RECLAMATION

Managing Water in the West

Technical Memorandum TM-85-833000-2017-22

2016 Annual Report
Paradox Valley Seismic Network
Paradox Valley Unit, Colorado

U.S. Department of the Interior
Bureau of Reclamation

May 2017

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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2016 Annual Report
Paradox Valley Seismic Network
Paradox Valley Unit, Colorado

Prepared by:

Lisa Block, Geophysicist — 5/25/2017 Date

Mark Meremonte, Geophysicist — 5/25/17 Date

Christopher Wood, Geophysicist — 5/25/17 Date

Glenda Besana-Ostman, Geophysicist — 5-25-17 Date

Peer Review Certification

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

Peer reviewed by:

Vanessa King, Geophysicist — 5/25/17 Date

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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 2016. 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 2016, including maintenance of the seismic stations and data acquisition systems and annual network performance. The earthquake data recorded during 2016 are discussed in section 4 and compared to historical seismicity trends.

2 Project Background

2.1 Paradox Valley Unit

Reclamation's Paradox Valley Unit (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 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.

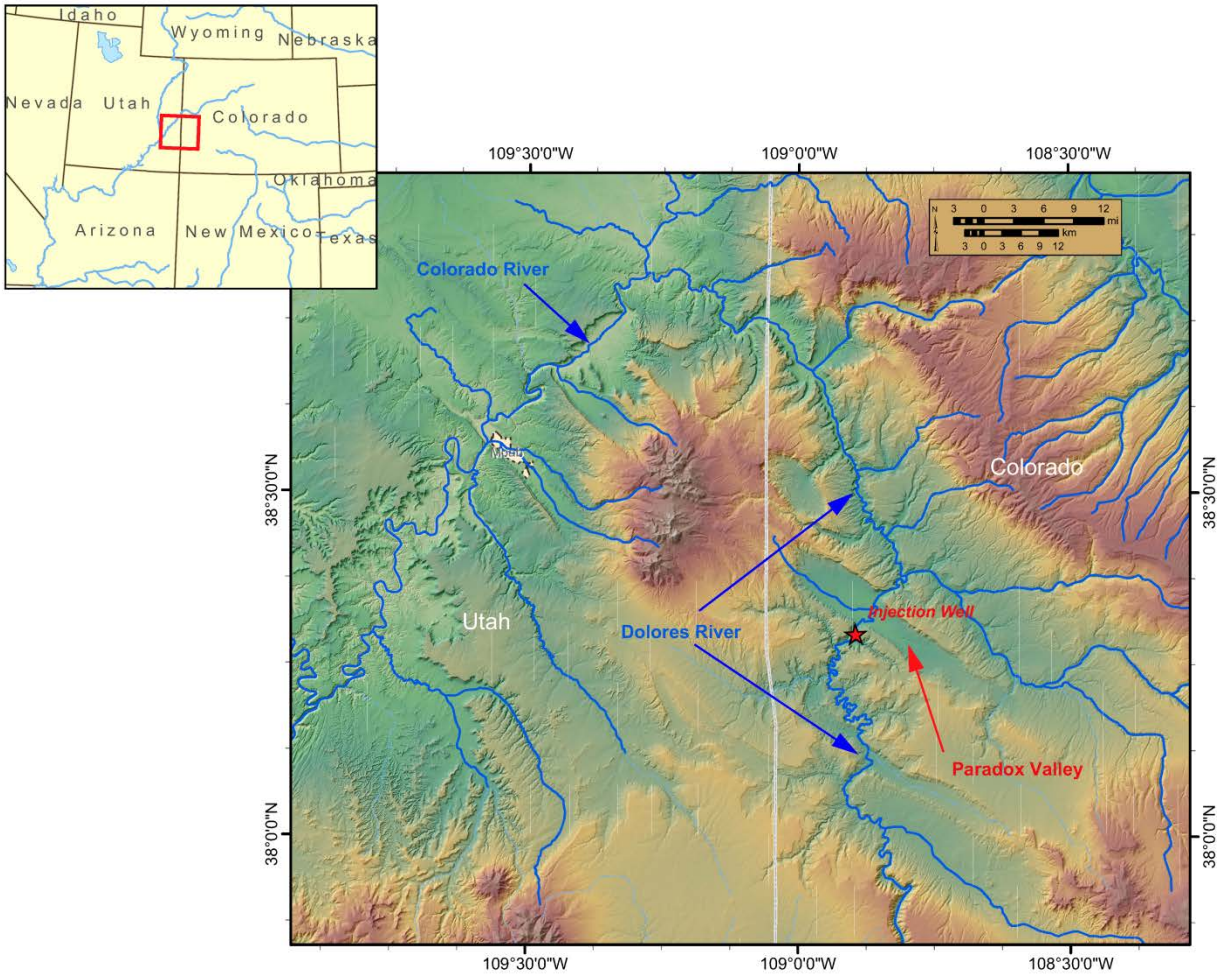


Figure 2-1. Location of the deep injection well at Reclamation's Paradox Valley Unit in western Colorado.

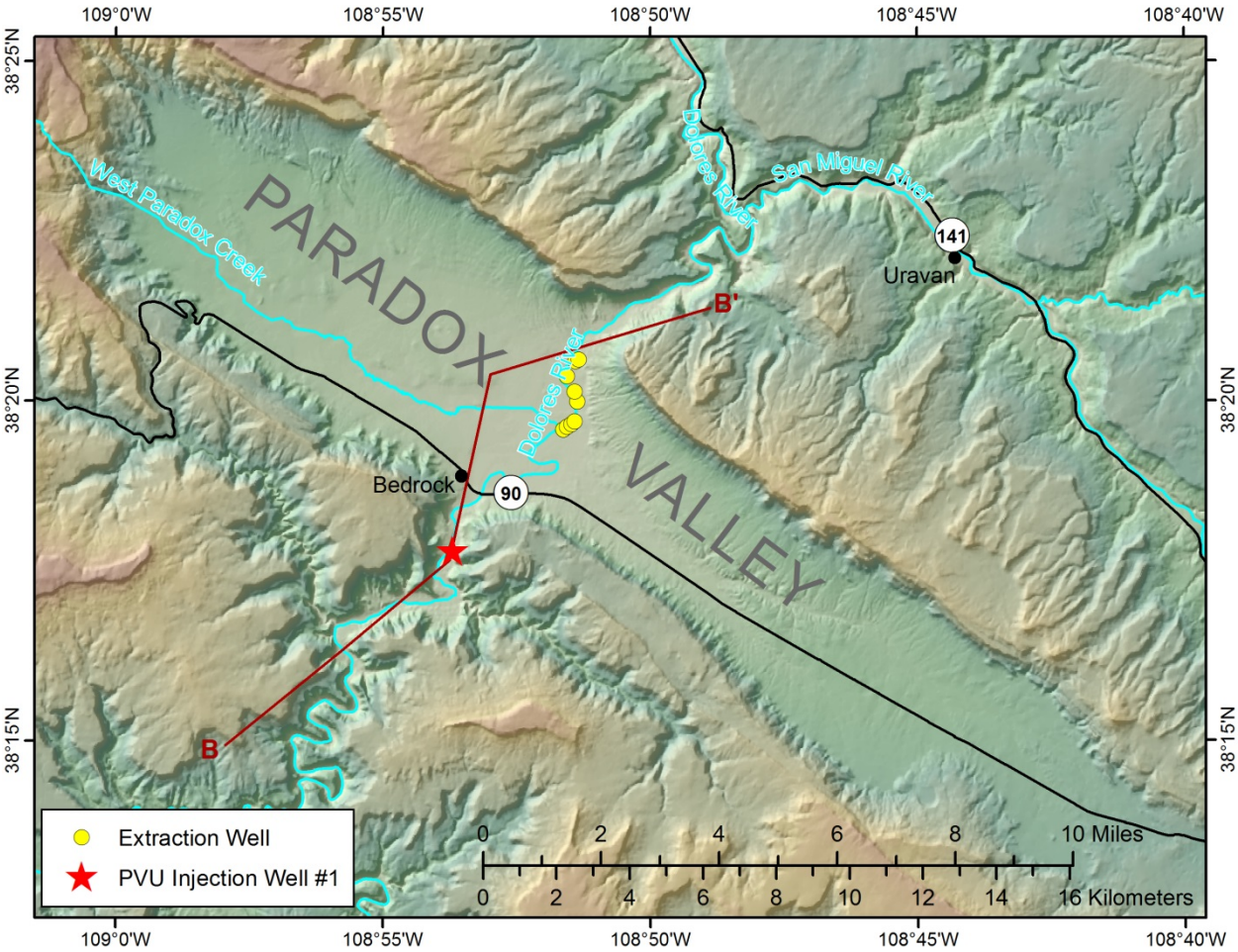


Figure 2-2. Location of the Paradox Valley Unit extraction wells (yellow circles) and injection well (red star). Cross section B-B´ is shown in Figure 2-3.

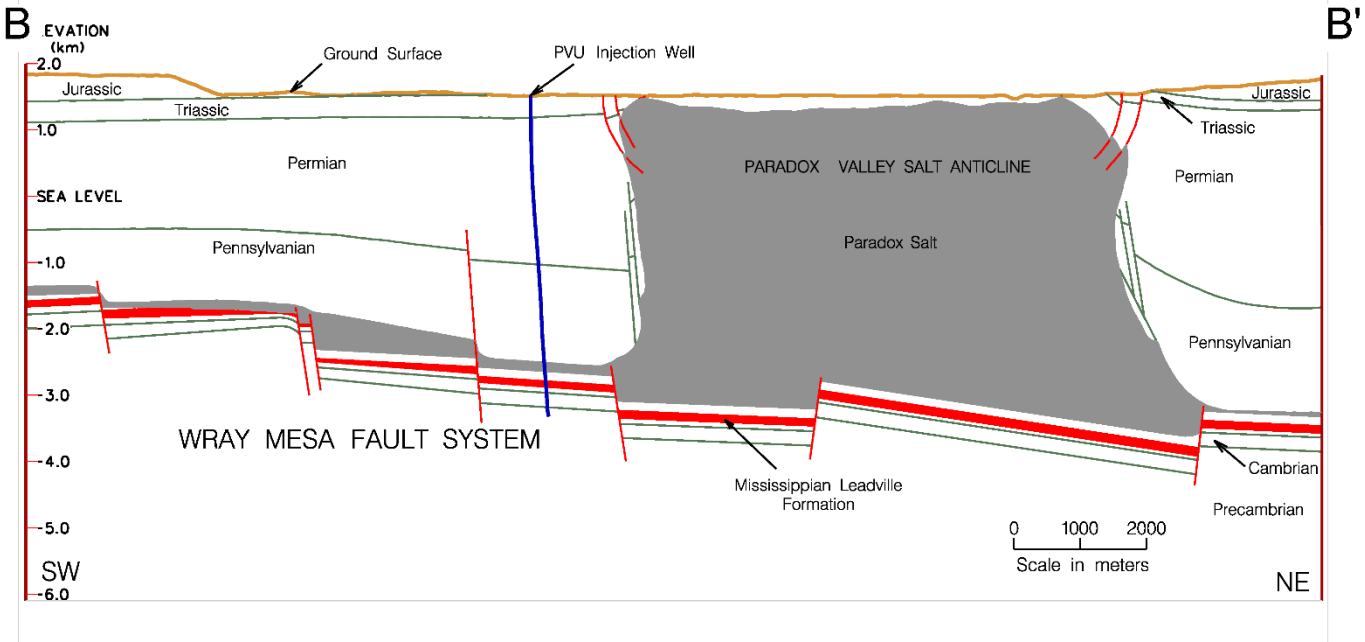


Figure 2-3. Vertical cross section roughly perpendicular to Paradox Valley, looking to the northwest. The location of the cross section is shown in Figure 2-2. Based on figure from Bremkamp and Harr (1988).

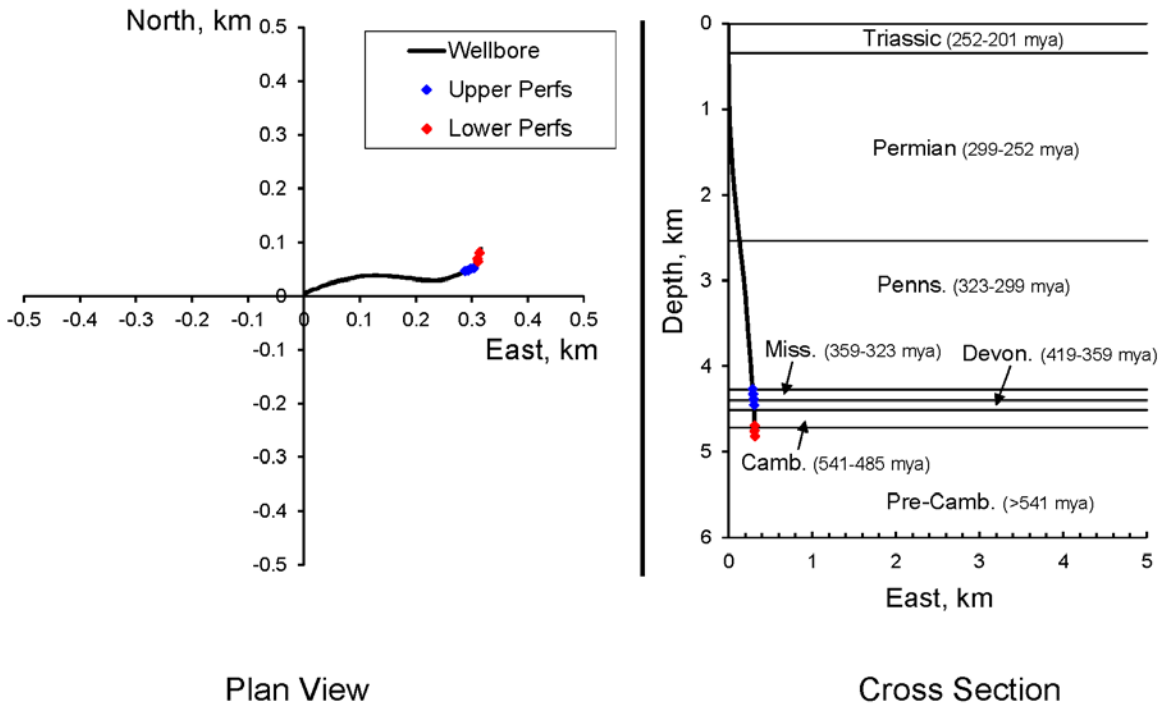


Figure 2-4: PVU injection well in plan view (left) and north-viewing vertical cross section (right). Figure includes the near-wellbore stratigraphy and locations of the upper and lower casing perforations. The ages of the geologic time periods are taken from the Geological Society of America Geologic 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 four major changes in injection operations. Each change was invoked to mitigate the potential for unacceptable seismicity or 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.

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 (1.6×10^9 liters). The injectate during *Phase I* was a mixture of 70% Paradox Valley Brine (PVB) and 30% fresh water.

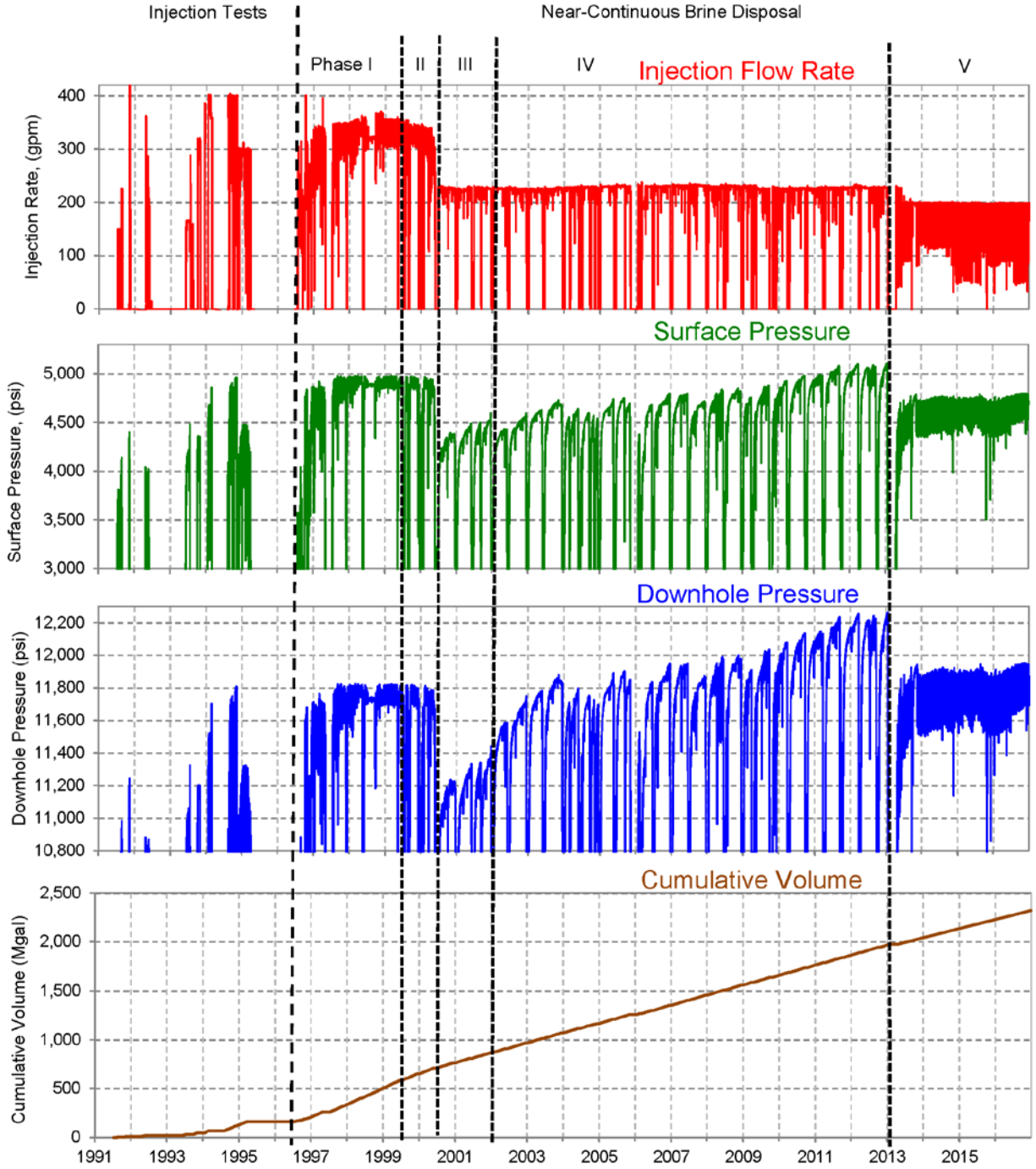


Figure 2-5: Daily average injection flow rate, daily average surface injection pressure, daily average downhole pressure at 4.3 km depth, and cumulative volume of brine injected during PVU injection operations. The downhole pressures are computed from the measured surface pressures using the density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

2.2.2 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 (0.4×10^9 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 (0.6×10^9 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 x 10^9 liters).

Because of the decreased flow rate in *Phase III* and *Phase IV* compared to the earlier phases, the surface pressure remained below the MASIP of 5,000 psi for over 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 – 2016)

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 determine an appropriate flow rate (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* has been 177 gpm, which is ~9.7% less than the average flow rate of 196 gpm during the previous three years (2010-2012). Through 2016, 347 Mgal (1.3 x 10^9 liters) of fluid has been injected during this phase.

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 and others, 1973; Raleigh and others, 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. For the first six 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 finally in 1994, when it was 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, 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.

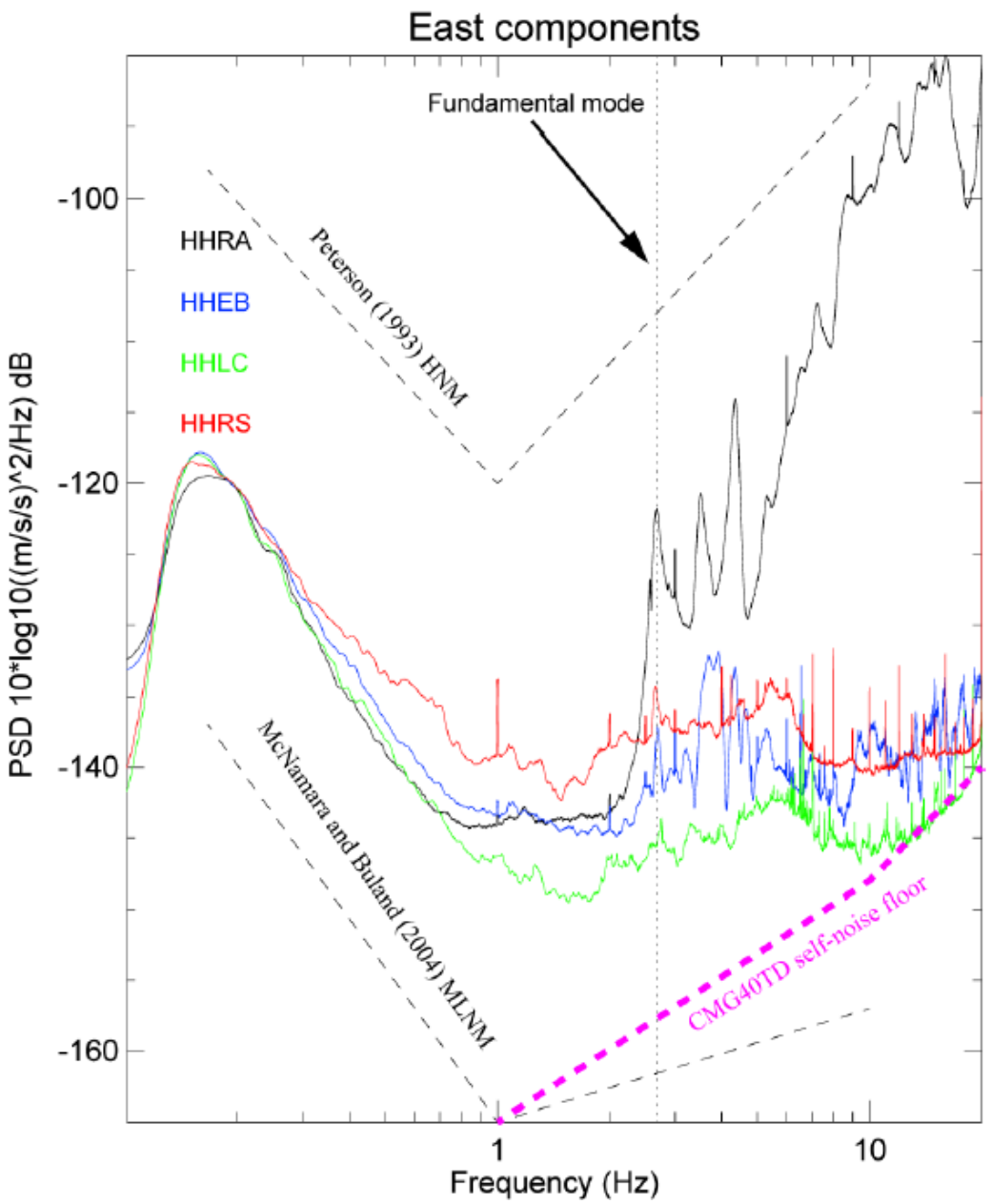


Figure 2-6: Stacked multi-taper acceleration power spectra from the east-west components of Guralp model CMG40TD seismometers installed at four first-generation stations near Hungry Horse Dam, Montana. Windows were 400 seconds in length, and represented ambient conditions (station HHRA was located close 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).

