12/18	7:34:05	38.3231	-108.9739	-2.2	3.7	0.0	7.5
1/12/18	9:10:09	38.3230	-108.9738	-2.2	3.7	-0.2	7.5
1/14/18	13:06:12	38.4055	-108.8793	-3.2	4.7	0.0	12.2
1/14/18	13:07:21	38.4050	-108.8610	-2.1	3.6	-1.0	12.4
1/24/18	2:12:57	38.2693	-108.8660	-1.3	2.8	0.3	3.9
1/27/18	4:11:39	38.3422	-108.8955	-3.1	4.6	-0.4	5.1
1/28/18	3:37:22	38.2678	-108.8857	-1.5	3.0	0.1	3.3
2/4/18	16:46:40	38.3103	-108.9734	-2.3	3.8	-0.3	7.0
2/10/18	22:37:57	38.4608	-109.0357	-5.0	6.5	-1.0	22.0
2/12/18	2:44:46	38.2738	-108.8722	-0.9	2.4	0.3	3.2
2/12/18	2:46:49	38.2683	-108.8705	-1.6	3.1	-0.6	3.8
2/13/18	4:17:13	38.2766	-108.8346	-2.2	3.7	1.2	5.7
2/16/18	10:57:28	38.2855	-108.8938	-2.1	3.7	0.4	1.2
2/21/18	6:55:00	38.3985	-108.9910	-3.7	5.3	0.4	14.1
2/21/18	23:07:47	38.3110	-108.8400	-2.7	4.2	-0.7	5.1
2/22/18	20:19:01	38.2846	-108.8994	-2.4	3.9	-0.4	1.4
2/22/18	22:30:47	38.2988	-108.8973	-1.8	3.3	-0.2	0.3
2/23/18	0:38:00	38.2840	-108.8318	-1.4	3.0	-0.7	5.7
2/23/18	16:32:11	38.2745	-108.9367	-0.2	1.8	0.7	4.4
2/24/18	6:16:21	38.3126	-108.9752	-2.4	3.9	0.4	7.2
2/27/18	6:46:57	38.2801	-108.8829	-3.5	5.1	-0.3	2.1
2/28/18	12:22:32	38.2851	-108.8994	-2.7	4.2	0.5	1.3
3/6/18	21:11:40	38.2844	-108.8837	-2.3	3.9	-0.2	1.7
3/7/18	6:33:51	38.3962	-108.9423	-2.0	3.5	-0.3	11.8
3/7/18	6:34:03	38.3978	-108.8847	-3.7	5.2	0.4	11.3
3/7/18	6:35:20	38.4023	-108.8777	-3.0	4.5	-0.2	11.8
3/7/18	6:35:28	38.4210	-108.9047	-2.6	4.1	-1.2	13.8
3/7/18	6:35:39	38.4157	-108.9015	-2.6	4.1	-0.5	13.2
3/8/18	11:58:25	38.3228	-108.6925	-8.7	10.2	0.8	17.9
3/8/18	13:49:49	38.3227	-108.6927	-8.7	10.2	2.3	17.9
3/8/18	15:42:39	38.3227	-108.6922	-8.7	10.2	1.9	18.0
3/8/18	16:28:58	38.3227	-108.6930	-8.7	10.2	1.6	17.9
3/11/18	15:11:32	38.3075	-108.8979	-3.0	4.5	0.7	1.2
3/13/18	9:14:05	38.2988	-108.8972	-1.8	3.3	0.2	0.3
3/13/18	13:17:28	38.3002	-108.8824	-3.9	5.4	1.1	1.2
3/14/18	17:39:20	38.4407	-108.9695	-4.0	5.6	0.7	17.3
3/14/18	17:46:11	38.3075	-108.8978	-2.9	4.5	1.3	1.2

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
3/18/18	10:33:00	38.4430	-109.0877	2.5	-0.9	0.5	23.4
3/21/18	17:41:46	38.4070	-109.0205	-2.2	3.7	-0.2	16.5
3/23/18	3:17:50	38.3076	-108.8977	-3.0	4.5	1.4	1.2
3/23/18	8:48:14	38.3074	-108.8980	-2.9	4.5	-0.1	1.2
3/24/18	11:08:04	38.3228	-108.6909	-8.8	10.3	0.8	18.1