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.

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.

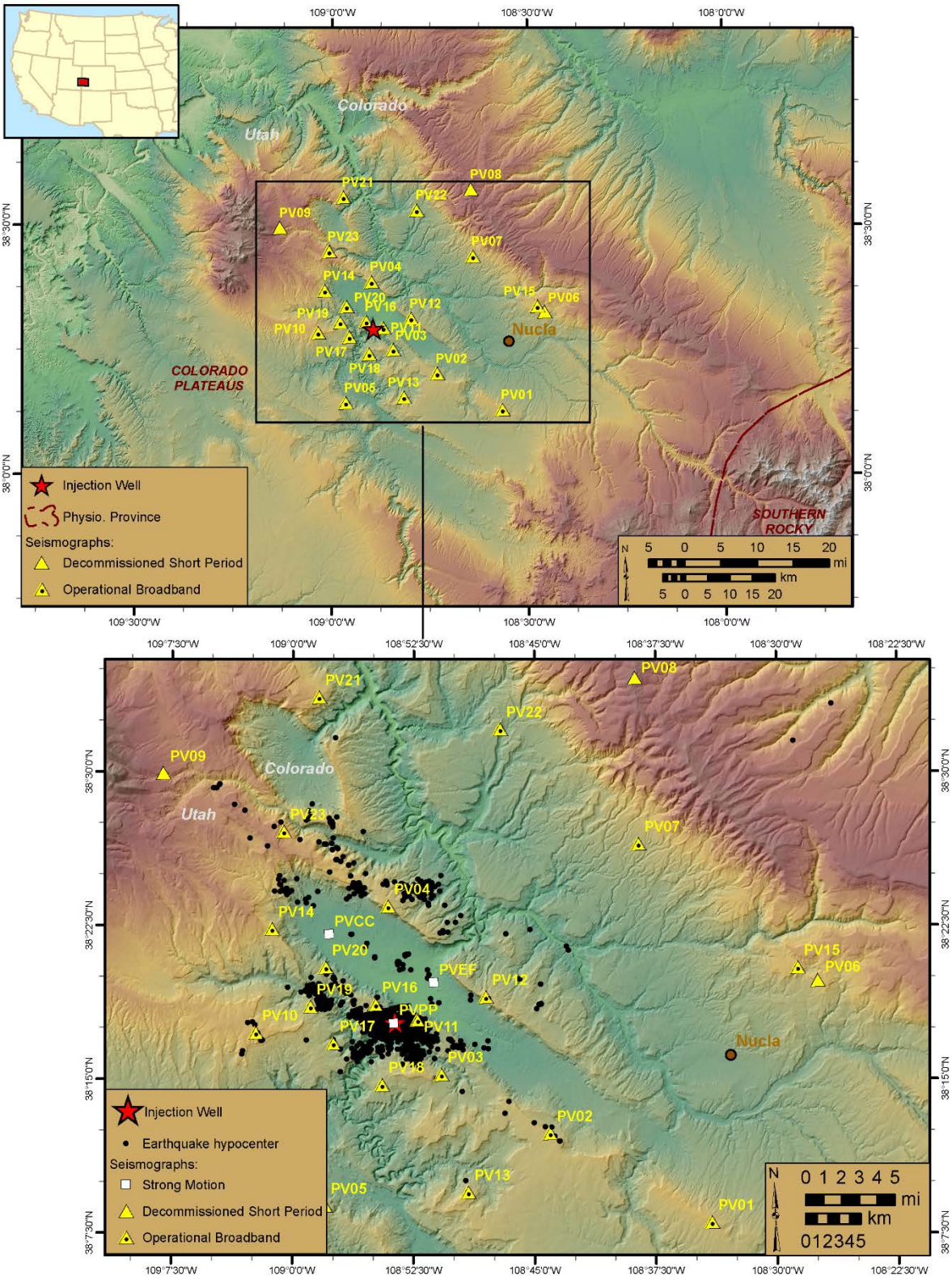


Figure 2-7: Locations of the PVSN seismic stations, PVU injection well, and epicenters of earthquakes ≤ 10 km deep. PVCC, PVEF, & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Physiographic provinces from Fenneman and Johnson (1946).

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 6,400 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 of injection demonstrated in Figure 2-8 strongly suggest that these earthquakes have been induced by PVU fluid injection.

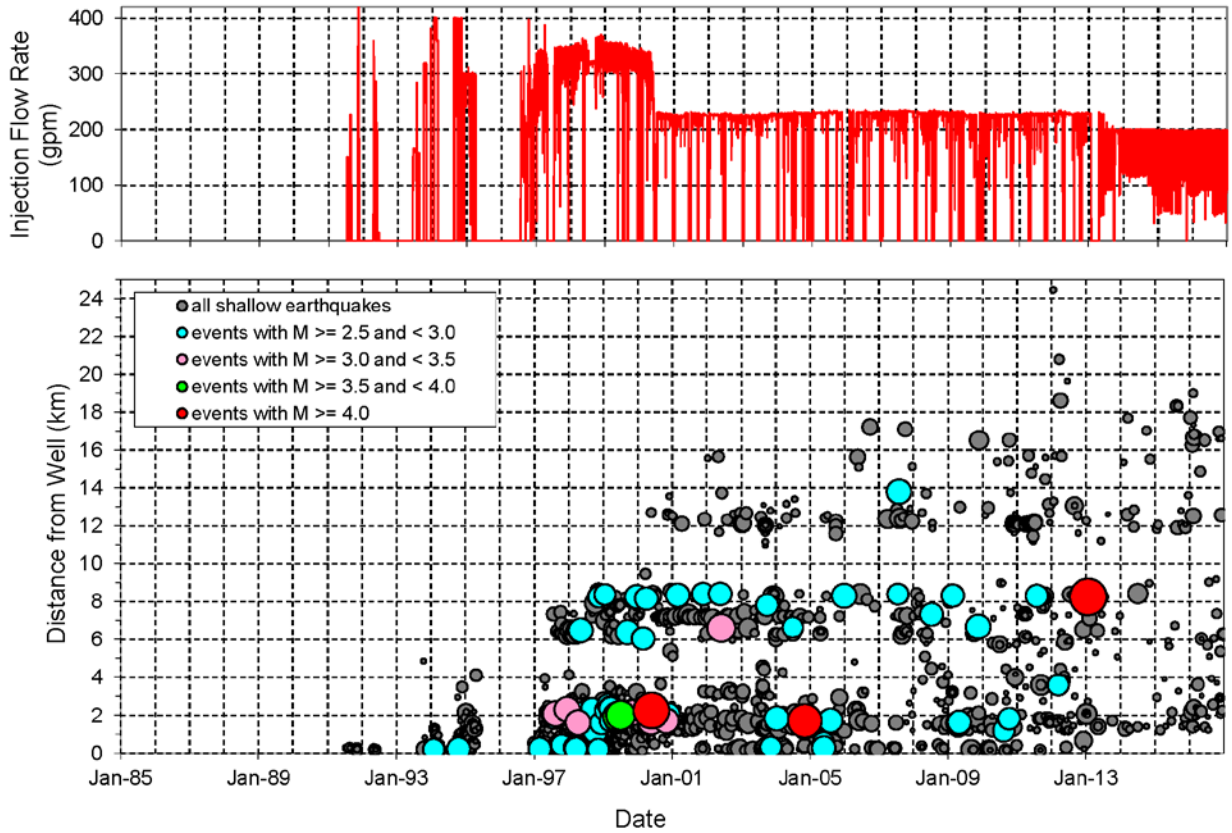


Figure 2-8: Lower plot: scatter plot of earthquakes having magnitude ≥ 0.5 and depth ≤ 10 km (relative to the ground surface elevation at the injection wellhead), plotted as a function of date and distance from the PVU injection well. Each circle represents a single earthquake, with the width of the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

Several distinct groups, or clusters, of induced seismicity have developed over the history of PVU injection operations. By the end of the injection tests in 1995, earthquakes were occurring to radial distances of roughly 4 km from the well (Figure 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 induced seismicity at the northern end of Paradox Valley has been expanding and its rate has increased (Figure 2-9e, f). In addition, seismicity has occurred in several previously aseismic areas, including: toward the southeast to a distance of ~18 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).

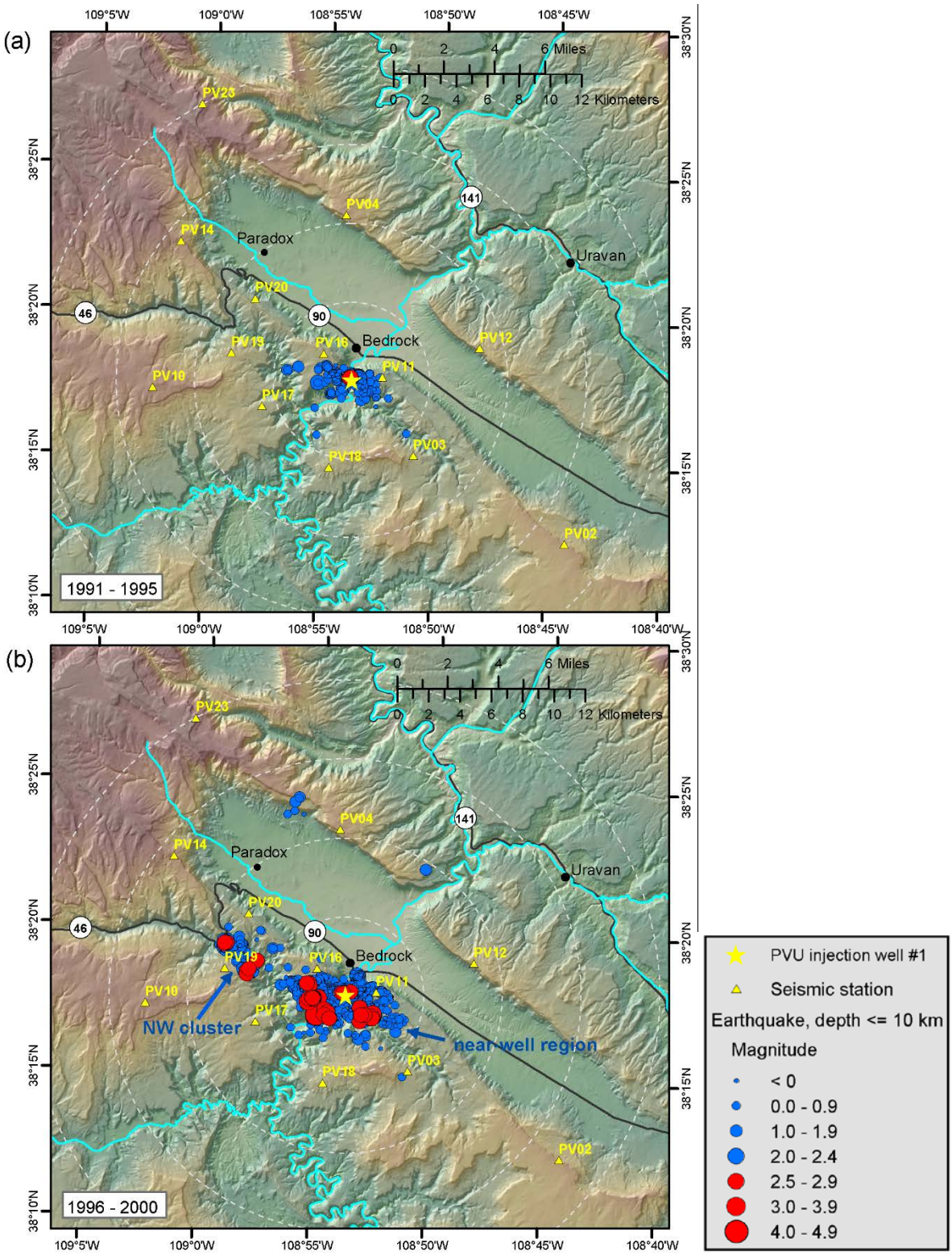


Figure 2-9: Maps showing the spatial distribution of shallow seismicity (depth ≤ 10 km) over time: (a) 1991-1995 (b) 1996-2000 (c) 2001-2004 (d) 2005-2008 (e) 2009 – 2012 (f) 2013 - 2016. Earthquake symbols are sized according to magnitude, and earthquakes with magnitudes ≥ 2.5 are shown in red. The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

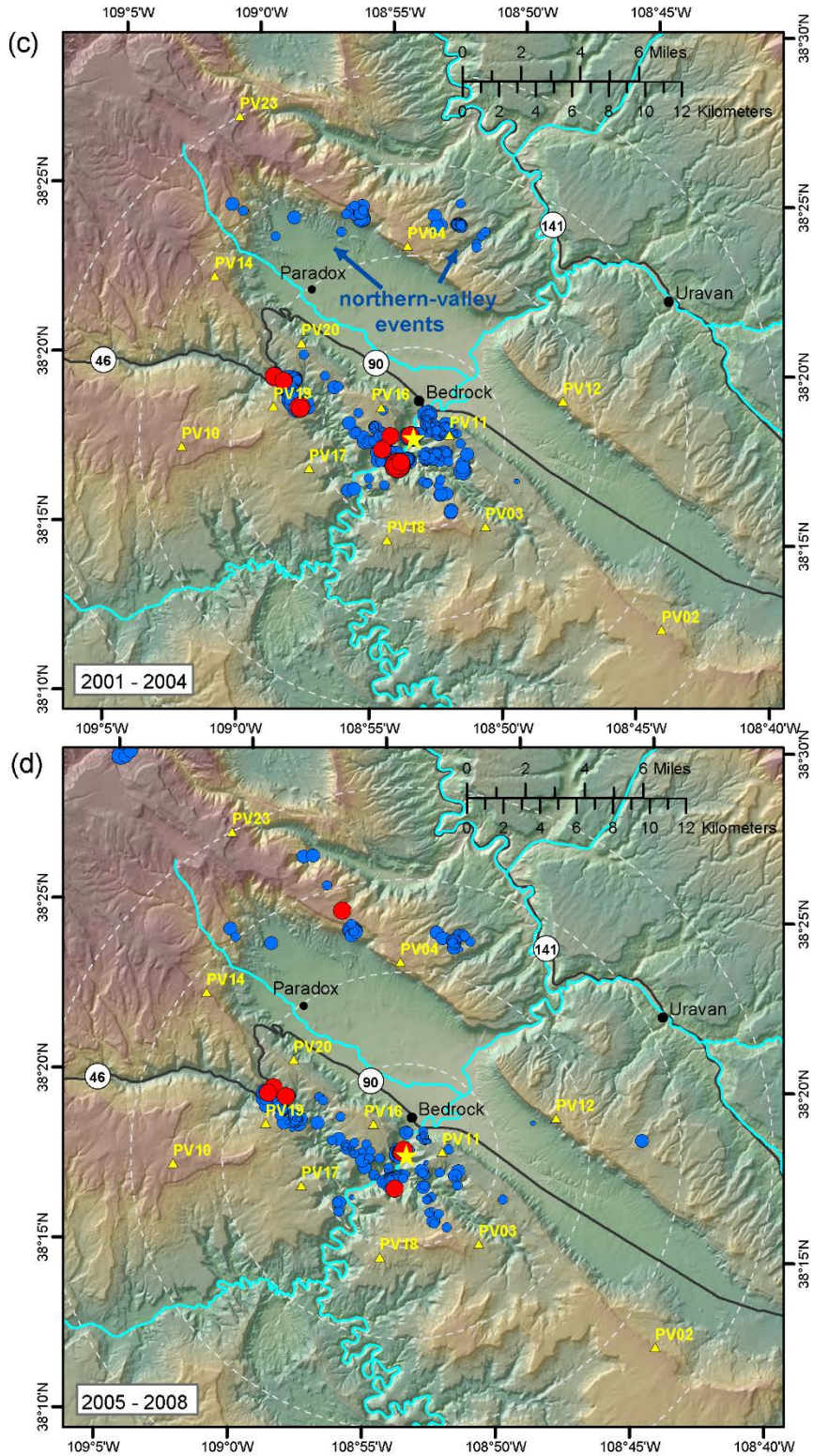


Figure 2-9, continued.

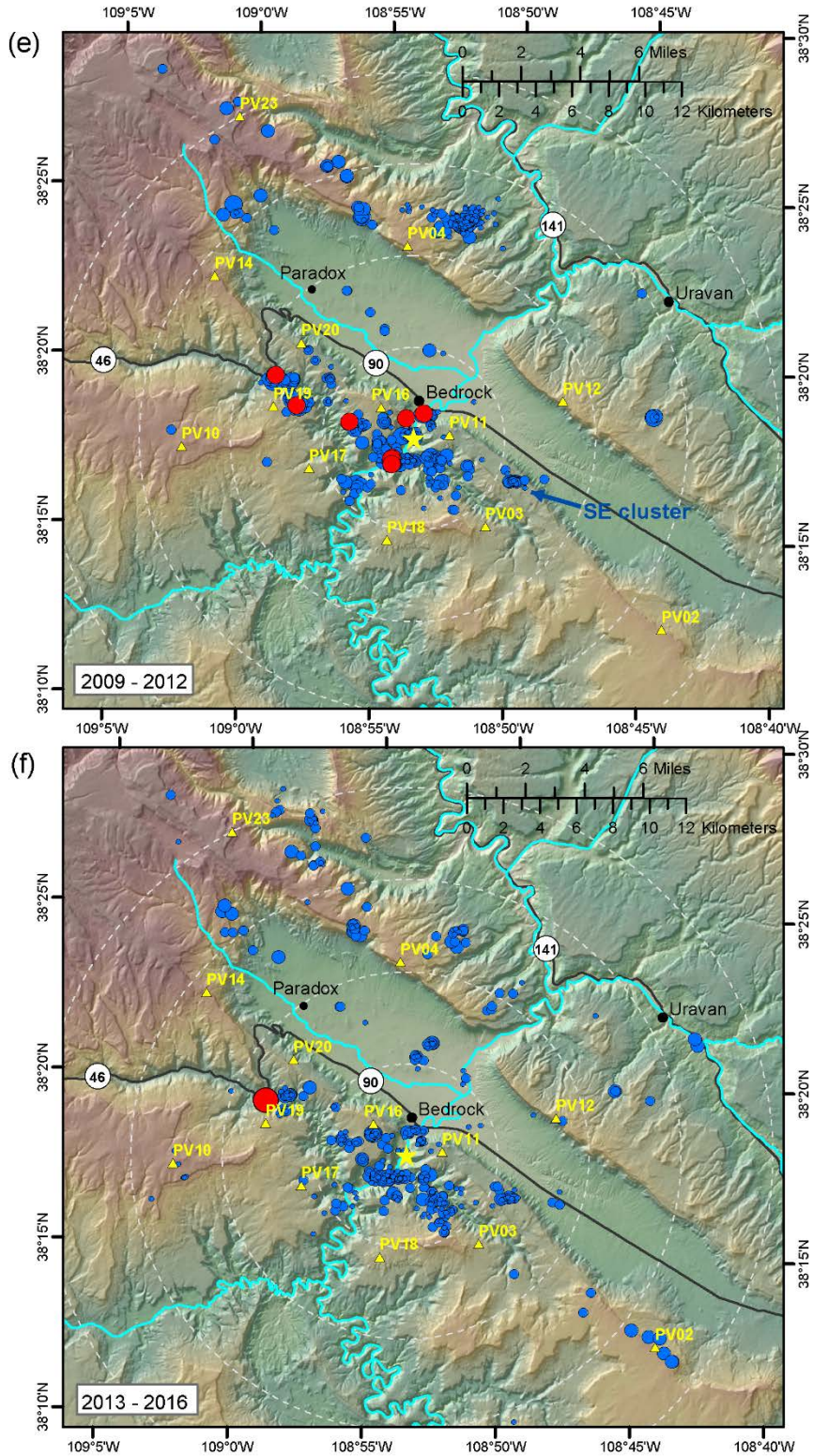


Figure 2-9, continued.

3 Network Operations

3.1 Network Maintenance and Upgrades

Five site visits were conducted during 2016. During these site visits, preventive and remedial maintenance was performed at 17 digital broadband seismic stations, 3 strong motion stations, and the data communication center at Hopkin's Field in Nucla, Colorado. The maintenance performed included replacing batteries, replacing or power-cycling seismometer power supply break-out-boxes (BOBs), replacing or power-cycling GPS BOBs to restore reliable timing, testing and replacing degraded cables and antennas, upgrading radio firmware, and repairing cables and conduit damaged by bear activity. In addition, battery fuses with low-voltage-disconnect (LVD) circuits were diagnosed as contributing to nighttime power failures at several broadband seismic stations; these were replaced with simple bladed fuses. Other activities included: raising the tower at radio repeater station PV02 by 5 feet, which resulted in significantly improved radio data communications for stations PV05 and PV13; upgrading the *Windows* computer at Hopkin's Field which runs the *Earthworm* data acquisition software; installing additional lightning protection hardware at several broadband stations; performing detailed radio surveys at Hopkin's Field to evaluate possible interference from the Federal Aviation Administration's (FAA's) radio communication system; and removing obsolete analog seismometers at several sites. Additional details of the work performed during the 2016 site visits are included in the site visit reports in Appendix A.

3.2 Network Performance

PVSN network performance depends on the performance of the hardware at individual seismic stations, the robustness of the radio data communications 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.

Six of the 20 PVSN broadband seismic stations experienced power supply, GPS timing, or other hardware failures in 2016 (Table 3-1). Station PV02 experienced nighttime power failures during the first week of February and excessive noise on its vertical component from early April until late June. Due to the excessive noise, data from this station were unavailable for event triggering or determination of reliable P-wave arrival times during this time period. (S-wave arrival times could still be determined from the horizontal components.) Station PV21 began having nighttime power failures in early February and then went offline on March 23 due to a hardware failure. The station was brought back online on June 22, but continued to have nighttime failures until further repairs were performed on August 9. Station PV22 was offline for six months, from late December 2015 until June 25, 2016, due a hardware failure. Station PV23 experienced nighttime power failures from late December, 2015 until June 23, 2016. It also experienced a loss of GPS timing from November 25 to December 8, 2016. Two additional stations lost GPS timing during 2016: station PV07 from May 29 to June 28 and station PV18 beginning on December 24 (until January 15, 2017). PVSN has experienced occasional loss of individual GPS station timing for several years (despite replacement of faulty components), and therefore Reclamation is currently

working with an electrical engineer to modify the station design to resolve this issue. In addition, the capability to log station power supply voltages is being added, to aid in diagnosing the nighttime power failures.

Nearly all stations experienced degraded radio communications during 2016, negatively impacting their ability to continuously transmit seismic data. Data loss from individual seismic stations caused by the degraded radio communications is summarized in Table 3-1 and can also be seen as decreased station uptime in the plots presented in Figure 3-1. Stations PV05 and PV13 experienced ~7-15% data loss for the first half of the year. In June, the tower at the radio repeater site used by these stations (PV02) was raised 5 feet, and data loss from remote stations PV05 and PV13 was essentially eliminated. The most significant loss of PVSN data occurred during August and September, when 14 of the seismic stations experienced periods of simultaneous severe data loss. The 14 stations affected were those that transmit their data through radio repeater stations PV04 (PV04, 14, 16, 17, 18, 19, 21, and 23) and PV12 (PV03, 10, 11, 12, 20, and 22). The data loss was intermittent during August, with up to 95% of the data from these stations being lost for recurring periods of several hours to a few days. The data loss was nearly continuous during the first three weeks of September. Because so many stations were essentially offline simultaneously during these time periods, and because the six stations that remained online are distant from most areas of PVU-induced seismicity, PVSN's event completeness threshold temporarily increased from about duration magnitude (M_D) 0.5 to approximately M_D 1.5. This rough estimate of magnitude completeness is based on a manual review of seismic data from induced earthquakes (from time periods when the network was functioning well), noting which stations had clear arrival times for earthquakes of different magnitudes. By comparing these observations to the list of 14 stations experiencing severe data drop-outs, and also considering how the triggering subnets are specified in the data acquisition software, we estimate that PVSN could have failed to detect some events with M_D < ~1.5 during August and September, 2016.

Data transmission improved substantially on Sept. 22 (UTC), after the local telephone company changed the frequency of its radio communications on nearby Gobbler's Knob. PVSN's data transmission improved further, with nearly all stations returning to ≥ 98% uptime (≤ 2% data loss), after the Oct. 29 – Nov. 4 PVSN site visit. During this maintenance trip, a faulty cable in the Hopkin's Field data communication building that transmits data from the PV04 and PV12 radio subnets was identified and replaced, and degraded antennas and cables were also replaced at stations PV04, PV11, and PV12.

The radio communication problems experienced in 2016 were primarily the result of degraded hardware (mainly cables and antennas), interference from another local radio operator, and insufficient tower height at one of PVSN's radio repeater stations (PV02). All three issues have since been resolved. One station, PV01, continues to experience slightly degraded radio data communication, despite the tests and repairs that have been performed. An increased standoff of one of the antennas on the tower at PVSN's data communication center at Hopkin's Field is planned for 2017 to try to resolve this remaining issue.

Table 3-1: Performance of PVSN seismic stations during 2016

Station	Performance
PV01	Experienced an average of ~7% data loss in November and December due to deteriorated radio data communications
PV02	Experienced late night to early morning downtimes during the first week of February due to a lack of power. The vertical component experienced excessively high noise levels from early April to late June, making the vertical-component data unusable during that time period.
PV03	Experienced intermittent severe data loss from 8/4/16 to 8/31/16 and continuous severe data loss from 9/1/16 to 9/22/16 due to deteriorated radio data communications
PV04	Experienced intermittent severe data loss from 8/4/16 to 9/8/16 and continuous severe data loss from 9/9/16 to 9/22/16 due to deteriorated radio data communications
PV05	Experienced an average of ~15% data loss from 1/1/16 to 6/27/16 and ~9% data loss from 9/9/16 to 9/21/16 because of poor radio data communications
PV07	The GPS clock was not providing reliable timing from 5/29/16 to 6/28/16.
PV10	Experienced intermittent severe data loss from 8/4/16 to 8/31/16 and continuous severe data loss from 9/1/16 to 9/22/16 due to deteriorated radio data communications
PV11	Experienced intermittent severe data loss from 8/4/16 to 8/27/16, continuous severe data loss from 8/28/16 to 9/22/16, and ~22% average data loss from 9/23/16 to 11/4/16 due to deteriorated radio data communications
PV12	Experienced intermittent severe data loss from 8/4/16 to 8/31/16 and continuous severe data loss from 9/1/16 to 9/22/16 due to deteriorated radio data communications
PV13	Experienced an average of ~7% data loss from 1/1/16 to 4/3/16 because of poor radio data communications
PV14	Experienced intermittent severe data loss from 8/4/16 to 9/8/16 and continuous severe data loss from 9/9/16 to 9/22/16 due to deteriorated radio data communications
PV15	Online and functioning normally throughout the year
PV16	Experienced intermittent severe data loss from 8/4/16 to 9/8/16 and continuous severe data loss from 9/9/16 to 9/22/16 due to deteriorated radio data communications
PV17	Experienced intermittent severe data loss from 8/4/16 to 9/8/16 and continuous severe data loss from 9/9/16 to 9/22/16 due to deteriorated radio data communications
PV18	Experienced intermittent severe data loss from 8/4/16 to 9/8/16 and continuous severe data loss from 9/9/16 to 9/22/16 due to deteriorated radio data communications. The GPS clock was not providing reliable timing from 12/24/16 to 1/15/17.
PV19	Experienced intermittent severe data loss from 8/4/16 to 9/8/16 and continuous severe data loss from 9/9/16 to 9/22/16 due to deteriorated radio data communications

PV20	Experienced ~7% average data loss from 1/1/16 to 8/3/16, intermittent severe data loss from 8/4/16 to 8/31/16, continuous severe data loss from 9/1/16 to 9/22/16, and ~17% average data loss from 9/23/16 to 11/4/16 due to deteriorated radio data communications.
PV21	Station began having late night to early morning downtimes in early February, 2016 (due to a lack of power) and then went offline on March 23. It was brought back online on June 22, but continued to have nighttime failures until further repairs were performed on August 9. Experienced intermittent severe data loss from 8/4/16 to 9/8/16, continuous severe data loss from 9/9/16 to 9/22/16, and an average ~21% data loss from 9/23/16 to 11/2/16 due to deteriorated radio data communications
PV22	The station was offline from 12/26/15 until 6/25/16 due a hardware failure at the station. Experienced ~6% average data loss from 6/26/16 to 8/3/16, intermittent severe data loss from 8/4/16 to 8/31/16, continuous severe data loss from 9/1/16 to 9/22/16, and ~10% average data loss from 9/23/16 to 11/2/16 due to deteriorated radio data communications.
PV23	Station had late night to early morning downtimes from late December, 2015 until June 23, 2016, due to a lack of power. Experienced intermittent severe data loss from 8/4/16 to 9/8/16 and continuous severe data loss from 9/9/16 to 9/22/16, due to deteriorated radio data communications. The GPS clock was not providing reliable timing from 11/25/16 to 12/8/16.

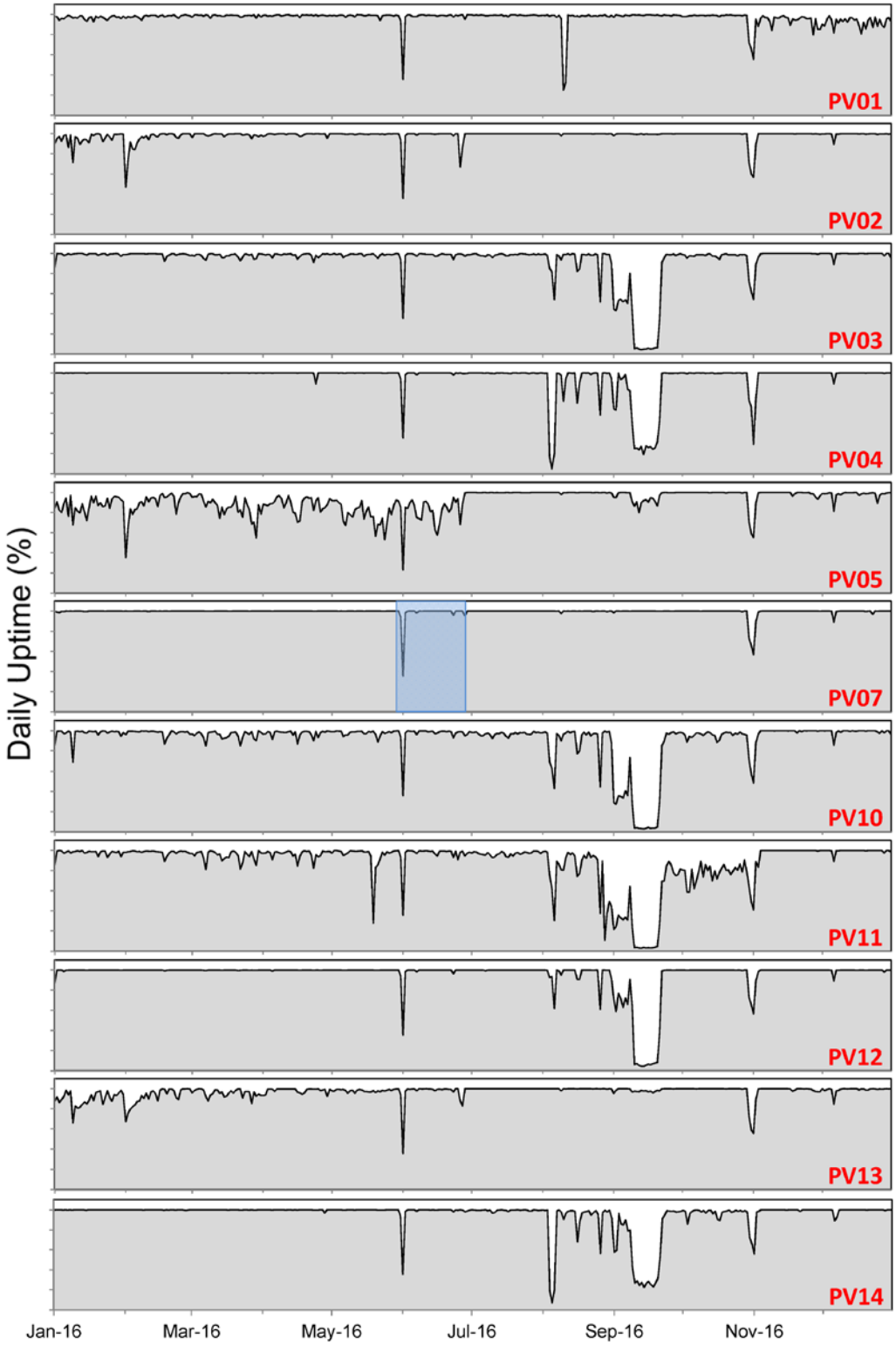


Figure 3-1: Daily uptime (%) for the PVSN seismic stations during 2016. The uptime values represent the percent of the day for which data from a given station were recorded. The vertical axes on the plots are scaled from 0 to 110%. Filled gray areas represent daily uptime, while dips in the filled volume show decreases in uptime (lack of data). Shaded blue areas indicate time periods with unreliable station timing.

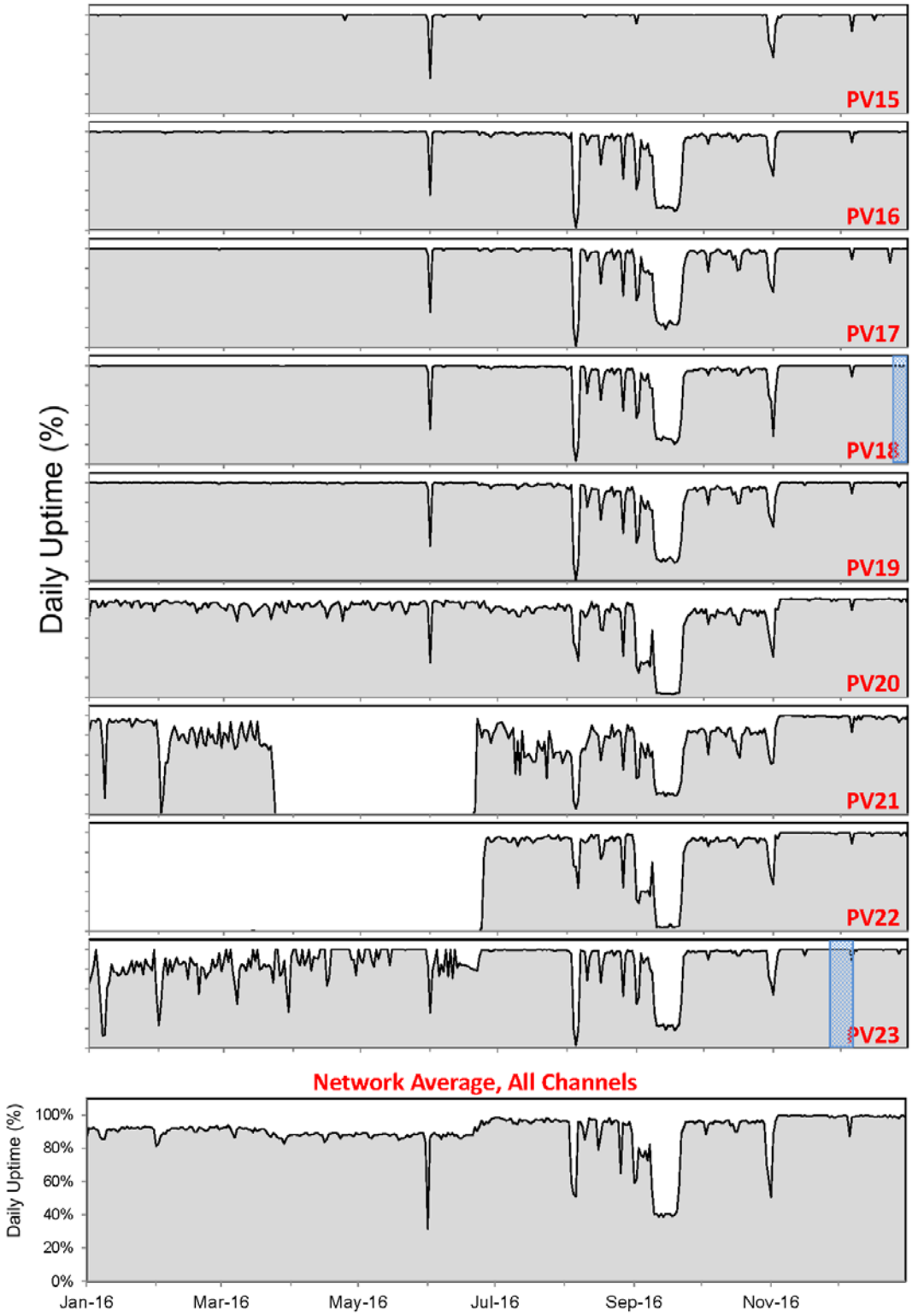


Figure 3-1, continued. The bottom plot shows the daily average performance for all PVSN channels.

The PVSN data acquisition computer systems were online during most of the year. The only data acquisition downtimes were due to planned maintenance or upgrade activities. Data acquisition was interrupted for 16 hours at the end of May due to a transition in the computer systems in Denver hosting the *Earthworm* data acquisition software (Table 3-2). This computer transition was required by IT security protocols. Data acquisition was interrupted during five additional short time periods in 2016, totaling approximately 27 hours. These downtimes were required for testing and replacement of radio communication hardware (Table 3-2). The total length of time that PVSN was offline during 2016 was 43.6 hours, or 1.8 days.

Considering data loss from hardware or power failures at individual seismic stations, radio communication data drop-outs, and PVSN downtimes, the 2016 annual uptimes for the PVSN telemetered high-gain seismic stations ranged from 44% to 99%, with 8 of the 20 stations having uptimes ≥ 95% (Figure 3-2; Table 3-3). These uptimes represent the percent of the year for which data from a given station were recorded.

Table 3-2: Times when PVSN was down or degraded in 2016

Time Period (UTC)	Reason
5/31 23:11 to 6/1 15:30 (16 hours 19 min.)	Offline for transition in data acquisition computer systems required by Reclamation IT security
8/4-8/6, 8/10-8/11, 8/16-8/17, 8/26, 8/31 9/1 – 9/22 (31 days)	Degraded due to failing radio data communications for 14 stations
10/30 15:50 to 20:05 and 21:50 to 22:50 (5 hours 15 min.) 10/31 14:05 to 21:35 (7 hours 30 min.) 11/1 14:18 to 11/2 2:34 (12 hours 16 min.)	Offline for scheduled testing and maintenance of radio data communication equipment
12/6 15:50 to 18:05 (2 hours 15 min.)	Offline for scheduled testing and maintenance of radio data communication equipment

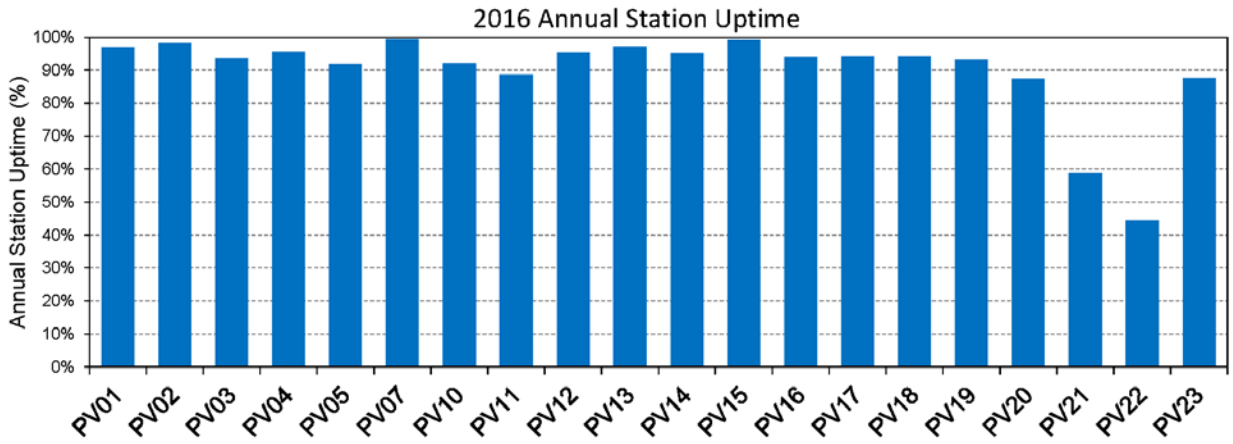


Figure 3-2. Graph of annual (2016) uptime for each PVSN telemetered high-gain seismic station.

Table 3-3: Annual PVSN station uptime in 2016.

Station	Annual Station Uptime in 2016
PV01	97%
PV02	98%
PV03	94%
PV04	95%
PV05	92%
PV07	99%
PV10	92%
PV11	89%
PV12	95%
PV13	97%
PV14	95%
PV15	99%
PV16	94%
PV17	94%
PV18	94%
PV19	93%
PV20	87%
PV21	59%
PV22	44%
PV23	88%

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%

**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.

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. However, if PVSN is online but several seismic stations are down simultaneously, then event detection can be compromised. In 2016, PVSN was offline for only 1.8 days, due to the scheduled downtimes required for maintenance activities (Table 3-2). However, event detection was compromised for about 9 intermittent days in August and 22 consecutive days in September when large amounts of data from 14 stations were lost due to failing radio communications. Considering the 1.8 days that PVSN was offline and giving a 50% rating for the 31 days in August and September when multiple stations were offline simultaneously yields an annual PVSN uptime of 95.3%. This is the lowest PVSN uptime since 2007 (Table 3-4), but still above the target threshold uptime of

95% specified by PVU's Seismic Monitoring Plan (Environmental Protection Agency, 2011, Appendix E).

3.3 Transition in Computer Systems and Data Acquisition Software

At the end of May, 2016, the computer systems in Denver running PVSN's primary data acquisition software (*Earthworm*) and data processing programs were de-commissioned and the applications were ported to new systems. This transition and its timing were mandated by Reclamation IT security protocols. The data acquisition software was installed on the new systems on May 3, and the old system was decommissioned on May 31. Data processing codes were successfully transitioned to the new computer systems in late May and early June. Interruption to data processing due to the computer transition was minimal.