3/27/18	6:44:59	38.3077	-108.8975	-3.0	4.5	0.4	1.3
3/30/18	17:30:49	38.4323	-109.0327	-3.5	5.0	0.4	19.3
4/9/18	4:27:35	38.2853	-108.8952	-2.3	3.9	-0.1	1.3
4/14/18	7:52:17	38.2823	-108.8740	-2.3	3.8	-0.3	2.4
4/19/18	14:16:41	38.2987	-108.8938	0.1	1.4	0.4	0.3
4/23/18	9:55:11	38.2740	-108.9340	0.5	1.1	0.3	4.2
4/26/18	12:31:37	38.2737	-108.9258	-1.0	2.5	-0.4	3.7
5/4/18	12:04:11	38.4032	-108.9292	-4.1	5.6	1.8	12.2
5/5/18	16:58:09	38.2800	-108.8822	-3.6	5.1	-0.4	2.2
5/8/18	23:43:11	38.2852	-108.8962	-2.3	3.8	1.3	1.3
5/9/18	2:45:14	38.2850	-108.8963	-2.3	3.9	0.4	1.3
5/9/18	7:42:26	38.3088	-108.8588	-3.1	4.7	-0.3	3.4
5/9/18	18:48:07	38.2853	-108.8960	-2.3	3.8	0.8	1.3
5/9/18	23:36:57	38.2850	-108.8959	-2.4	3.9	0.0	1.3
5/10/18	3:08:42	38.4150	-108.9785	-4.6	6.1	0.6	15.0
5/10/18	7:20:35	38.3617	-108.9267	-3.9	5.4	0.0	7.7
5/14/18	16:21:16	38.4138	-108.9445	-3.1	4.6	-0.2	13.7
5/16/18	11:57:50	38.3239	-108.9499	-2.9	4.5	-0.1	5.7
5/21/18	8:22:30	38.2769	-108.8759	-0.9	2.5	-0.4	2.7
5/23/18	1:02:27	38.4047	-109.0168	-4.2	5.7	0.4	16.1
5/23/18	18:10:18	38.2847	-108.9065	-2.1	3.6	-0.2	1.7
5/25/18	9:09:29	38.3119	-108.9756	-2.4	3.9	0.6	7.3
5/26/18	10:12:07	38.3102	-108.8677	-3.0	4.5	-0.4	2.8
6/10/18	4:23:31	38.2843	-108.9000	-2.3	3.9	0.4	1.4
6/18/18	12:07:47	38.3142	-108.9773	-1.9	3.5	-0.3	7.5
6/23/18	14:07:12	38.3064	-108.9149	-3.2	4.7	-0.3	2.1
6/24/18	2:17:57	38.2693	-108.8075	-2.3	3.8	-0.1	8.2
6/26/18	15:09:27	38.2785	-108.8093	-1.8	3.3	-0.4	7.8
6/29/18	6:59:56	38.2777	-108.8262	-2.4	4.0	1.5	6.4
6/29/18	17:14:46	38.2717	-108.9343	-0.7	2.2	-0.1	4.4
6/29/18	21:16:49	38.3125	-108.9705	-2.1	3.6	-0.4	6.8
7/3/18	10:24:32	38.3080	-108.9707	-1.4	3.0	0.9	6.7
7/3/18	19:10:47	38.3241	-108.9689	-2.2	3.7	-0.2	7.2
7/6/18	2:26:07	38.3080	-108.9707	-1.5	3.0	0.2	6.7
7/8/18	6:08:27	38.2762	-108.9332	-0.4	1.9	-0.1	4.0
7/8/18	15:52:50	38.2777	-108.8268	-2.4	3.9	0.6	6.3
7/8/18	20:57:43	38.2835	-108.9008	-2.1	3.6	0.1	1.5
7/11/18	9:09:50	38.4095	-108.9400	-3.5	5.1	0.8	13.1
7/15/18	5:39:34	38.2860	-108.9049	-2.4	3.9	-0.4	1.5
7/18/18	7:28:55	38.3957	-108.8703	-4.0	5.5	-0.3	11.2

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
7/18/18	7:28:59	38.4056	-108.8677	-4.4	5.9	0.1	12.3
7/18/18	7:30:22	38.4057	-108.8673	-4.4	5.9	-0.1	12.4