Unfortunately, the short transition period in computer systems did not leave sufficient time for thorough testing of the data acquisition software on the new system, and problems were later discovered with its performance. In addition to changing physical computer systems, other changes were made simultaneously, including: changing from a physical Linux server to a virtual Linux machine running under *Windows*, changing from *Suse* Linux to Linux *Cent-OS*, changing from Reclamation's internal version of *Earthworm* to open-source version 7.8, and modifying configuration settings within *Earthworm*. The multiple simultaneous changes and unavailability of the previous system makes diagnosing and resolving the performance issues more difficult. Initial evaluation of the error messages generated by *Earthworm* suggests that many of the problems are caused by missed "heartbeats", which means that the software modules are not exchanging information fast enough to perform their functions as quickly as needed, as required by real-time data acquisition systems. The errors occur much more frequently during the day than at night, suggesting that they are related to other computer or network usage. Additionally, although the version and configuration of *Earthworm* running on the new Denver system and the backup computer system at Hopkin's Field in Nucla, Colorado, both experienced the same changes at the beginning of June, the Nucla system has displayed very few errors. This observation lends further evidence that the problems are related to Denver IT resources rather than *Earthworm* software changes. The problems could be related to a number of issues, including the fact that the virtual machine now running *Earthworm* in Denver was not configured for latency-sensitive applications (as suggested by the *VMware* manufacturer (VMware, 2015)), IT networking delays may have increased, and *Earthworm* may not be optimally configured to handle computer and network delays.

Because of the superior performance of the backup *Earthworm* system operating independently at PVSN's data acquisition center in Nucla, Colorado, the decision was made to transmit seismic data directly from this system to the new data processing computer systems in Denver for event detection and data processing. This change was implemented on August 17, 2016, and the Nucla system currently remains PVSN's primary data acquisition system.

4 Seismic Data Recorded in 2016

4.1 Annual Summary

Two hundred and twenty-four earthquakes were recorded within or near the perimeter of PVSN during 2016. 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 2016 are classified into four categories based on their depths (relative to the ground surface elevation at the injection well, 1.524 km) 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 2016 in each of the location categories are summarized in Table 4-1. The 2016 local earthquake catalog is included in Appendix B.

All but two of the 224 local earthquakes recorded during 2016 have depths ≤ 10 km. Of these relatively shallow earthquakes, 131 occurred within 5 km of the injection well, 45 occurred at distances between 5 and 10 km from the well, and 46 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 to be induced by PVU brine injection. The largest shallow earthquake during 2016 occurred on February 5th, with a magnitude of M_D 2.1. It occurred approximately 2.2 km northwest of the injection well, at a depth of 4.2 km.

One of the two deep events recorded during 2016 occurred ~18 km east of the injection well (Figure 4-1). Its estimated depth is 13.7 km, relative to the ground surface elevation at the injection well, and its magnitude is M_D 0.2. Few earthquakes with comparable depths have been recorded in this area in the past. One earthquake with an estimated depth of about 14 km occurred ~2 km southeast of the 2016 earthquake in 2013 (with M_D 0.3). Two earthquakes with estimated depths of 10 to 11 km occurred ~3.7 km north of the 2016 event in 2014 and 2015 (with M_D 1.8 and M_D 0.9, respectively). These events are tentatively considered naturally occurring because of their relatively deep hypocenters. However, the velocity model used to compute the locations of the local earthquakes may not be very accurate in this region (because of a lack of historical earthquake data to constrain the model). In addition, the seismic network is relatively sparse in this area, and the closest seismic station (PV12) is relatively far away from the earthquakes, at a horizontal distance of ~10 km. Hence, the computed depths of these events

have more uncertainty than those of the events occurring closer to the injection well. If the seismicity in this region increases, or if additional data or analyses indicate that the depths of the earthquakes are a few km shallower than these initial estimates, our interpretation about whether the events are naturally occurring or induced will be re-evaluated.

The other deep event recorded during 2016 occurred 27 km northwest of the injection well (Figure 4-1). Its estimated depth is 13.0 km, relative to the ground surface elevation at the injection well, and its magnitude is M_D 1.3. Because stations PV21 and PV22 were both offline when this earthquake occurred, the maximum azimuthal gap in station coverage is large, 279°. Hence, the computed hypocenter is not well-constrained. However, four other earthquakes with epicenters within ~0.5 km of the 2016 event epicenter and with comparable depths have been detected in the past, one as early as 1999. This historical seismicity suggests that these earthquakes are most likely naturally occurring.

The local earthquakes recorded by PVSN during 2016 are plotted as a function of date, earthquake magnitude, and location category in Figure 4-2. The very low seismicity rates during August and September are likely due to the decreased network performance discussed in section 3.2. Increased rates of shallow near-well seismicity occurred during March, late April–early May, and June. The rate of shallow intermediate-range seismicity was substantially higher during the second half of the year than during the first half. Rates of shallow distant seismicity were highest in February–March and November–December.

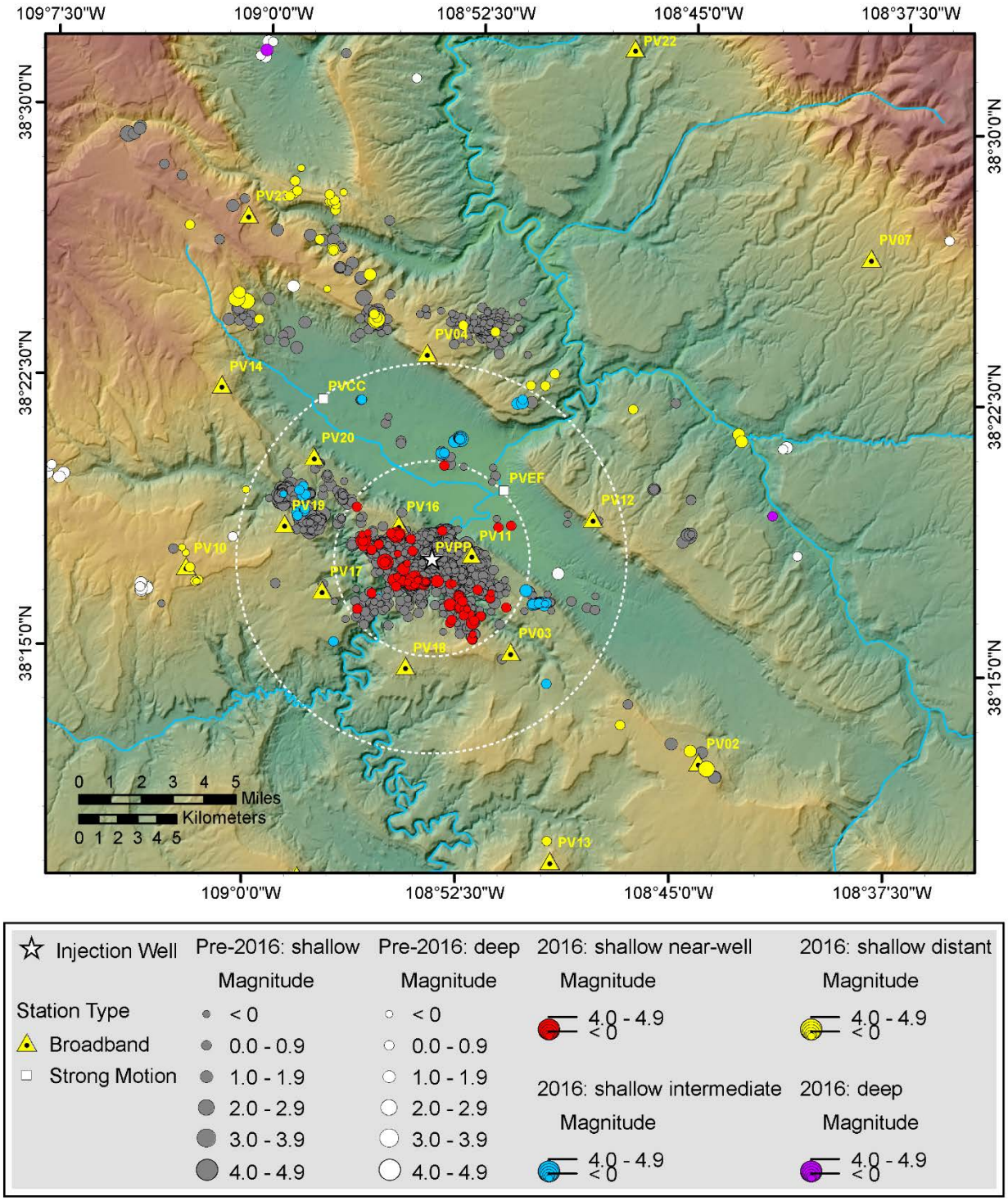


Figure 4-1: Locations of local earthquakes recorded by PVSN during 2016 (colored circles) and previous years (gray and white circles). The events that occurred during 2016 are color-coded using the event location categories described in the text. Events identified as "shallow" have depths ≤ 10 km (relative to the ground surface elevation at the injection well); those identified as "deep" have depths > 10 km. The white dashed circles indicate radial distances of 5 and 10 km from the injection well.

Table 4-1: Summary of earthquakes recorded during 2016 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	131	26	-1.2 – 2.1
shallow intermediate		> 5 to 10 km	45	14	-0.7 – 1.5
shallow distant		> 10 km	46	14	-1.2 – 1.9
TOTAL SHALLOW			**222**	**54**	**-1.2 – 2.1**
deep	> 10 km	all distances, within or near perimeter of PVSN	2	1	0.2 to 1.3
TOTAL			**224**	**55**	**-1.2 – 2.1**

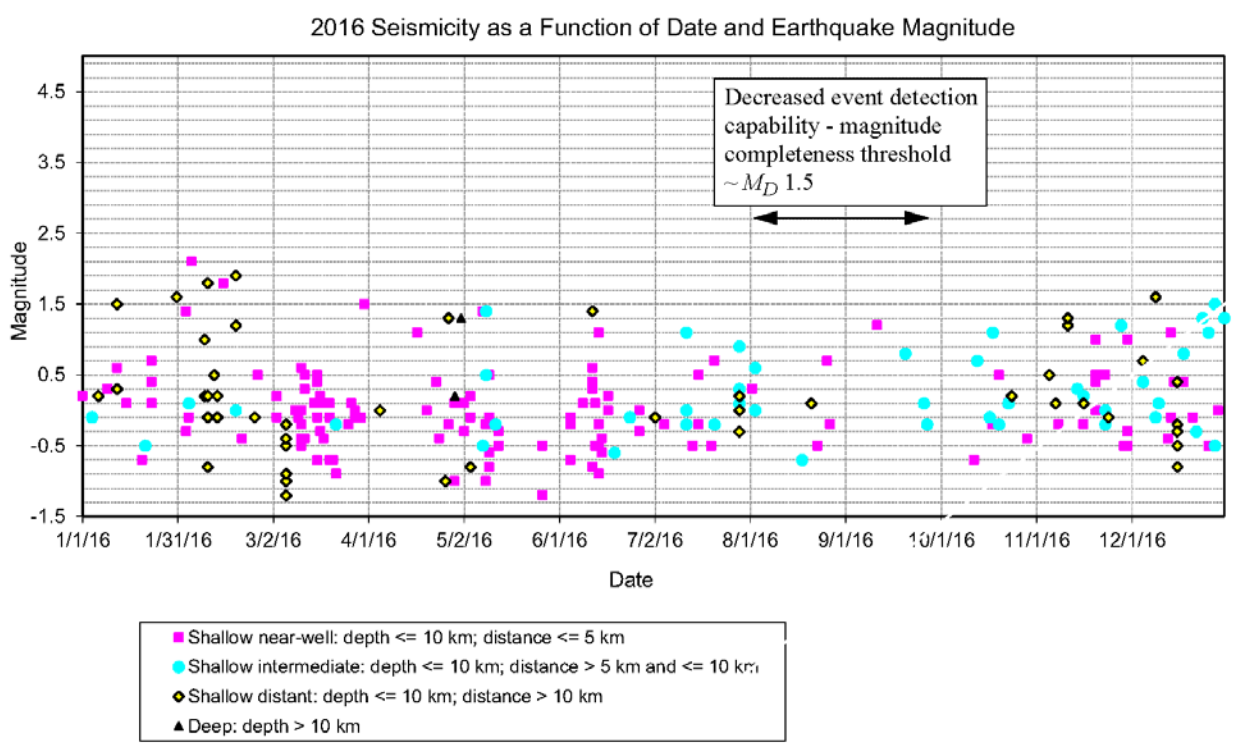


Figure 4-2: Earthquakes recorded by PVSN during 2016, plotted as a function of date, magnitude, and event location category.

4.2 Shallow Earthquakes

4.2.1 Seismicity near the Injection Well

The hypocenters of the earthquakes that occurred in 2016 within 7 to 9 km of the injection well are compared to those from previous years in the map in Figure 4-3 and in the vertical cross sections presented in Figure 4-4. In these figures, the earthquakes that occurred during 2016 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, most of the earthquakes induced within ~7-9 km of the injection well during 2016 occurred in areas of previous seismic activity.

The most substantial change in the seismicity within 7-9 km of the well during 2016 was the development of two seismicity clusters within Paradox Valley, 5.0 to 6.5 km north of the injection well (Figure 4-3). A few isolated earthquakes had been detected sporadically in this area since 2012, with 1 to 5 events being recorded per year. Rates increased substantially in 2016, with 14 earthquakes occurring in this area. Nine of them occurred in about a one-month period from Nov. 28 to Dec.31. The epicenters of these earthquakes form two small clusters. These earthquakes occurred beneath the Paradox Valley salt diapir, at estimated depths of 5.9 to 7.2 km (relative to the ground surface elevation at the injection well). The largest earthquake in this area during 2016 was an M_D 1.5 event, which occurred on December 28.

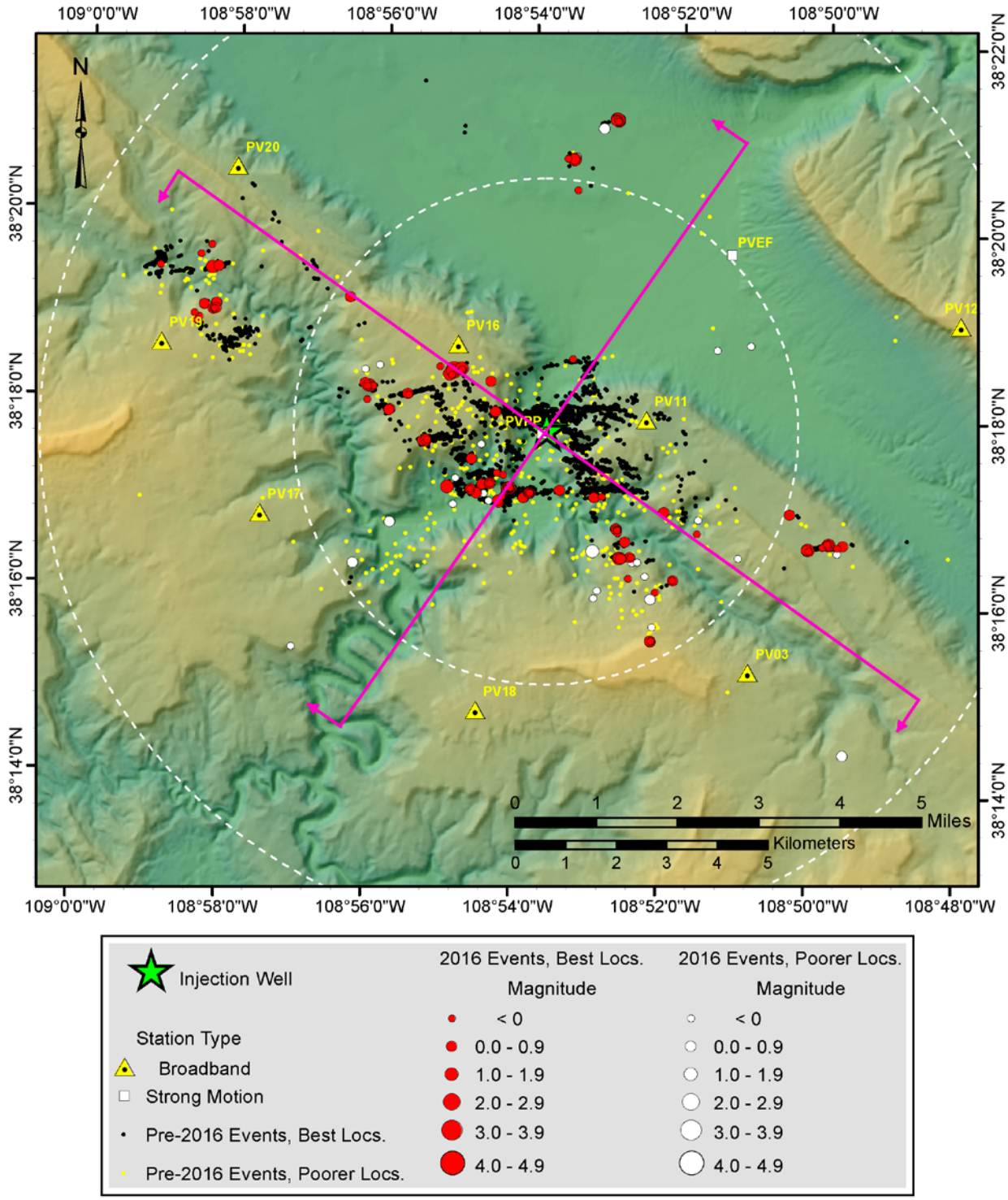
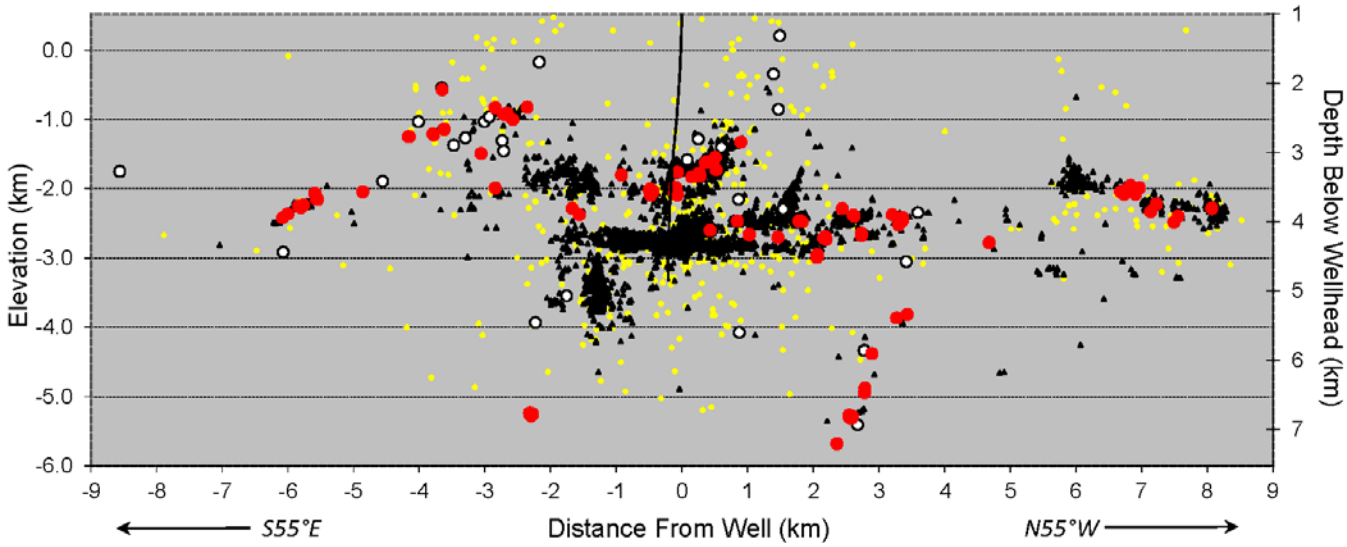


Figure 4-3: Map showing the epicenters of shallow earthquakes (≤ 10 km depth) in the vicinity of the injection well in 2016, compared to the locations of previously-induced events. The white dashed circles indicate radial distances of 5 and 10 km from the injection well. The magenta lines indicate the orientations of the cross sections presented in Figure 4-4.

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



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

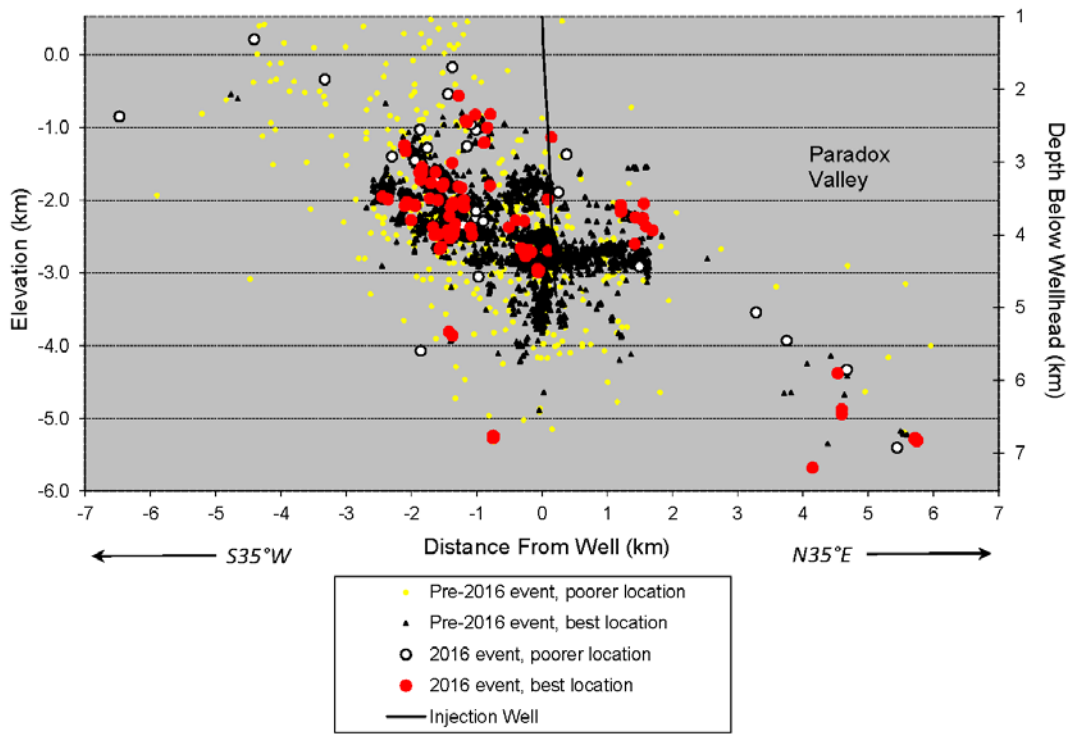


Figure 4-4: Vertical cross sections showing the hypocenters of earthquakes occurring within approximately 7-9 km of the injection well in 2016, compared to the locations of previously-induced events: (a) section parallel to Paradox Valley (b) section perpendicular to Paradox Valley. The orientations of the cross sections are indicated by the magenta lines in Figure 4-3.

4.2.2 Distant Earthquakes

During 2016, 46 earthquakes with computed depths ≤ 10 km were detected at distances greater than 10 km from the injection well. Twenty-nine of these earthquakes occurred around the northern edge of Paradox Valley, where seismicity has been detected every year since 2000. For comparison, twenty-three events occurred in this northern-valley region in 2015. The seismicity in this area is migrating farther north, with several earthquakes occurring in a previously aseismic region east of seismic station PV23 during 2016 (Figure 4-1). The northern-valley earthquakes recorded during 2016 range in magnitude from M_D -1.0 to M_D 1.9, and their depth estimates range from 2.5 to 7.1 km (relative to the ground surface elevation at the injection well). The largest earthquake that occurred in this area during 2015 had a magnitude of M_D 1.0. During 2016, six earthquakes with $M_D > 1.0$ occurred in this region.

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 2016. Six earthquakes occurred east of Paradox Valley and just north of the Dolores River (~5 to 7 km southeast of station PV04), at distances of ~9 to ~11.5 km from the injection well (Figure 4-1). These earthquakes range in magnitude from M_D -0.3 to M_D 0.9, and their depth estimates range from 3.1 to 5.3 km. Four of these earthquakes occurred in July, and the other two occurred in October and November. Prior to 2016, only one earthquake had been detected in this area, an M_D 1.2 event with an estimated depth of 2.2 km, which was recorded in 2000.

Three shallow distant earthquakes occurred east of Paradox Valley and south of the Dolores River, at distances of 12.8 to 17.0 km from the PVU injection well. No seismicity had previously been detected within 2 km of any of these earthquakes. One event is a geographically isolated earthquake with a magnitude of M_D -0.1 and estimated depth of 5.0 km. It occurred in July. The other two earthquakes are nearly co-located and occurred about 2 hours apart on November 11. They have magnitudes of M_D 1.2 and M_D 1.3 and estimated depths of 9.0 and 8.9 km, respectively. The closest historical events are two earthquakes ~2.2 km east of the 2016 earthquakes. Those events occurred in 2014 and 2015 and have computed depths of 10.8 and 10.3 km, just below our depth classification limit (Figure 4-1).

Four shallow distant earthquakes occurred southeast of the injection well during 2016 (Figure 4-1). Two of these occurred near seismic station PV02, at distances of 16.5 to 17.7 km from the well. The closer event has a magnitude of M_D 1.4 and estimated depth of 8.6 km, and the farther event has a magnitude of M_D 1.5 and estimated depth of 7.7 km. Four other events had previously been detected near PV02, all since late 2014. Those earlier events had shallower depth estimates, ranging from 4.6 to 6.2 km. During 2016, a third event occurred along the azimuth from the well toward PV02, but at a considerably closer distance of 12.8 km. This earthquake has a magnitude of M_D 0.1 and depth estimate of 3.8 km. In 2015, an earthquake with similar magnitude (M_D 0.2) and a somewhat deeper depth estimate (4.7 km) occurred 1.2 km northeast of the 2016 earthquake. The epicenter of the fourth shallow distant earthquake that occurred southeast of the well during 2016 is near station PV03, 15.6 km from the well (Figure 4-1). It has a magnitude of M_D -0.1 and computed depth of 6.6 km. No other earthquakes have been detected within ~7 km of this event.

During 2016, five very small earthquakes occurred 12.0 to 12.6 km west of the injection well, near seismic station PV10 (Figure 4-1). The magnitudes of these events range from M_D -1.0 to M_D -0.2, and their depth estimates range from 2.6 to 3.1 km. Only two events with depths ≤ 10 km had been detected in this general area previously: an M_D 0.9 event with an estimated depth of 9.9 km recorded in 2012 and an M_D -0.7 event with an estimated depth of 2.0 km recorded in 2014. A cluster of naturally occurring earthquakes that have been recorded since 1992, with estimated depths of 11.5 – 12.2 km, lies approximately 2.5 km southwest of the shallow earthquakes recorded in 2016 (Figure 4-1).

4.2.3 Comparison to 2015 Seismicity

The number of shallow earthquakes observed at all distances from the injection well increased in 2016 compared to 2015 (Table 4-2). During 2016, 131 earthquakes were detected within 5 km of the injection well, compared to only 77 in 2015, an increase of 70%. An even larger percent increase was observed in the 5-to-10 km distance range, with the number of earthquakes increasing from 20 in 2015 to 45 in 2016, an increase of 125%. At distances > 10 km, the number of shallow earthquakes increased from 35 in 2015 to 46 in 2016, an increase of 31%. If only earthquakes with magnitude ≥ M_D 0.5 are considered (PVSN's nominal magnitude completeness threshold), then the percent increases in seismicity rates are even larger: 160% for the 0-5 km distance range, 367% for the 5–10 km distance range, and 40% for distances > 10 km (Table 4-3).

Table 4-2: Number of earthquakes with depth ≤ 10 km recorded in 2015 and 2016, 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 2015	Number of Events Recorded in 2016	Percent Change
0 to 5	77	131	70
> 5 to 10	20	45	125
> 10	35	46	31

Table 4-3: Number of earthquakes with depth ≤ 10 km and magnitude ≥ M_D 0.5 recorded in 2015 and 2016, as a function of distance from the injection well

Distance Range (km)	Number of Events Recorded in 2015	Number of Events Recorded in 2016	Percent Change
0 to 5	10	26	160
> 5 to 10	3	14	367
> 10	10	14	40

Because PVSN's event detection capabilities were substantially poorer during 2016 than during 2015, the percent increases in seismicity rates from 2015 to 2016 listed in Table 4-2 and Table 4-3 should be considered to be lower bounds. As discussed previously, the network performance was significantly impaired during most of August and September, 2016, because of deteriorated radio data communications, and PVSN's magnitude completeness threshold increased to approximately M_D 1.5 during this time period. Hence, some induced earthquakes with magnitude

< M_D 1.5 were likely missed during these months, and therefore the 2016 seismicity rates are almost certainly underestimated.

The numbers of earthquakes recorded during 2016 and 2015 are plotted as a function of magnitude in Figure 4-5. 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. For the 0-5 km and 5-10 km distance ranges, seismicity rates were higher for all magnitudes in 2016 compared to 2015. In addition, the maximum earthquake magnitudes increased. The largest earthquake that occurred within 5 km of the injection well in 2016 had a magnitude of M_D 2.1, compared to a maximum earthquake magnitude of only M_D 1.1 for this distance range in 2015. Similarly, the maximum earthquake magnitude for the 5-10 km distance range was M_D 1.5 in 2016, compared to M_D 0.9 in 2015. For earthquakes occurring more than 10 km from the injection well, rates of the smallest ($M_D < 0$) and largest ($M_D > 1$) earthquakes increased in 2016 compared to 2015, but rates of intermediate-magnitude events decreased (Figure 4-5, lower plot). As for the smaller distance ranges, the maximum magnitude of shallow distant earthquakes also increased: M_D 1.9 in 2016, compared to M_D 1.6 in 2015.

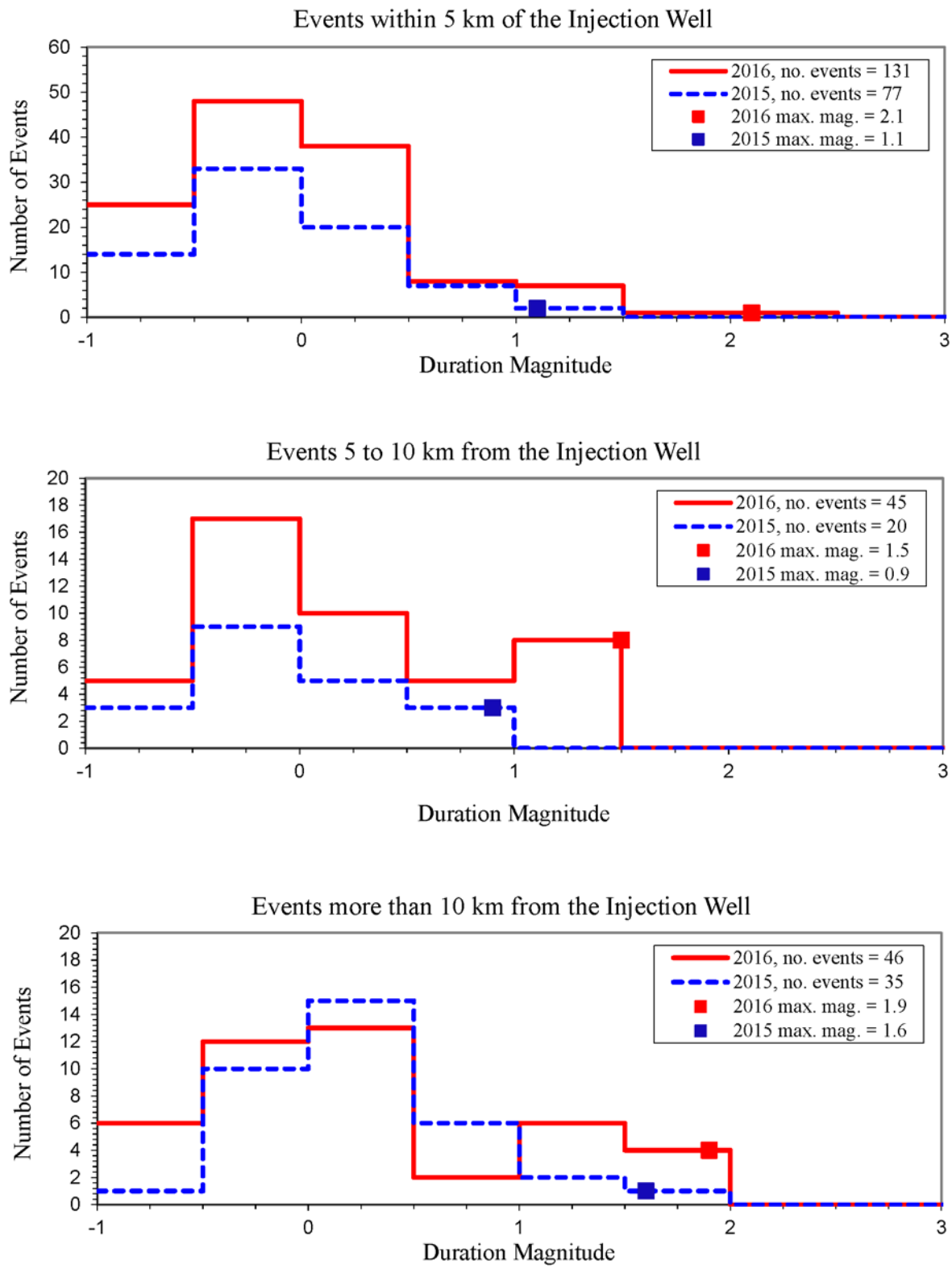


Figure 4-5: Magnitude histograms of events within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and more than 10 km from the well (bottom) during 2016 (solid red lines) and 2015 (dashed blue lines). The squares indicate the maximum earthquake magnitude for a given distance range and year.

4.3 Historical Seismicity Trends

The rates and magnitudes of earthquakes that occurred during 2016 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 4-6 show the historical occurrence of shallow seismicity (depth ≤ 10 km) as a function of date and earthquake magnitude during long-term injection at PVU (1996-2016). 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 4-6 for reference. In order to better observe the trends in recent years, similar plots that only include data from 2010-2016 are presented in Figure 4-7. Lastly, we show the annual seismicity rates for 2010-2016, for the different distances from the well, in Figure 4-8.

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 high in 2016. The maximum magnitude of events occurring within 5 km of the injection well in 2016 (M_D 2.1) was the highest since early 2013 (Figure 4-7b). The annual near-well seismicity rate had increased slightly in 2015 but experienced a much larger increase in 2016. The annual rate of M 0.5+ events in this near-well area in 2016 was comparable to rates observed in 2011 and 2012, prior to the extended injection well shut-in and decrease in flow rate implemented in early 2013 (Figure 4-8a).

The seismicity rate observed at distances of 5 to 10 km from the injection well also rebounded substantially in 2016. The seismicity rate began increasing in early to mid-2016 (Figure 4-6c and Figure 4-7c). The 2016 annual rate was roughly four and a half times that experienced during each of the previous two years (2014 and 2015) and was 81% of the average rate experienced during the three years prior to the change in injection operations (2010 to 2012) (Figure 4-8b). Although the maximum earthquake magnitude in this distance range in 2016 (M_D 1.5) was higher than in 2015 (M_D 0.9), it was still lower than for most recent years (M_D 2.3 in 2014; M_L 4.4 in 2013; M_D 2.0 in 2012; M_D 2.7 in 2011).

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 4-8c). The annual rate still remains modest compared to long-term historical trends, which at times experienced very high rates due to intense swarms of activity lasting days to weeks. The maximum magnitude of the distant induced earthquakes in 2016 was M_D 1.9, which is higher than the 2015 maximum magnitude (M_D 1.6) but still comparable to maximum magnitudes in many previous years.

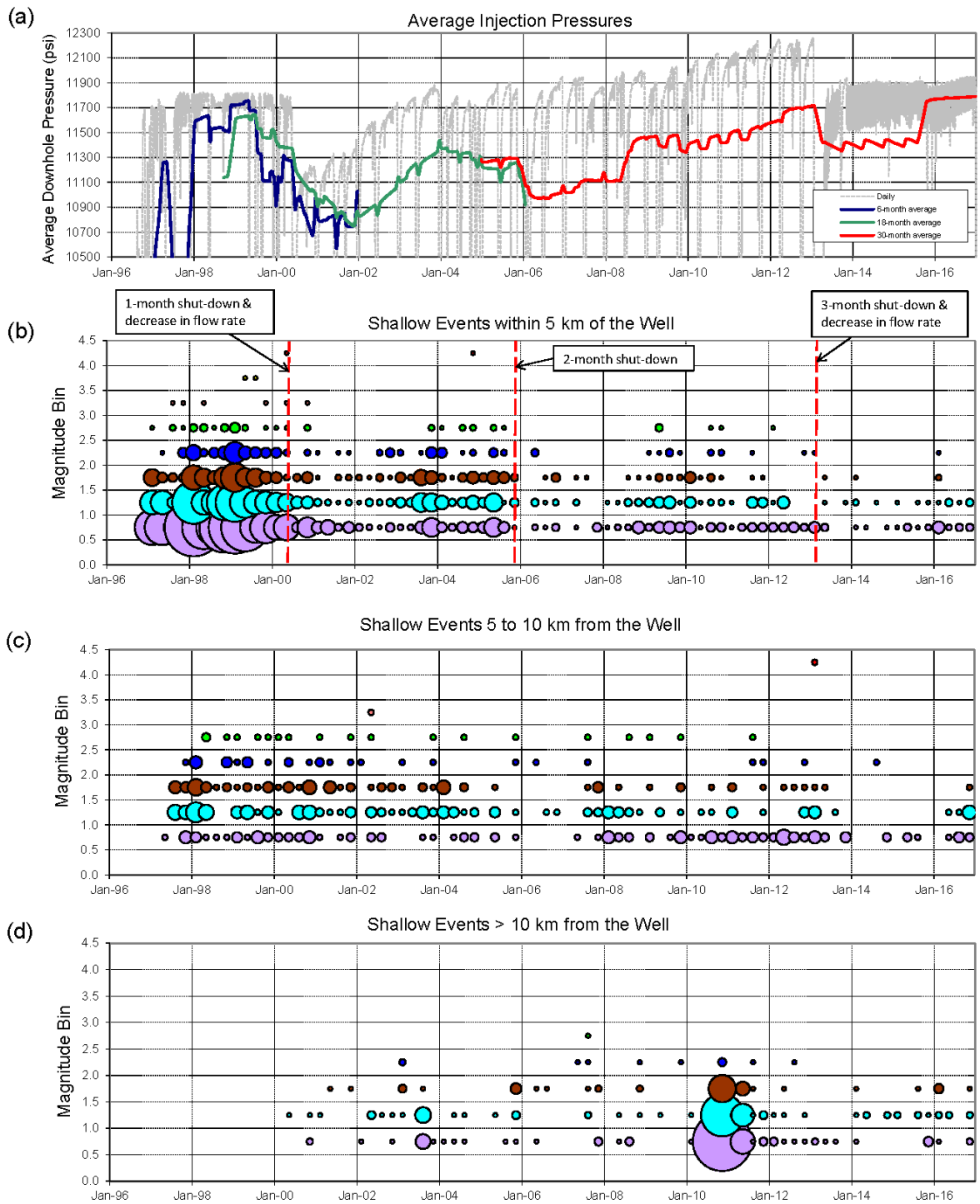


Figure 4-6: Injection well downhole pressure data averaged over daily, 6-month, 18-month, and 30-month time periods (a) and occurrence of shallow seismicity (depth ≤ 10 km) as a function of date and magnitude: within 5 km of the injection well (b), at distances of 5 to 10 km from the well (c), and more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

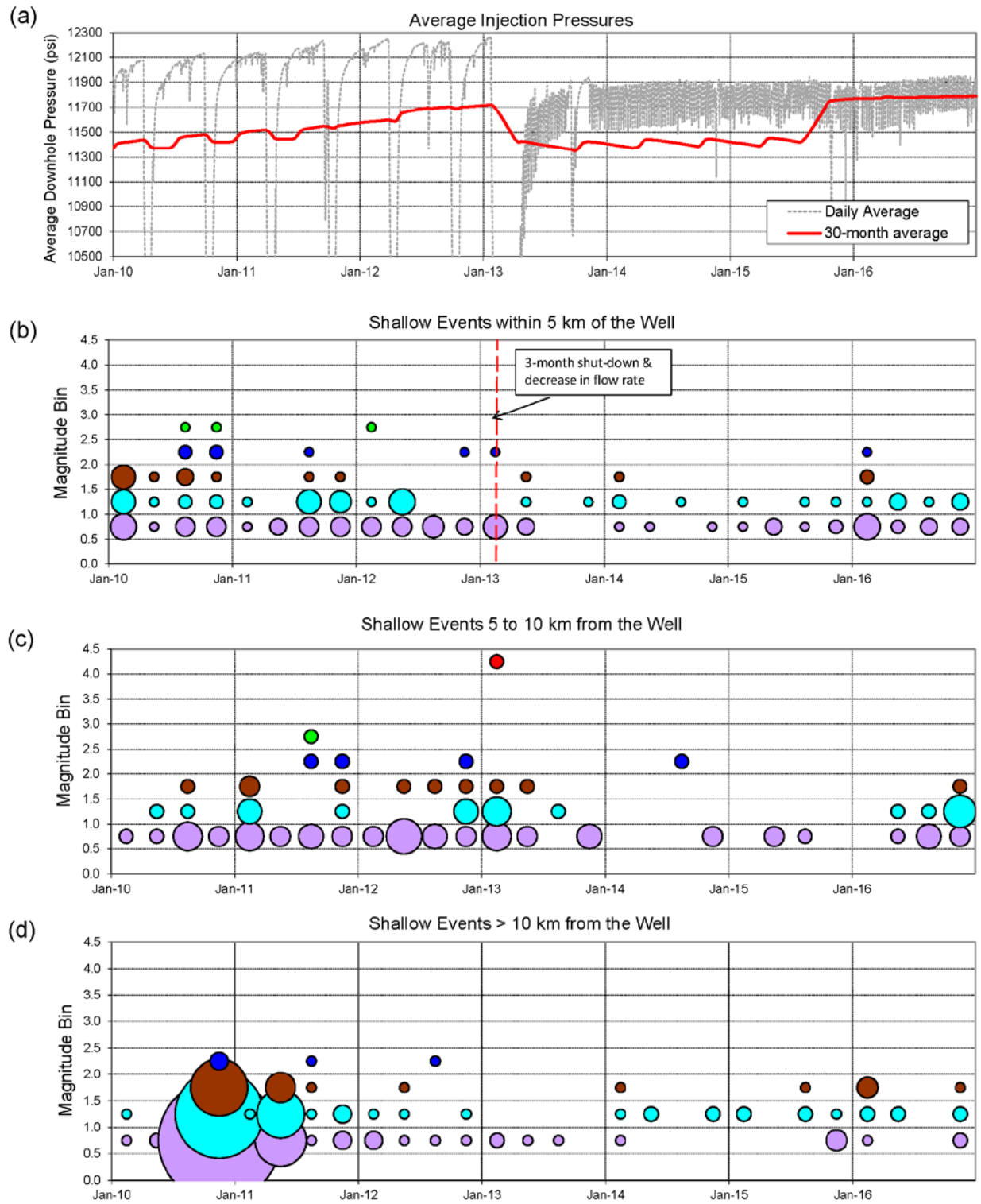


Figure 4-7: Same as Figure 4-6, but only showing data from 2010-2016.