7/20/18	23:03:25	38.2822	-108.8984	-2.8	4.3	-0.2	1.6
7/21/18	3:35:31	38.2821	-108.8985	-2.8	4.3	0.3	1.6
7/28/18	2:50:39	38.2799	-108.8550	-1.0	2.5	-0.2	4.0
7/29/18	9:07:24	38.2825	-108.8852	-3.0	4.5	0.2	1.8
7/31/18	22:38:25	38.4299	-108.9634	-4.1	5.6	0.5	16.0
8/3/18	13:47:44	38.4300	-108.9634	-4.1	5.6	-0.1	16.0
8/7/18	2:59:16	38.2831	-108.9035	-1.9	3.4	-0.6	1.7
8/9/18	12:02:26	38.3002	-108.9122	-3.7	5.3	-0.2	1.6
8/9/18	14:20:15	38.2752	-108.9253	-0.2	1.7	0.3	3.6
8/11/18	11:04:39	38.3192	-108.8603	-3.8	5.3	-0.2	3.9
8/23/18	4:46:20	38.2763	-108.8794	-0.8	2.4	0.4	2.6
8/23/18	20:20:27	38.3100	-108.9686	-2.4	3.9	-0.5	6.6
8/24/18	0:42:57	38.2759	-108.8796	-0.8	2.3	-0.4	2.7
8/24/18	10:36:37	38.4297	-108.9636	-4.0	5.6	0.2	15.9
8/25/18	17:34:08	38.4300	-108.9634	-4.1	5.6	0.9	16.0
8/26/18	0:13:39	38.4300	-108.9634	-4.1	5.6	0.3	16.0
8/26/18	7:40:35	38.3133	-108.9765	-2.4	3.9	-0.4	7.4
8/26/18	8:37:19	38.4300	-108.9634	-4.1	5.6	1.4	16.0
8/26/18	22:46:10	38.2855	-108.8990	-2.2	3.7	0.2	1.3
8/29/18	17:28:54	38.2857	-108.8930	-2.0	3.6	-0.6	1.2
9/1/18	1:03:14	38.4299	-108.9636	-4.1	5.6	-0.1	16.0
9/1/18	2:48:44	38.4300	-108.9638	-4.1	5.6	0.4	16.0
9/1/18	3:51:49	38.2974	-108.8978	-2.9	4.4	0.1	0.3
9/3/18	4:08:29	38.4388	-109.0407	-4.1	5.6	1.3	20.3
9/4/18	18:28:42	38.4322	-109.0210	-2.2	3.7	0.6	18.7
9/5/18	22:44:11	38.3498	-108.9075	-3.7	5.2	0.0	6.0
9/7/18	14:35:56	38.2935	-108.9250	-2.7	4.2	-0.2	2.6
9/8/18	23:53:16	38.2716	-108.8805	-0.8	2.3	1.7	3.0
9/9/18	12:50:09	38.1503	-108.5693	-3.1	4.7	1.6	32.8
9/10/18	9:47:02	38.3518	-108.8808	-5.3	6.8	1.4	6.3
9/10/18	11:52:50	38.3109	-108.7370	-7.8	9.3	1.8	13.9
9/11/18	16:39:31	38.4072	-108.9338	-4.3	5.8	1.0	12.7
9/13/18	0:54:47	38.4071	-108.9336	-4.3	5.8	0.4	12.7
9/13/18	3:00:14	38.4072	-108.9338	-4.3	5.8	1.1	12.7
9/15/18	15:02:38	38.2778	-108.8282	-2.3	3.8	0.4	6.2
9/21/18	5:16:58	38.2853	-108.8917	-2.1	3.6	0.0	1.3
9/21/18	5:18:47	38.2855	-108.8917	-2.1	3.6	-0.3	1.3
9/21/18	9:37:22	38.2853	-108.8915	-2.1	3.6	0.6	1.3
9/21/18	22:02:49	38.4406	-108.9694	-4.0	5.6	0.3	17.3
9/22/18	9:28:03	38.3138	-108.9640	-1.5	3.0	0.9	6.3
9/23/18	7:02:44	38.4025	-108.8728	-4.1	5.6	0.4	11.9
9/23/18	7:29:00	38.4024	-108.8727	-4.1	5.6	0.3	11.9
9/23/18	9:15:15	38.4025	-108.8727	-4.1	5.6	0.2	11.9