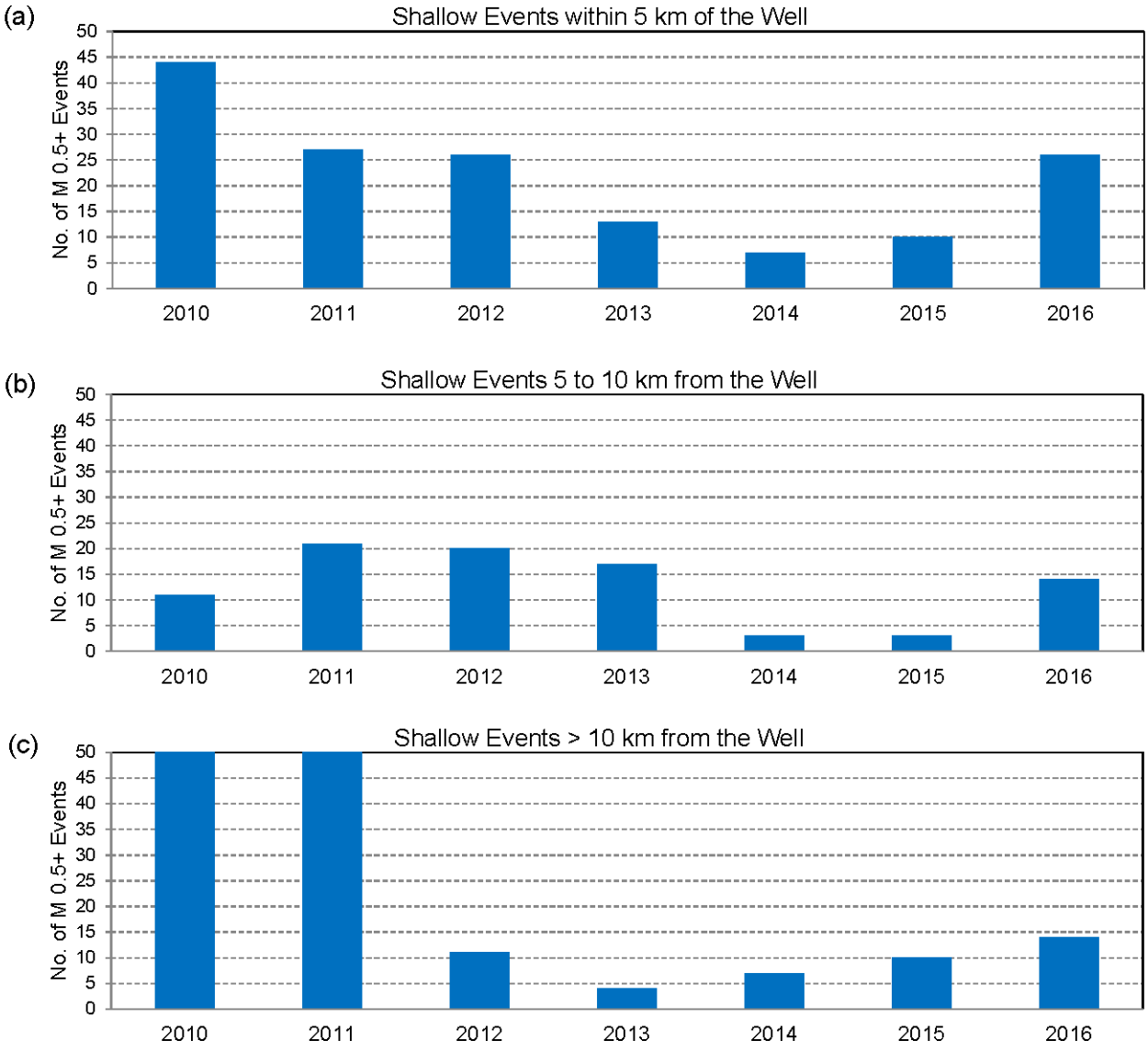


Figure 4-8: Annual number of shallow earthquakes (depth ≤ 10 km) with $M_D \geq 0.5$: within 5 km of the injection well (a), 5 to 10 km from the well (b), and more than 10 km from the well (c). Data from 2010 to 2016 are shown. High counts in 2010 and 2011 for events more than 10 km from the well are clipped.

5 Publication

In 2016, Reclamation published one paper in a professional peer-reviewed technical journal. The paper is titled “Pressure/Flow Modeling and Induced Seismicity Resulting from Two Decades of High-Pressure Deep-Well Brine Injection, Paradox Valley, Colorado”. It was published in the September-October 2016 issue of *Geophysics*, a journal of the Society of Exploration Geophysicists (King et al., 2016). This paper presents the results of pressure/flow modeling that was conducted using injection flow rates and surface pressures that have been recorded at the PVU injection well since the beginning of long-term injection in 1996. The modeling suggests that reservoir properties such as permeability may have changed near the well in the early years of injection, but that they have remained approximately constant over at least the last ten years. The paper also shows that the geographical expansion of induced seismicity is consistent with a simple 1D pore pressure diffusion model. The pressure/flow data and the spatiotemporal patterns of induced seismicity are both consistent with far-field reservoir pressurization, rather than near-wellbore reservoir degradation. Hence, cleaning or reworking the existing injection well would be anticipated to have minimal effect on the wellhead pressures. The analyses presented in this paper were performed in support of the PVU Alternatives Study.

6 Conclusions

The rates of PVU-induced seismicity increased in all distance ranges in 2016 compared to recent years. The rate of M 0.5+ earthquakes observed within 5 km of the injection well rebounded abruptly in 2016 after having remained low for the previous three years. The 2016 rate was 160% higher than that experienced in 2015 and the same as the rate experienced in 2012, prior to the extended shut-in of the injection well and decrease in flow rate implemented in early 2013. The rate of M 0.5+ earthquakes occurring between 5 and 10 km from the well increased 367% compared to the previous year and was 81% of the average rate experienced during the three years prior to the change in injection operations (2010 to 2012). The rate of M 0.5+ earthquakes occurring more than 10 km from the well increased 40% in 2016 compared to 2015, continuing a trend of increasing distant seismicity rates that has been observed since 2013.

The maximum earthquake magnitudes also increased in 2016 compared to 2015. For earthquakes occurring within 5 km of the injection well, the maximum magnitude increased from M_D 1.1 in 2015 to M_D 2.1 in 2016. In the 5-to-10-km distance range, the maximum earthquake magnitude increased from M_D 0.9 in 2015 to M_D 1.5 in 2016. For the earthquakes occurring more than 10 km from the well, the maximum earthquake magnitude increased from M_D 1.6 in 2015 to M_D 1.9 in 2016.

The rebound in seismicity rates and increasing earthquake magnitudes observed in 2016 suggest that the beneficial effects of the extended shut-in of the injection well and operational changes implemented in 2013 on the induced seismicity are diminishing. Wellhead pressures have also been increasing more steadily since early 2016. The trends of induced seismicity and pressures observed since the PVU operational changes were implemented in 2013, including the increase in rates and magnitudes of earthquakes observed in 2016, are analyzed in more detail in Block (2017).

7 References

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Appendix A

2016 Site Visit Reports

Paradox Valley Seismograph Network
Site Visit Report

Site Visit No: PVSN-2016-1 Departure Date: 02/08/2016 Return Date: 02/13/2016

Prepared by: Mark Meremonte

PURPOSE:
Trip undertaken to upgrade backup Earthworm (EW) data acquisition system at Nucla Comm Hub, repair strong motion stations, install two demonstration seismographs: one a short period and the other a strong motion, test cellular and ADSL modems, and review ambient RF signals.

WORK SUMMARY:
At Nucla Comm Hub, decision made to keep the real-time data acquisition systems of Scream and Earthworm on separate computer servers: Scream on Windows 2008 server system and Earthworm on a Penquin Linux CentOS server. Earlier the plan was to put both on the Windows 2008 server platform to simplify remote management and physically reduce hardware maintenance. However, following subsequent discussions about software performance, operations, and maintenance, it made sense to retain the separation of servers/platforms. Therefore, new Penquin server installed running Earthworm V7.7 which will be used as a backup trigger archive to primary Denver Earthworm V7.7 data acquisition production system.

The three strong motion stations – PVEF, PVPP, PVCC -- were visited and repaired. However, due to several spare failed legacy POTS (analog phone) communication equipment in succession, PVCC was unable to be configured as the others but, because of the availability of Asymmetric Digital Subscriber Line (ADSL; data communications technology that enables faster data transmission over copper telephone lines rather than a conventional voiceband modem), it was configured to interface over ADSL connection using a Lantronix serial-to-IP converter (see Figure 8) to provide continuous real-time data. Therefore, station is operating provisionally until BOR IT Security approves the ADSL modem use and BOR's DMZ (network demilitarized zone is a physical or logical subnetwork that contains and exposes an organization's external-facing services to a larger and untrusted network) is configured to allow dataflow into the PVSN Denver Earthworm production system. At that point, the strong motion data can be integrated with the PVSN Earthworm real-time data acquisition production system providing additional important data.

Major push for this PVSN visit was installation of two demonstration seismographs which may be used as successors to the legacy Guralp DM24/CMG-40T and K2/FBA-23 seismographs. The seismographs were provided by Refraction Technology, Inc. (RefTek) and consisted of a 24-bit digitizer (RT-130S) paired either with a short-period velocity transducer (GeoPhone-2Hz) or micro-mechanical accelerometer (MEMS-147A). Data recorded will be integrated and compared/analyzed with current PVSN data to evaluate suitability of systems for possible instrumentation replacement/upgrade candidates. The RT-130S/GeoPhone-2Hz seismograph was installed at PV02 (Figures 1-4) and the RT-130S/MEMS-147A accelerograph (Figures 5-8) was installed at PVCC.

Fig. 1 – 2Hz GeoPhone on concrete base.

Fig. 2 – 2Hz GeoPhone with sealed cover.

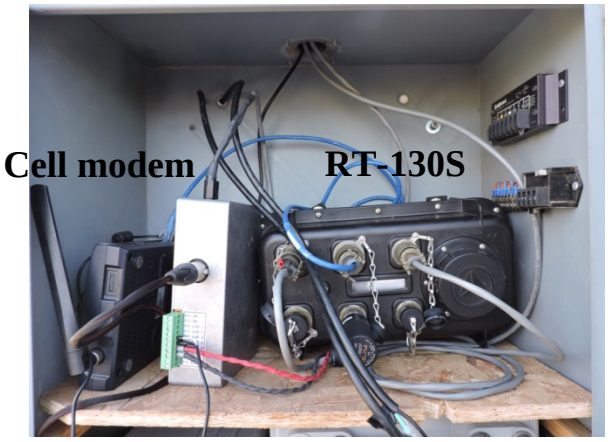


Fig. 3 – RT-130S RefTek logger with cell modem.

Fig. 4 – Solar power regulator charging.

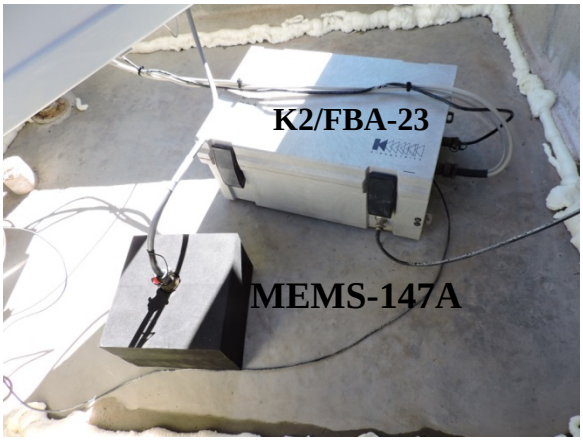


Fig. 5 – MEMS-147A accel. with K2 logger.

Fig. 6 – RT-130S RefTek logger with ADSL modem

Fig. 7 – ADSL modem (bottom) and router (top).

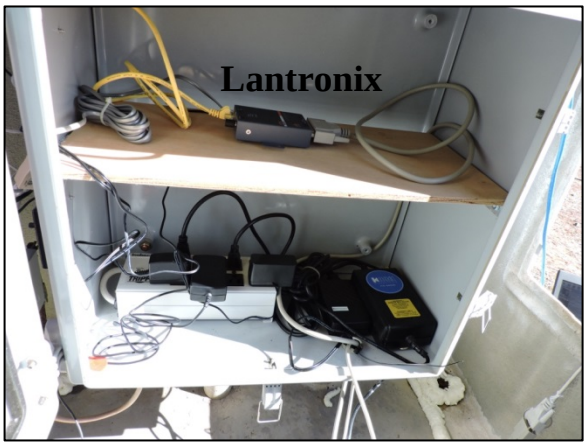


Fig. 8 – K2 connected to Lantronix serial-to-IP.

Second major push was to test cellular and ADSL communications within the Paradox Valley region. Working with the Nucla-Naturita Telephone Company (NNTC), we installed a cell modem at PV02 and an ADSL modem/router at PVCC to provide continuous real-time data recording of the demonstration seismographs described above. Once IT Security approves dataflow through the BOR DMZ, we can begin review of the data and robustness of cellular communications. In addition, if cell modem usage is a success, then we can plan/proceed to test cell modem communication at a repeater site (such as at PV02) to review if cellular bandwidth can handle data throughput from at least 3 stations and also check if communication dropouts can be reduced or eliminated by bypassing Nucla Comm Hub and FAA communication systems altogether (see next paragraph for further discussion of FAA comm system).

We also performed a review of ambient RF signals in the vicinity of the Nucla Comm Hub to help understand the nuances of RF signals related to communication dropouts which the network has been exhibiting since move to new communication tower. Much discussion has been undertaken about this problem with NNTC owner/manager, FAA representatives, and RF Engineers. One fact that resonates from these discussions is the FAA's change of communication technique on new tower to ADS-B (Automatic Dependent Surveillance-Broadcast) system and use of higher power RF signals from the outdated communication technique used on the old tower. A second fact is that the PVSN coax cables installed on tower pass through the lobe (large doughnut-shaped lobe) of the FAA's Omni RF signal which may cause signal degradation as the signal flows over coax between our antennas on tower top to radios in the comm hub. To test whether signal degradation is due to the FAA communication system, cavity filters designed to eliminate FAA frequencies are being built and will be installed.

In addition, a review of RF signals at PV02 verified that Verizon 980 MHz signal is available at site from an azimuth of south-southwest. This verifies that Verizon is not available from Gobbler's Knob whence NNTC's local cell signal emanates but does offer opportunity to test a Verizon (DOI's contract cellular service carrier) activated cell modem for use with seismic systems with link through the BOR DMZ to PVSN Earthworm system.

I want to thank Glenda Besana-Ostman, Mike Gilliam, Justin Schwarzer, Scott Cartwright, NNTC (Kent Tomlinson, Chris Tomlinson, Todd), and RefTek for their hard work and professionalism. NNTC has provided demo Cell and ADSL systems to enable real-time comm connections and RefTek has provided

the demo seismic systems and their server to enable data to be recorded while we complete BOR IT authorization to receive data though BOR firewall to DMZ systems.

PERSONNEL:
Glenda Besana-Ostman, Mike Gilliam, Justin Schwarzer, and Mark Meremonte

ACTIVITIES BY SITE:
Nucla Comm Hub:

- installed Penquin Server with EW V7.7
  - running in parallel with original system (with in-house EW software)
  - setup to interface with VM Scream V4.0 server in Denver over T1 line to bypass Nucla Scream server with V3.1 switch
- KVM needs to be replaced.

Strong Motion stations:

- PVEF: reinstalled and operating over POTS (analog phone) link
  - FBA-23 oriented to GN (geographic North)
  - Shelter cleaned and re-caulked
  - ADSL from NNTC is available here

- PVPP: operating over POTS link
  - Found circuit breaker blown again (2nd time I know of)
  - Shelter needs to be cleaned and re-caulked
  - POTS line needs to be restrung and buried
    - NNTC able to perform this job
  - ADSL is available here

- PVCC: Provisionally operating (data flowing but not able to be accessed at this time)
  - ADSL: ADSL service installed by NNTC for demonstration purposes
    - ADSL modem and router w/ 4 ports installed

  - SM Station Comm: with ADSL filter, tried several modems and TMC5s here w/o successful comm over traditional POTS link
    - Before ADSL, modem/TMC5 system was also unable to communicate over traditional POTS link
    - SM system at office unable to maintain link over either comm link
    - Therefore setup SM station with Lantronix device to provide continuous real-time record

        - For this link to be active, need to get authorization from BOR IT security to Rx data thru firewall to DMZ EW system
        - Once RFC (Firewall Change Request) is accepted we can begin to receive real-time data & incorporate into routine EQ location analysis

    - PVSM: Demonstration RefTek (Refraction Technology) RT-130 datalogger and MEMS-147A accelerometer installed here in parallel with K2/FBA-23 system
        - Station setup as PVSM (PV Strong Motion)
        - RT-130 logger supports TCP/IP stack and connected to ADSL router to Public Network
        - Data are flowing to RefTek RTPD (RefTek Transport Protocol Deamon) server at their Dallas, TX, office
        - Once RTPD ports are opened on BOR Firewall, we will receive data on our DMZ RTPD server
        - Then will be able to incorporate data into PVSN and SMMP (Dam Safety SM Program) routine activities and review instrumentation and data

Broadband Stations:

- PV02: station is operating (access to site was thru much snow; chains required on all 4 wheels)
    - Reviewed solar regulator and batteries
    - System is operating properly and within parameters: 13.3V batteries; 2.9A solar amps; 0.5A load amps or 7W power usage
    - Yes, the battery terminal blocks are gas fuse versions
        - May want to replace with original car bladed version fuse blocks
        - Some thought that the gas fuse versions may be problematic causing station to die in cold temps
        - Did not have time to replace on this visit

    - Cellular: NNTC 1.8 GHz Cell modem installed in old analog shelter for demonstration purposes
        - 3G cell service setup with comm link to NNTC cell tower on Gobbler's Knob ~4 mi distant
        - Signal strength is ~35db (very good)

    - PVSP: Demonstration RefTek (Refraction Technology) RT-130 datalogger and Geophone Short Period 2 Hz velocity transducer installed here in parallel with Guralp DM24/CMG-40T system
        - Station setup as PVSP (PV Short Period)

        - RT-130 logger supports TCP/IP stack and connected to NNTC cellular Public Network
        - Data are flowing to RefTek RTPD (RefTek Transport Protocol Deamon) server at their Dallas, TX, office
        - Once RTPD ports are opened on BOR Firewall, we will receive data on our DMZ RTPD server
        - Then will be able to incorporate data into PVSN routine activities and review instrumentation and data

PVSN Communications Analysis:

- Mike Gilliam & Justin Schwarzer performed RF analysis at both Nucla Comm Hub and nearby PV02
    - Mike's analysis is described in "Radio Frequency Survey Summary" section below.
    - Brief analysis summary:
        - FAA Freqs most likely problematic especially when transmitting at 750 MHz
        - Verizon cell service likely available at PV02 repeater site

- NNTC discussion with Kent Tonlinson (owner/manager) and Mark Meremonte & Glenda Besana-Ostman
    - FAA implemented new ADS-B (Automatic Dependent Surveillance-Broadcast) aviation communication system when transferred from old to new tower
        - https://www.faa.gov/nextgen/programs/adsb/
        - System uses 2 frequencies at 798 and 1090 MHz with power output of 750 Watts
        - Transmits not only to incoming & outgoing local traffic but also to all commercial flights overhead
        - Emphasizes the ADS-B system is very likely the cause of our comm difficulties
        - Agrees that cavity filters designed to remove these FAA frequencies may resolve issue

    - NNTC has reviewed the 3 repeater sites and is confident good NNTC cell coverage exists to each
        - PV02 has good line-of-site at ~4 miles to Gobbler's Knob
        - PV12 has possible 2 hills in its line-of-site of 7.5 miles to Gobbler's Knob
            - but good line-of-site to Paradox cell tower at 9.5 miles
        - PV04 has pretty good line-of-site at ~15.5 miles to Gobbler's Knob
            - and pretty good line-of-site to Paradox cell tower at 3.8 miles
        - Question is whether the signal can handle data usage?

        - At PV02 we have verified good NNTC cell coverage and are currently transmitting PVSP successfully
        - Probable SM stations PVEF and PVCC could connect via NNTC cellular but PVPP too far inside canyon.
    - Local radio company can help maintain communication

- NNTC's comment about State tower and facility on Gobbler's Knob
    - Keep current spread spectrum infrastructure
        - Need to perform spread spectrum RF line-of-site survey from repeaters (PV02, 04, & 12)
        - Gobbler's Knob is higher elevation than airport and more central to PVSN
        - appears good line-of-site to PV01 which transmits directly to comm hub (PV07 & PV15 also transmit directly)
    - Transfer radios and antennas to state facility (computers if necessary)
        - will need to rent space for radios/computers and antennas
    - T1 line can be installed because several already installed
    - No need to maintain infrastructure: HVAC, generator, batteries, gas, electricity
    - NNTC can help install systems especially antennas on tower (have experience and equipment)
    - Local radio company can help maintain system and communication

Radio Frequency Survey Summary – prepared by Mike Gilliam

PVSN Nucla Comm Hub -- 2/10/16, 1400 hrs. local time, Sunny 49 degrees F

<u>Nucla Airfield FM Site Survey</u>
833.889 MHz - 35 dbm
837.963 MHz - 38 dbm
852.778 MHz – 55 dbm
855.778 MHz – 38 dbm
I noticed a strong frequency band between 833 MHz – 855 MHz. This was determined to be the Montrose County Sheriff's Dept. FM radio band. This was a new upgrade from the old 350-400 MHz band that was previously used. This frequency band was also present at PV02. I do not believe this to be a factor in any interference with our GE iNet II communications.

904.444 MHz – 76.9 dbm
905.370 MHz – 64 dbm
906.296 MHz – 77 dbm
910. 370 MHz – 76 dbm
913.704 MHz – 46 dbm
915.704 MHz – 49 dbm
915.741 MHz – 42 dbm

919.630 MHz – 52.5 dbm
922.963 MHz – 77 dbm
923.333 MHz – 47 dbm
925.556 MHz – 59 dbm
926.667 MHz – 56 dbm
926.852 MHz – 49 dbm
These are all within our band of GE iNet II FM radios. 902-928 MHz. This is indicative of frequency hop. I observed our 3 GE iNet II radios hopping within this band as expected. PV02 recorded similar values. No interference was recorded at PV02 in 902-928 MHz band.

930.00 MHz – 63.3 dbm
931.111 MHz – 67.5 dbm
This will require further research with FCC to determine the operator of this frequency and its purpose. However, due to low dbm strength, it is not indicative of interference. I will follow up with my research on these frequencies.

978 MHz, 1030 MHz * 2/10/16 Nucla, 2/11/16 PV02
Prior to departure, I did some research on the new FAA "ADS-B "Nextgen National Airspace Strategy. According to local sources (NNTC Techs, Airfield Contacts), the FAA utilized implementing new ADS-B communications when we built the new communications tower at Nucla in 2012/2013. The frequencies of ADS-B were confirmed by the FAA RF Contractor, Harris, to be 978 and 1030 Mhz. Power output was confirmed to be 750 Watts Max. After discussing with our engineering contractor, VLF Designs, it was determined that the 978 MHz frequency at 750 Watts would be problematic for our GE iNet II FM radios at 902-928 MHz. This would correspond with our increase in dropouts after moving to the new tower. As well, looking over photos and observing the differences between the old tower and new tower, a few things stood out – the Omni antennas on the new tower are below our FM antennas. On the old tower, the FAA Omni antennas were substantially above our FM Yagi and Omni antennas.

Observations with FM Analyzer:
978 MHz was not observed during my survey. More research into this frequency determined that 978 MHz is a location frequency for ADS-B. Commercial Aircraft can utilize the Nucla tower to "confirm" their location and correlate that with their in air GPS. This would explain why the band was not observed as no aircraft were in the area during my survey.

1030 MHz was observed.
1030.556 MHz – 66 dbm
This strength is low compared to our dbm observed on the GE iNet II radios at the Nucla Hub. The 1030 was constant and at low power. I believe this to be somewhat of a "transponder" type device. Further research is required.

In conclusion, I still think it is a good idea to contact the operator at the Nucla Airfield to try to correlate drop outs with commercial aircraft fly overs that use the 978 MHz ADS-B frequency for position fixes. The 750 Watt output for 978 MHz would make sense for transmitting information to aircraft at altitudes above 30k feet. I did notate some Dates/Times of commercial aircraft flyovers during the field time in Nucla, Naturita, and Paradox. This could be confusing, as my interpretation of

ADS-B is that it is an option for aircraft that fly over, not a requirement. This would correlate with random drop outs. Seasonal drop out patterns would as well correlate with seasonal flight patterns and schedules from Denver to West Coast and vice versa. I will continue research.

On a positive note: An inline cavity filter is a possibility that has been confirmed with our engineering contact and TESSCO (FM Radio US GOV Contractor). I am working on a design of in line cavity filters to block out all frequencies to our GE iNet II radios except for 902-928 MHz. Another field exploration trip will be required to test the filters at Nucla Hub.

Gobbler's Knob: Discussed with NNTC about use of Gobbler's Knob State of Colorado tower above Paradox Valley as central receive point.

GX450 Verizon Sierra Wireless Cellular Survey:

PVSN PV02 -- 2/12/16, 1430 hrs, Sunny, 50 degrees F

GX450 Modem Test:

Rabbit Ears

RSSI: -69
RSRP / LTE: -95
4G
RSRQ: -9

Omni Antenna w/ Diversity

RSSI: -71
RSRP / LTE: -99
4G
RSRQ: -11

YAGI (no diversity)

RSSI: -69
RSRP / LTE: -108
Orientated to 175 degrees magnetic was best signal.
Quality was very poor across the board.

Thoughts:

PV02 could be used as a data uplink site for surrounding stations to upload FM data via wireless to Denver.

Paradox Valley Seismograph Network
Site Visit Report

Site Visit No: PVSN-2016-2 Departure Date: 06/22/2016 Return Date: 06/29/2016

Prepared by: Mark Meremonte

Personnel: Glenda Besana-Ostman, Mike Gilliam, Justin Schwarzer, Mark Meremonte

Work Summary:

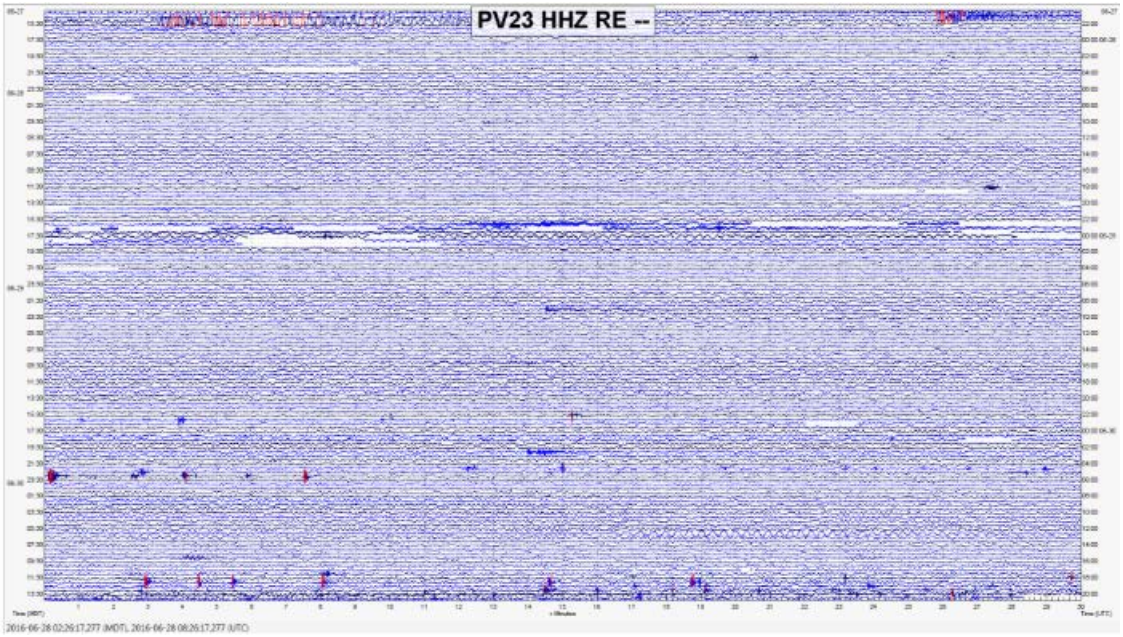
June 22:

- Drove to Paradox, CO
- During drive discovered Comm Hub Generator failed to power on during a planned power outage
    - Had Dan Gunns Generator Repair in Grand Junction call Brad Mckinney at airport
    - Turns out radiator fluid level sensor detected fluid low due to fluid moving to overflow reservoir by air expansion in radiator stemming from the high air temps.
    - Addition of water in radiator by Brad resolved issue and generator powered up just in time before the APC units' batteries were exhausted.
    - Dan Gunns will visit sight in August to perform PM and review radiator ==> possibly install higher PSI pressure cap (14 to 20 psi) to prevent similar condition in future
    - Now scheduled with him to perform 2 PMs per year instead of one
- Stopped at PV21 along the way: (station has been down since 23 March 2016)
    - Initial state of DM24_BoB w/ upgrade fuses:
        - Radio transmit (TX) LED -- Solid on
        - DM24 TX LED -- off
        - DM24 DC-clean -- (did not check)
        - GPS_BoB LED -- no pulsing, Solid on
    - Power cycled DM24_BoB to resolve comm issues with DM24 logger
        - DM24 & GPS returned to normal operations
        - did not replace DM24 because already has upgraded BoB installed
    - Bear heavily damaged GPS cable conduit; see figures below:

        - Repaired conduit with new conduit section
        - Fortunately GPS cable still intact but needed to be taped to protect
    - Reviewed antenna azimuth to PV04 ==> good S/N & good Signal strength:
        - RF Power 30 db; S/N 25 db; signal strength -78 to -82 db ==> good
        - However, PV21 still exhibiting significant gaps in data flow to PV04
        - May raise PV04 tower top 5' to accommodate better line-of-site to all remote stations transmitting to this access point (AP) including PV21
    - Future: wrap tower base/shelter with 2"x 4" welded wire to possibly help mitigate bear damage.
    - Future: replace battery gas fused Wago blocks with blade fused Wago blocks
        - solar side already has a blade fused Wago block installed
        - Comment: The battery gas fused blocks may be contributing to night time outages in the winter

June 23:

- PV23:
    - Discovered voltage drop across battery gas fuses of 0.4-0.6 volts ==> significant
        - Thus after dark when charging disengages, voltage available to system for overnight operation is already ~ 0.5V lower
        - then at some point when batteries drop to 11.9V the solar regulator thinks the voltage is at 11.4V which is its internal LVD and system shuts down till sun shines again
    - battery gas fused Wago blocks replaced with blade fused Wago blocks to resolve issue described above
        - Comment: The battery gas fused blocks may have been also contributing to night time outages in the winter
    - All 3 batteries replaced
    - Subsequent review over past 3 days indicate system not shutting down at night anymore:



- PV04:
    - Installed Cu braided cable among existing Cu rods and Cu/Al splice to create ground star array to prepare for installation of 2 spline balls in future.
        - Note: Cu rod star array wire configuration needs to be adjusted.
        - Need Matrix-5 spline ball mount here.
    - May raise tower top 5' to accommodate better line-of-site to all remote stations transmitting to this AP including PV21
    - Note: both solar and batteries already have blade fused Wago Blocks

- Nucla Comm Hub
    - Installed bandpass filters to attempt filtering out FAA frequencies
        - As a result of powering down these APs, the PV02, 04, 12 repeaters and direct transmit stations PV01, 07, 15 tried to associate to other radios
        - This period where remote & repeater radios tried to re-associate lasted approximately from about 9:30 am to Noon MDT.
    - Removed defunct old EW Penquin server (New EW V7.8 Penquin server installed last October 2015)

June 24:

- PV05:

    - Completed ground star configuration with Cu braided cable; no spline ball required here because not highest point in area

- replaced 5-element Yagi with 6-element
  - Reviewed antenna azimuth to PV02 ==> fair S/N & fair Signal strength:
    - RF Power 30 db; S/N 24 db; signal strength -87 to -89 db ==> Fair
    - After raising PV02 tower top 5', RF Power 30 db; S/N 25-26 db; signal strength -84 to -87 db ==> Better!
- All 3 batteries replaced
- Note: both solar and batteries already have blade fused Wago Blocks
- S13 short period seismometer removed.

- PV10:
  - Unable to install Cu rods for proper ground star array
    - Cu plates will be needed here to complete star array as configured at PV22 (see below)
    - Install spline ball here with a DAVIT type mount
  - S13 short period seismometer removed.

- PV19:
  - Road to site is worst I have seen -- 3 large deep ditches (consider ATV in future visits)
  - Completed ground star configuration with Cu braided cable; no spline ball required here because not highest point in area
  - Note: both solar and batteries already have blade fused Wago Blocks
  - Wrapped tower base/shelter with 2"x 4" welded wire to possibly help mitigate bear damage: (Note: 2nd photo is of PV02 Repeater site wrapped in welded wire)

June 25:

- PV22: (station down since 26 December 2015)
    - Initial state of DM24_BoB w/ upgrade fuses:
        - Radio TX LED -- Solid on
        - DM24 TX LED -- off
        - DM24 DC-clean -- 5.3V (should be 13.6V)
        - GPS_BoB LED -- no pulsing, Solid on
    - Power cycled DM24_BoB to resolve comm issues with DM24 logger
        - DM24 & GPS returned to normal operations
            - However, later DM24_BoB appeared to stop operating with both Radio TX and DM24 TX LEDs displaying solid red
            - Therefore replaced it with another DM24_BoB w/ upgrade fuses ==> system operating again
                - Will test this replaced DM24_BoB back in lab; may have been pilot error because of bad connection from PC using wrong com port of 3 instead of 4.
    - GPS_BoB was replaced last 05 August 2015
        - However unable to remove due to special headed Torx bolts
        - That Bob removed now and good BoB now installed properly
        - Old BoB has broken power wire which needs to be repaired.
    - As similar w/ gas fused blocks at PV23, there is voltage drop across battery gas fuses of about 0.5V
        - Therefore, battery gas fused Wago blocks replaced with bladed fused Wago blocks
    - Completed grounding system:
        - 3 Cu 14"x 14"x 1/4" plates installed to create star array
        - Spline ball installed using Matrix-5 mount and Cu/Al splice:

- While here we tested various other instrumentation:
  - Tested spare CMG-40TD:
    - Z, N, E components are good but DM24 internal clock is unable to sync to GPS
  - Tested 5 newer design Guralp GPS antennas of which 3 upgraded with new chips and internal batteries by Matriix-5 and 1 older, fatter style Guralp GPS
    - All tested fine
  - Tested 5 DM24_BoBs including test unit used by Matrix-5
    - All tested fine (Note: Radio & DM24 TX LEDs on Matrix-5 test unit are burnt out.
- Reviewed antenna azimuth to PV12 ==> Good with good S/N & good signal strength:
  - RF Power 30 db; S/N 26 db; signal strength -78 to -83 db ==> good
  - However, PV22 still exhibiting numerous gaps in data flow to PV12
  - May raise PV12 tower top 5' to accommodate better line-of-site to all remote stations transmitting to this AP including PV22

June 26:

- PV02:
  - Raised tower top 5'
    - Thus Yagi to Nucla Comm Hub raised 5’ and Omni to PV05 & PV13 raised 4’; could raise it another 1’ if needed.

-

    - After couple of days of data review from stations on PV02 repeater the numerous dropouts on PV05 are gone. Here is past 24 hour record for these 3 stations:

    - Of course will monitor for a period of time to completely satisfy myself that raising Omni 5' has resolved the dropouts permanently
        - If this pans out, I will entertain possibility of raising tower tops at other repeater stations (PV04 & 12) and at PV20 which is low for both these repeaters.

- Battery gas fused Wago blocks replaced with blade fused Wago blocks in both shelters.
    - Solar side already has blade fused Wago block

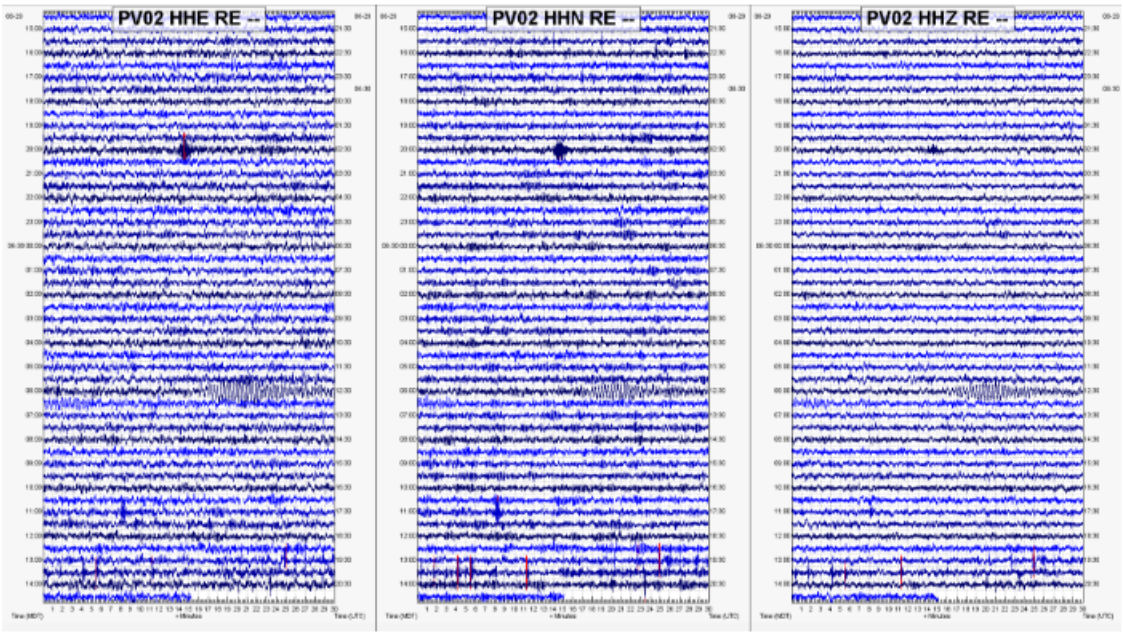
        - Comment: The battery gas fused blocks may have been contributing to night time outages in the winter
    - Wrapped tower base/shelter with 2"x 4" welded wire to possibly help mitigate bear damage
    - Removed demonstration RefTek SP station PVSP:
        - Bear damaged external 3-battery bank installed in Rubbermaid box
            - Box was rolled over and hot wires torn loose & free
            - Subsequently the wires shorted and melted plastic wire jacket inside old analog electronic shelter
            - A small corner of the RefTek datalogger was melted in process but all other instrumentation (NNTC's cell modem & Steiner power pack) in good shape
            - Fortunately, the 3 internal batteries were still operating, being charged by solar system, and powering the instrumentation.

        - Temporary Solar panels removed and were not damaged by bear
        - The SP seismometer was removed and not damaged by bear either
            - Our temporary underground vault performed well with no water getting inside vault
            - Vault base still level and oriented properly
            -

June 27:

- Reviewed PV04 & PV12 S/N & Signal strengths
    - PV04 -- RF Power 30 db; S/N 19 db; signal strength -92 to -97 db ==> not good
        - These are not good values for S/N & signal strength and easily could contribute to non-robust comm
        - Good indicator that tower top may need to be raised 5'
    - PV12 -- RF Power 30 db; S/N 20 db; signal strength -90 to -96 db ==> not good
        - These are not good values for S/N & signal strength and easily could contribute to non-robust comm
        - Good indicator that tower top may need to be raised 5'

- PV02:
    - Returned to attempt swap of seismometer:
        - The interest was to install spare and then swap the digitizer caps which contain the internal clock mechanism because spare internal clock unable to sync to GPS unit.
        - However, on opening both systems, their internal design was different to point unable to swap circuit boards
        - Therefore, returned original seismometer to vault
    - Note: After returning original CMG-40TD to the vault and subsequent reviewing of system past several nights, it is apparent that Z-component is behaving better now
        - On initial return of seismometer to the vault, the large erratic amplitude ceased returning to a normal/nominal amplitude consistent with other stations with still some non-seismic behavior
        - However, over next several hours the system began to behave better. Below is figure for PV02 3 components over past 24 hours (HHZ-vertical, HHN-North/South, HHE-East/West):



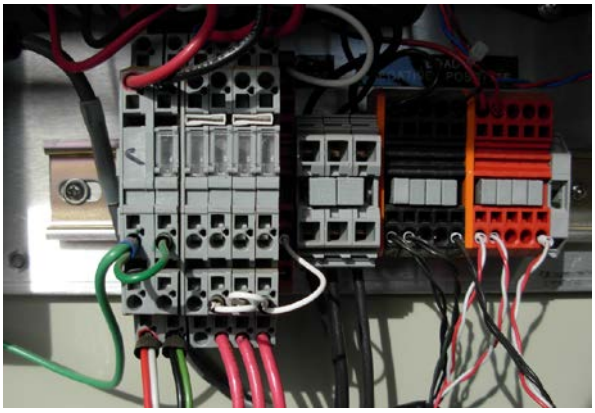
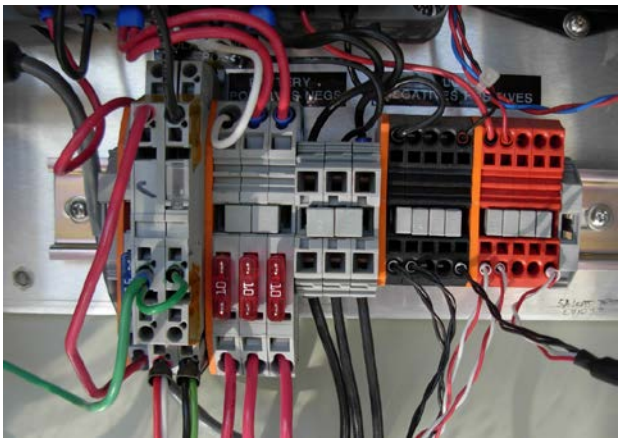
- Note: In my past experience in the late 1990s, it was discovered that the CMG-40Ts' mass had a tendency to stick to one side due to excess glue or heat causing the glue to be more tacky. On some of our old CMG-40Ts we had a small, thin piece of film added to prevent this from happening. We also discovered that shaking the seismometer sometimes broke the mass loose. Thus I believe our strong handling of system may have helped return the system to normal operations

- PV13:
  - Completed ground star configuration with Cu braided cable with Cu/Al splice prepared to receive spline ball using Matrix-5 type mount
    - Future: Because these rods are short (< 4'), we will install 3 Cu plates here to provide more robust grounding
  - Battery gas fused Wago blocks replaced with blade fused Wago blocks
  - Blade fused Wago block added to solar gas fused blocks
  - All 3 batteries replaced
  - S13 short period seismometer removed

- SM Stations:
  - Swapped CFlash cards at each of the 3 SM stations
    - Only 1 trigger found on PVEF system -- it was man-made noise
  - Removed demo RefTek SM station PVSM

June 28:

- PV01:
    - Reviewed antenna azimuth to Nucla comm hub Omni ==> fair S/N & fair signal strength:
        - RF Power 30 db; S/N 23 db; signal strength -87 to -88 db ==> Fair
        - There is a heavily treed ridge between here and airport; cannot see airport from top of tower
        - Future: May need to raise Yagi antenna higher to obtain better line-of-site to Nucla comm hub Omni
    - Battery gas fused Wago blocks replaced with blade fused Wago blocks
    - Blade fused Wago block added to solar gas fused blocks

    - All 3 batteries replaced
        - Note: We only had two new 2016 batteries so one battery was replaced by a battery dated 2012
    - S13 short period seismometer removed.
        - Both batteries of old analog system removed & solar system disabled
    - Future: Need to install at least 2 Cu rods (or Cu plates) here to complete ground star configuration with Cu braided cable; no spline ball required here because not highest point in area
    - Comment:
        - It is apparent this station is located too low on ridge with no line-of-site to Nucla Comm Hub for this 900 MHz freq; it was fine for lower analog freqs used
        - Just a half mile up the road/ridge is a high point on same ridge with more good line-of-site but will test first if we ever want to move it.