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
9/23/18	11:35:41	38.4026	-108.8725	-4.1	5.6	0.4	11.9
9/23/18	11:37:16	38.4048	-108.8667	-3.5	5.0	-0.4	12.3
9/23/18	12:17:48	38.4027	-108.8727	-4.1	5.7	0.0	11.9
9/23/18	14:44:20	38.4026	-108.8728	-4.1	5.6	1.4	11.9
9/23/18	16:42:54	38.4025	-108.8728	-4.2	5.7	0.2	11.9
9/23/18	19:30:19	38.4027	-108.8729	-4.1	5.6	0.8	11.9
9/23/18	19:31:47	38.4025	-108.8728	-4.1	5.6	0.2	11.9
9/23/18	19:39:27	38.2838	-108.9009	-2.3	3.9	0.0	1.5
9/23/18	20:25:42	38.4024	-108.8727	-4.0	5.6	0.0	11.9
9/23/18	20:26:41	38.4005	-108.8592	-3.3	4.8	-0.9	12.0
9/23/18	20:27:38	38.4040	-108.8638	-3.5	5.1	-0.6	12.2
9/25/18	0:32:52	38.4028	-108.8731	-4.1	5.6	0.3	11.9
9/25/18	0:33:18	38.2918	-108.9142	-2.4	3.9	-0.7	1.8
9/25/18	0:34:45	38.4075	-108.8690	-3.7	5.3	-0.1	12.5
9/25/18	0:34:45	38.4057	-108.8697	-3.8	5.3	-0.2	12.3
9/25/18	11:13:11	38.4023	-108.8730	-4.0	5.5	0.6	11.9
9/25/18	11:18:30	38.4025	-108.8731	-4.0	5.5	1.0	11.9
9/25/18	11:19:04	38.4067	-108.8683	-3.7	5.3	-0.5	12.4
9/25/18	11:20:56	38.4025	-108.8730	-4.0	5.6	0.5	11.9
9/26/18	16:54:01	38.4027	-108.8739	-4.0	5.6	0.1	11.9
9/27/18	4:47:25	38.4025	-108.8740	-4.0	5.5	0.2	11.9
9/27/18	4:48:31	38.4032	-108.8668	-3.5	5.0	-0.9	12.1
9/27/18	7:14:31	38.4025	-108.8740	-4.2	5.7	0.1	11.9
9/27/18	19:48:13	38.4033	-108.8755	-4.0	5.5	0.2	12.0
9/28/18	10:13:33	38.4032	-108.8756	-4.0	5.5	0.2	12.0
9/28/18	10:27:12	38.4024	-108.8731	-4.0	5.5	-0.8	11.9
9/28/18	10:27:13	38.4026	-108.8731	-4.0	5.5	-0.3	11.9
9/28/18	10:27:24	38.4120	-108.8680	-3.7	5.2	-0.3	13.0
9/28/18	10:29:11	38.4113	-108.8708	-3.6	5.1	-1.1	12.9
9/28/18	14:57:37	38.4127	-108.8787	-3.8	5.3	-1.2	13.0
9/28/18	15:43:57	38.4062	-108.8728	-3.3	4.8	-1.1	12.3
9/28/18	15:44:03	38.4028	-108.8744	-4.0	5.5	0.0	11.9
9/28/18	15:46:10	38.4060	-108.8660	-3.4	4.9	0.3	12.4
9/28/18	15:46:43	38.4068	-108.8637	-3.2	4.7	-0.2	12.5
9/28/18	15:46:54	38.4031	-108.8748	-4.0	5.5	-0.2	12.0
9/28/18	15:49:31	38.4032	-108.8747	-4.0	5.5	0.1	12.0
9/28/18	15:50:15	38.4112	-108.8692	-3.6	5.1	-1.0	12.9
9/28/18	15:50:53	38.4117	-108.8520	-4.0	5.5	-1.0	13.3
9/28/18	15:51:24	38.4032	-108.8746	-4.0	5.5	0.1	12.0
9/28/18	17:04:21	38.4068	-108.8670	-3.3	4.8	0.3	12.5
9/28/18	22:33:16	38.4031	-108.8757	-4.0	5.5	-0.1	11.9
9/29/18	14:00:27	38.4046	-108.8764	-4.0	5.6	0.1	12.1
9/30/18	10:26:37	38.4038	-108.8759	-4.0	5.5	0.1	12.0
9/30/18	11:56:35	38.4023	-108.8733	-4.1	5.6	0.1	11.9
9/30/18	12:05:19	38.4025	-108.8736	-4.1	5.6	0.2	11.9

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
9/30/18	12:05:30	38.4025	-108.8737	-4.0	5.6	-0.2	11.9
9/30/18	12:05:44	38.4113	-108.8693	-3.6	5.1	-0.9	12.9
9/30/18	12:06:11	38.4070	-108.8290	-1.5	3.0	-0.3	13.6
10/2/18	18:31:30	38.4107	-108.8667	-4.1	5.6	-1.1	12.9
10/3/18	20:03:48	38.4039	-108.8747	-4.1	5.6	-0.6	12.1
10/3/18	22:37:10	38.2827	-108.9064	-2.1	3.6	-0.1	1.8
10/4/18	6:00:49	38.3016	-108.9366	-2.6	4.1	0.3	3.7
10/4/18	16:18:55	38.2583	-108.8775	-2.5	4.1	-0.5	4.5
10/4/18	22:51:22	38.4053	-108.8630	-3.4	4.9	-0.5	12.4
10/4/18	23:15:05	38.2812	-108.9450	-0.6	2.1	-0.9	4.7
10/4/18	23:24:27	38.4032	-108.8747	-4.0	5.5	0.2	12.0
10/4/18	23:26:54	38.4220	-108.8975	-2.2	3.7	-0.1	13.9
10/4/18	23:27:16	38.4032	-108.8746	-4.0	5.5	0.3	12.0
10/4/18	23:29:06	38.4077	-108.8637	-4.0	5.5	-0.3	12.6
10/4/18	23:55:04	38.4034	-108.8749	-4.0	5.5	0.4	12.0
10/4/18	23:55:38	38.4034	-108.8748	-4.0	5.5	-0.1	12.0
10/5/18	0:00:53	38.4073	-108.8712	-3.7	5.2	-0.2	12.5
10/5/18	0:08:25	38.4545	-109.0072	-3.7	5.2	0.2	20.1
10/5/18	0:08:51	38.4033	-108.8748	-4.0	5.5	0.6	12.0
10/6/18	0:26:20	38.4041	-108.8755	-4.1	5.6	0.2	12.1
10/6/18	6:32:46	38.4298	-108.9636	-4.1	5.6	1.2	16.0
10/6/18	13:16:45	38.4036	-108.8757	-4.0	5.5	0.1	12.0
10/6/18	17:13:26	38.4027	-108.8732	-4.0	5.6	0.0	11.9
10/7/18	10:21:40	38.2951	-108.9070	-2.8	4.3	-0.2	1.1
10/10/18	15:11:42	38.2807	-108.9447	-0.3	1.8	-0.5	4.7
10/11/18	20:49:00	38.2852	-108.8970	-2.3	3.8	0.3	1.3
10/16/18	5:19:14	38.4295	-108.9626	-4.0	5.5	0.8	15.9
10/16/18	5:20:37	38.4297	-108.9628	-4.0	5.6	0.0	15.9
10/17/18	15:56:58	38.2949	-108.9125	-2.6	4.1	0.1	1.5
10/21/18	19:07:15	38.3112	-108.7370	-7.7	9.2	1.2	13.9
10/23/18	6:16:50	38.4027	-108.8729	-4.1	5.6	0.9	11.9
10/23/18	6:17:00	38.4057	-108.8777	-2.1	3.6	-0.2	12.2
10/23/18	9:38:00	38.2758	-108.8827	-1.1	2.6	0.8	2.5
10/24/18	13:35:29	38.2851	-108.8971	-2.3	3.8	-0.1	1.3
10/24/18	17:27:56	38.4043	-108.8683	-4.3	5.8	0.3	12.2
10/27/18	8:59:34	38.3979	-108.8824	-3.6	5.2	0.2	11.3
10/27/18	9:16:27	38.3978	-108.8828	-3.6	5.2	0.7	11.3
10/27/18	9:17:10	38.3979	-108.8826	-3.6	5.2	0.3	11.3
10/28/18	20:35:29	38.2917	-108.7212	-9.8	11.3	0.4	15.2
10/30/18	8:09:00	38.2573	-108.8732	0.2	1.3	-0.3	4.8
11/3/18	18:43:52	38.3111	-108.7375	-7.6	9.2	1.7	13.9
11/4/18	3:34:17	38.2841	-108.9153	-1.7	3.3	0.1	2.3
11/5/18	2:32:38	38.4300	-108.9628	-4.1	5.6	-0.1	16.0
11/6/18	8:44:30	38.2999	-108.9305	-2.4	4.0	0.1	3.1
11/8/18	0:54:35	38.4087	-108.8722	-3.8	5.3	-0.4	12.6

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
11/8/18	22:25:17	38.4044	-108.8687	-4.2	5.8	0.3	12.2
11/10/18	2:39:55	38.4045	-108.8688	-4.3	5.8	0.9	12.2
11/12/18	19:26:38	38.2078	-108.6515	-5.8	7.3	0.2	23.5
11/13/18	7:39:26	38.3373	-108.7632	-4.8	6.3	0.9	12.4
11/14/18	14:14:54	38.3402	-108.8875	-4.3	5.8	-0.1	4.9
11/14/18	20:47:48	38.4047	-109.0162	-3.9	5.5	0.5	16.0
11/16/18	12:12:17	38.2743	-108.9297	1.8	-0.2	-0.2	3.9
11/20/18	2:23:35	38.2678	-108.9318	0.3	1.2	1.1	4.5
11/20/18	21:54:09	38.2778	-108.8253	-2.5	4.0	1.2	6.4
11/23/18	7:06:13	38.2829	-108.9133	-1.8	3.4	0.4	2.2
11/27/18	3:42:56	38.4730	-109.0818	2.5	-0.9	-0.1	25.5
11/27/18	4:24:35	38.4705	-109.0335	-3.3	4.8	0.7	22.8
11/27/18	9:02:08	38.4687	-109.0203	-2.3	3.8	-0.1	22.0
11/27/18	14:07:18	38.4643	-109.0485	-3.6	5.1	-0.6	23.0
11/28/18	16:04:13	38.4648	-109.0397	-3.6	5.1	0.2	22.6
12/3/18	21:24:52	38.3517	-108.8809	-5.2	6.8	0.0	6.2
12/5/18	1:06:03	38.4293	-108.9167	-0.3	1.8	0.1	14.9
12/5/18	11:26:49	38.2673	-108.9428	-1.0	2.5	-0.2	5.3
12/8/18	9:10:17	38.2762	-108.8790	-0.9	2.4	0.5	2.7
12/14/18	4:46:52	38.3516	-108.8805	-5.2	6.8	0.6	6.2
12/15/18	3:06:16	38.2608	-108.8670	0.0	1.5	0.0	4.7
12/15/18	5:31:11	38.2620	-108.8670	0.7	0.8	-0.3	4.6
12/17/18	2:57:57	38.3515	-108.8807	-5.2	6.8	-0.6	6.2
12/20/18	1:45:20	38.3422	-108.8913	-4.3	5.8	0.2	5.1
12/21/18	3:13:21	38.3201	-108.9490	-3.6	5.1	0.6	5.4
12/21/18	21:35:14	38.3123	-108.9776	-2.4	3.9	-0.2	7.4
12/26/18	2:50:24	38.3518	-108.8803	-5.3	6.8	-0.1	6.3
12/28/18	6:05:16	38.2855	-108.8918	-2.0	3.5	0.1	1.3
12/30/18	14:39:28	38.2870	-108.9101	-2.1	3.7	-0.2	1.7
12/31/18	14:37:15	38.3517	-108.8805	-5.3	6.8	0.2	6.3
12/31/18	14:39:25	38.2630	-108.8643	-1.2	2.8	-0.7	4.6

[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] Magnitudes listed are duration magnitudes, unless specified otherwise