- PV07:
    - GPS failed here: (last good time approx. 29 May 2016 @ 20:00:00 UTC)
        - Note: PV07 GPS previously repaired on 31-JUL-2015
        - Power cycle resolved GPS issue

            - However, still replaced GPS with Matrix-5 tested GPS
                - Will open up failed GPS in the lab to check if it has, indeed, a bad internal battery
                - Comment: possibly a bad internal battery in GPS antenna units is contributing to cause of GPS's failing.
        - Battery gas fused Wago blocks replaced with blade fused Wago blocks
        - Blade fused Wago block added to solar gas fused blocks
        - All 3 batteries replaced
        - Star ground configuration exists here already
            - Future: need to install Cu braided cable, Cu/Al splice, and spline ball using Matrix-5 mount
- PV20:
    - Reviewed antenna azimuth to PV12 repeater ==> fair S/N & fair Signal strength:
        - RF Power 30 dB.; S/N 24 dB.; signal strength -86 to -87 dB. ==> Fair
        - Replaced 5-element with 7-element in July 2015
    - Tried to point to PV04 repeater -- unable to get good S/N & Signal strength
        - RF Power 30 dB.; S/N ?? dB.; signal strength < -95 dB. ==> bad
    - Tried to angle antenna up several degrees direct to PV12 but to no effect
    - Future: may need to raise tower top 5' to provide better antenna line-of-site to PV12
    - Star ground configuration exists here already
        - Future: need to install Cu braided cable; no spline ball here

June 29:

- PVCC:
    - Returned to reformat all spare CFlash cards to keep with Andy Nicholas's office including a CFlash card reader
- Andy Nicholas' office:
    - Discussed this trip's network activities
    - Discussed deteriorated state of SM concrete pads especially at PVPP
        - May move PVPP and PVEF to concrete floors of each nearby facility
        - These floors much better coupled to Earth
        - Also will facilitate connection to ADSL communications
    - Discussed pros & cons of installing NNTC ADSL or connecting WAI Company's ADSL already available in each facility
        - Need to contact WAI IT manager John Adams to discuss
        - Need to complete BOR IT security approval for ADSL and request approval to use ADSL through WAI's connection
    - Discussed procedure to swap CFlash cards on K2s if significant event occurs before
        - Need to write up SOP to perform this operation
        - Need to send driver for Addonics Flash card reader

- Installed Swarm on Andy's office desktop
  - Now able to monitor network and waveforms to see for himself how well data are flowing or not
  - Showed him how to use the program to look more closely at stations and phenomena of interest
- Discussed the deteriorating roads
  - We may purchase a 2-person ATV with cab to better provide efficient and safe access to stations
  - Storage would be at injection well warehouse

Comments/thoughts:

1. The DC-Clean (which is a DC-DC converter) output of the DM24_BoB to the DM24 logger is ~ 13.6V on all DM24_BoBs tested this trip. However, the DM24, itself, also has a DC-DC converter built into it. A review of several DM24 logs I recorded locally at sites show that the voltage delivered to loggers is between 12.0 & 13.0 volts -- quite a spread. In a number of EW Production system logs of older model of the CMG-40TD I have seen voltages down to below 11.0 volts.

In past discussion of the voltage differences stemming from station winter outages I have commented: (see emails of 7 March 2016 on the subject):

> "Scream PV23 logs do show voltage over past year oscillating between 11.2 - 12.6 V whether winter, spring, summer or fall. This is at odds with the DM24_BoB supplying a constant voltage of 13.2V to DM24 digitizer.
>
> Then at PV21, which is a newer DM24, the Scream logs show a constant voltage of 13.2V up to station offline and then again at point station comes back online. Thus voltage information massaged by BoB is completely erroneous with respect to batteries.
>
> At PV02, not sure if newer or older DM24, but the Scream logs show a constant voltage around 13.1V up to offline/online period. Thus, again, voltage information massaged by BoB is completely erroneous with respect to batteries."

Some of these voltage differences is likely due to the DC voltage drop over the power cable to DM24 in the vault which range from 30 to over 60'. Other, due to electronic fatigue.

2. We have been reviewing online experiences, comments, and use of the spline ball.

> Example: "controversy has resulted with the use of spline balls, static dischargers and wicks mounted on antennas and the top of towers. These devices are said to provide a constant discharge thus decreasing the potential for a direct strike. Some users claim a diminished amount of direct hits after installing these devices."
>
> *Reference:*
>
> "The "Grounds" for Lightning and EMP Protection", by Roger Block, published by PolyPhaser Corporation.

At this time, the consensus is that the spline balls provide little protection over a standard lightning rod. They likely do not decrease the ions in the region of influence to reduce the possibility of a lightning strike. I am searching for documentation rather than online discussion. However, at this time I am rapidly coming to conclusion (combined with my 30 years of experience of being involved in permanent and portable seismic installations in the whole of the U.S, Caribbean, Central America, Haiti, Turkey, Am. Samoa, Alaska, Rocky Mountains) to utilize standard grounding techniques with possible use of a simple "blunted point" (not ball) lightning rod at top of the tower with braided cable down to the 3-4 star arrays we are currently installing with more common use of Cu plates (than the 8' Cu rods which are man/woman power exhausting) embedded in combination of soil, sand, & GAF (Ground Augmentation Fill is a combination of organic soil materials which optimize the conductivity of the soil around the Cu plate in our case) or just connect the tower, itself, at its base to a robust ground star array.

Some recent investigations indicate blunted points are better than sharp points. Reading on the subject in Wikipedia I found this info:

> “Calculations of the relative strengths of the electric fields above similarly exposed sharp and blunt rods show that while the fields are much stronger at the tip of a sharp rod prior to any emissions, they decrease more rapidly with distance. As a result, at a few centimeters above the tip of a 20-mm-diameter blunt rod, the strength of the field is greater than over an otherwise similar, sharper rod of the same height. Since the field strength at the tip of a sharpened rod tends to be limited by the easy formation of ions in the surrounding air, the field strengths over blunt rods can be much stronger than those at distances greater than 1 cm over sharper ones.
> ...
> The results of this study suggest that moderately blunt metal rods (with tip height to tip radius of curvature ratios of about 680:1) are better lightning strike receptors than sharper rods or very blunt ones.”
>
> *Reference:*
> C. B. Moore, William Rison, James Mathis, and Graydon Aulich, "Lightning Rod Improvement Studies". Journal of Applied Meteorology: Vol. 39, No. 5, pp. 593–609. Langmuir Laboratory for Atmospheric Research, New Mexico Institute of Mining and Technology, Socorro, New Mexico. April 10, 1999.

Thus, for every instance of future use of spline ball I may end up using an approved lightning rod which can be easily extended to a higher point than the spline ball and I may remove existing spline balls at some sites to facilitate better, higher yagi/omni antenna placement. However, while the differences in function between the spline ball and blunted point are minor, the logistics of replacing the spline balls with blunted points are significant. Similarly, discontinuing the use of the 8' Cu rods and using Cu plates instead would reduce much physical effort and be safer. I (we) are still researching the matter.

3. With preliminary observations, it is apparent that raising the tower top at PV02 has significantly increased robustness of comm signal from PV05 & PV13 to PV02. Jury still out or waiting for more data or time but this may be indication that other repeater and/or station towers may need to be raised to

resolve comm problems. I do not believe extending the booms at the Nucla Hub will resolve the comm issues and, frankly, I am not climbing that tower to uninstall heavy booms and reinstall heavier booms. If there is interest to do this, I recommend hiring a tower outfit.

Paradox Valley Seismograph Network
Site Visit Report

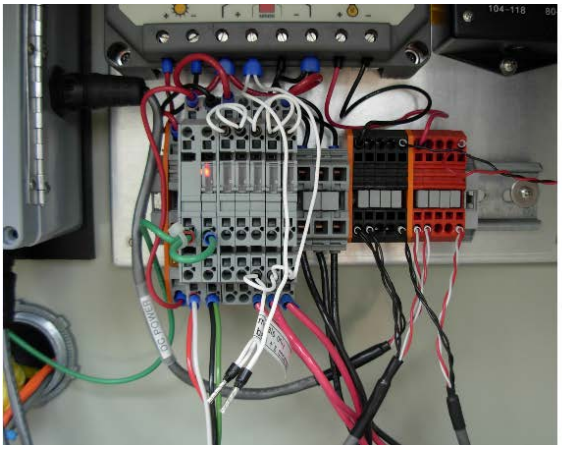
Site Visit No: PVSN-2016-3 Departure Date: 08/09/2016 Return Date: 08/11/2016

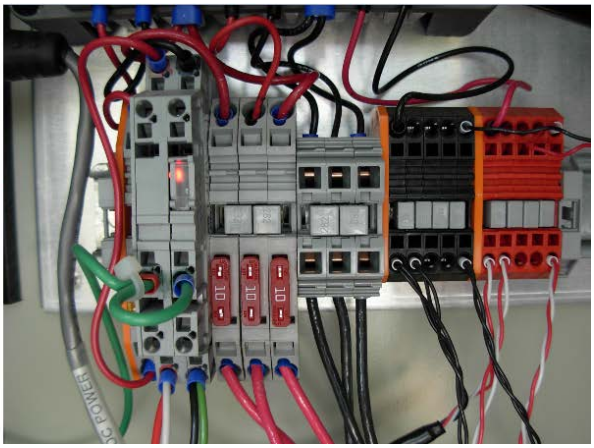
Prepared by: Mark Meremonte

Personnel: Mike Gilliam, Justin Schwarzer, Mark Meremonte

Work Summary:
August 9:

- Drove to Paradox, CO
- stopped at PV21 along the way: (Station powering down at night)
  - Bear slightly damaged GPS cable conduit
    - Repaired conduit
  - Replaced battery gas fused Wago blocks with blade fused Wago blocks
    - Solar side already has a blade fused Wago block installed

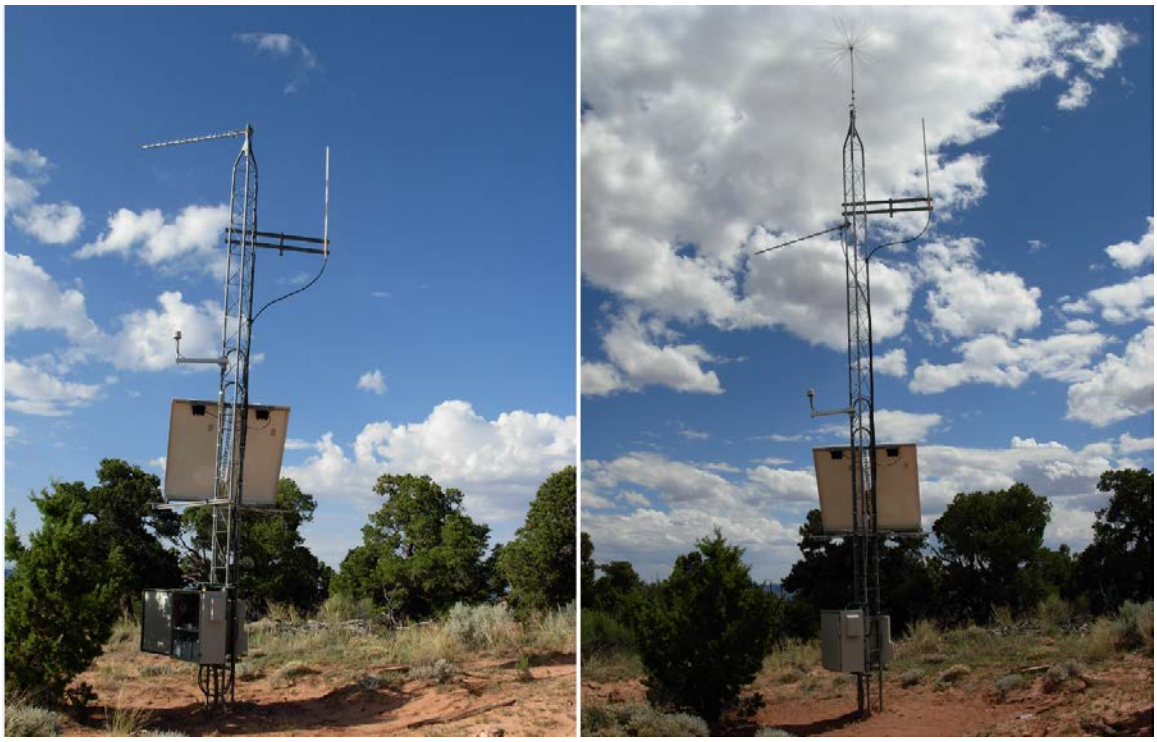




  - Reviewed antenna azimuth to PV04 ==> good S/N & good Signal strength:
    - S/N 25 db; signal strength -78 to -82 db ==> good
    - However, PV21 still exhibiting significant gaps in data flow to PV04
  - Wrapped tower base/shelter with 2"x 4" welded wire to help mitigate bear damage, as shown below.

August 10 & 11:

- PV04:
    - Completed ground star configuration with Cu braided cable and spline ball with DAVIT mount
    - Raised tower top 5' thereby raising Omni antenna enhancing line-of-site to remotes
        - Subsequently reviewed PV21 S/N and signal strength from PV04:
            - S/N 26 db (good); RSSI -78 to -82 db ==> good
            - However, PV21 still exhibiting significant gaps in data flow
    - Raising tower top 5’ did not change height of the Yagi pointed back to Nucla Comm Hub
        - Replaced COAX cable and Yagi antenna due to broken connection when system was removed to raise tower
            - Replaced 18-element (14 dBd) with 20-element slightly higher gain (15 dBd) antenna
        - Subsequently reviewed PV04 S/N and signal strength from Nucla:
            - S/N 18 dB (poor); RSSI -95 dBm (poor)
            - New Yagi had no effect on increasing S/N & signal strength
            -
        - NOTE: On my current readings of non-LOS (Line-of-Site) and LOS environments where it is likely PV04 and PV12 may not have completely LOS conditions, using higher gain antennas on one end or both could be detrimental due to the possibility of signals bouncing and arriving at the antenna from different angles. Thus, on non-LOS conditions, it is desirable to have an antenna with a wide beam width and a lower gain.
    - Future: May be prudent to replace both PV04 & PV12 with lower gain (smaller element) antennas to help overcome non-LOS conditions and/or perform similar at Nucla Comm Hub AP for these 2 repeaters. This will be a topic to discuss with BOR Radio Team.



August 11:

- PV01: (station failed during site visit)
    - Initial state: all systems powered off:
        - Solar regulator indicated low voltage condition w/ no solar power input and power to load severed
        - Battery voltages at 11.3 -11.4V
    - Discovered solar panel fuse block blown:
        - Replaced fuse block to resolve issue
        - Also replaced solar power regulator (ProStar 30) as a precaution
            - Apparently the solar fuse block died 3-5 days earlier with power solely from the batteries; Once batteries reached the LVD (low voltage disconnect) of the solar regulator at 11.4V, the regulator powered down all systems
    - Replaced older 2012 battery that we were unable to replace on last visit
        - Now all 3 batteries are replaced as of summer 2016
    - Future: Need to install at least 2 Cu rods (or Cu plates) here to complete ground star configuration with Cu braided cable; no spline ball required here because not highest point in area.

Paradox Valley Seismic Network
Site Visit Report

Site Visit No: PVSN-2016-4 Departure Date: 10/29/2016 Return Date: 11/04/2016

G. Besana-Ostman, M. Gilliam, and S. Trujillo

Summary

The main activities undertaken during this fieldwork included tests and diagnostics on radios, cables, and antenna, as well as replacement of faulty cables and antennas at the PVSN data acquisition center at Hopkin's Field (PVHOP), PVSN radio repeater stations, and remote stations. During the site visit, determination of possible radio frequency range interference at PVHOP was also undertaken continuously for several days. Moreover, the cellular signal reception at each visited site was verified, and strong motion station PVCC was put back online using regular phone connection.

Data transmission improved significantly subsequent to the above systematic diagnostics on radios, cables, and antennas and the undertaking of corresponding replacement of defective parts or equipment. Consequently, station radio link dropouts went down to as little as 1% for a number of stations while the rest have 100% radio connectivity and data transmission. Other activities that might be critical for the PVSN for the upcoming winter season like battery and wago blocks replacement were not done due to time constraints. Based on experiences and new skills learned and developed by all team members through this fieldwork, team work and redundancy on both systems and skillsets are of utmost importance to make field maintenance a success and fruitful effort.

Stations Visited

Below were the activities completed at seismic stations during the 7-day field work.

October 29, 2016

PVHOP

- Installed 25' transmission cable LMR-400 with Omni antenna with frequency range of 800MHz-1.1GHz attached to the Keysight FieldFox RF analyzer. This Omni antenna used during this observation was a spare that came with Keysight analyzer. LMR-400 was installed through an existing phone line outlet while antenna was temporarily installed on the ice bridge outside the PVHOP shelter.
- Recording of data on FieldFox analyzer started at 6:06pm with the following LAN connection 140.215.65.204/255.255.255.0/140.215.65.253.
- NOTE: 1. Spare cables (LMR-200s and LMR-400s with right connector), Omni and Yagi antennas should always be available. 2. Need to take inventory of what is available in the PVHOP shelter, storage, and Bldg. 54.

October 30, 2016

PVHOP

- Checked recording and monitoring setup with FieldFox; data were recorded on the internal drive and in trace format. Changed target drive to USB, format is CSV, recording started at 10:10am. Keysight software was not available to read data, download failed. Cannot ping 140.215.65.204; called S. Cartwright to check IP connectivity. Switched IP into 140.215.65.205, connection worked. By the end of the day, data were not recorded on the USB. Took snapshots of FieldFox screen during frequency monitoring; peaks indicated no apparent frequency interference.
- Radio power testing- Scream was shut down by C. Wood remotely. Polyphasers on the wall: IS-B50LN-C2
- NUCC AP1: GE iNetII SN# 1917921 with 3' LMR-200/0.49W
- NUCC AP2: GE iNetII SN# 1917962 with 3' LMR-200/0.34W
- NUCC AP3: GE iNetII SN#1917973 with 3' LMR-200/0.0W
- Replaced 3' LMR-200 cable on NUCC AP3, new Watt meter reading was 0.42W
- Connectivity of PV04 with NUCC AP3 was confirmed by C. Wood remotely, which showed that RSSI was 10dBm higher after cable replacement.
- NOTE: 1. Undertaking of the actual power test on radios at the lab is a must. A print out of the step-by-step procedure of power test on radio along with the field notes would be very helpful. 2. Location of radio at the hub can be improved by installing a longer LMR-200 cable to situate radios on a shelf instead of being on the cable bridge/tray in the ceiling.

October 31, 2016

PVHOP

- Retested power on Radio #2 GE iNetII SN# 1917962 with new 3' LMR-200/0.38W
- Checked recording and monitoring setup with FieldFox on USB- still no data on USB (1kb size).
- Firmware upgrade to version 8.1 on radios was implemented by C. Wood with S. Cartwright remotely.
- C. Wood was not able to reboot radio remotely on Pv12. Disconnected FieldFox setup at PVHOP to bring to PV12.

PV12

- Stopped by the NNTC office to borrow cellular modem.
- On-site, PV12 station was in good condition; Yagi antenna was oriented along 95° azimuth; Dm24's transmission LED was not blinking.
- Remote login and reboot remotely had failed. Initially power cycled the radio, no change. Connected to radio locally using a laptop via a serial cable. Firmware was still in version 2.6; remote login was successful afterwards. RSSI was -90dBm to -80dBm.

- All radios were powered down. FieldFox was used to monitor radio signal present in the area. FieldFox screen display indicated signals at 927.990MHz with power of -75dBm to -80dBm.
- Power test on PV12-AP SN# 829631 0.5W/ 0.02W (reflection).
- Power test on PV12 SN# 1917896 0.38 to 0.6W/ 0.1 to 0.02W (reflection).
- Byrd Antenna test: PV12-AP
    - VSWR : 1.1 (low)/1.36 (high)
    - % Match : 99.7% (low)/97.7 (high)
    - Return Loss : -27dB (low)/-15.5dB (high)
    - Rho : 0.043 (low)/0.168 (high)
- Byrd Antenna test: PV12
    - VSWR : 1.13 (low)/1.65 (high)
    - % Match : 96.4% (low)/94.1 (high)
    - Return Loss : -14.4dB (low)/-12.3dB (high)
    - Rho : 0.189 (low)/0.245 (high)
- Replaced 2' LMR-200 jumper cable between polyphaser and PV12 radio; retested power on radio: 0.46W-0.6W/ 0.2 to 0.15W (reflection).
- Climbed tower and reoriented antenna along 85° azimuth (magnetic); RSSI changed to -88dBm; reoriented to 77° azimuth; RSSI was -82dBM.
- Cellular signal was not detected at the site using the NNTC cellular modem.
- NOTE: 1. Radios on site can be powered down by either removing a fuse or the terminal adapter from the radio. 2. Use of tripod, Brunton compass and wooden post painted with bright color to get a good azimuthal orientation of the antenna was very efficient.

November 1, 2016

PVHOP

- FAA powered down its tower. All radios at the PVHOP turned off.
- FieldFox analyzer monitoring initialized.
- Byrd Antenna test: NUCC AP1: GE iNetII SN# 1917921 with Omni (900-930Mhz)
    - VSWR : 1.13 (low)/1.25 (high)
    - % Match : 99.6% (low)/98.9% (high)
    - Return Loss : -24.5dB (low)/19.4dB (high)
    - Rho : 0.063 (low)/0.105 (high)
- Byrd Antenna test: NUCC AP2: GE iNetII SN# 1917962
    - VSWR : 1.14 (low)/1.31 (high)
    - % Match : 99.6% (low)/98.2% (high)
    - Return Loss : -24.2dB (low)/17.3dB (high)
    - Rho : 0.062 (low)/0.138 (high)
- Byrd Antenna test: NUCC AP2: GE iNetII SN# 1917973
    - VSWR : 1.31 (low)/1.67 (high)

  - % Match : 98.2% (low)/93.8% (high)
  - Return Loss : -17.1dB (low)/12.1dB (high)
  - Rho : 0.133 (low)/0.245 (high)
- Climbed tower using a rented bucket from NNTC and replaced antennas. NUCC AP1- Omni FG 9023 Laird (890-960MHz); NUCC AP2- 7-element SN# YAS900W at 68° back azimuth; NUCC AP3 18-element SN# BM YD8900 at 108° back azimuth.
- Byrd Antenna test: NUCC AP1: GE iNetII SN# 1917921
  - VSWR : 1.27 (low)/2.13 (high)*
  - % Match : 98.5% (low)/% (high)*
- *Due to the relatively high VSWR and % Match values, the old Omni antenna was attached back to the tower, see previous measurements.
- Byrd Antenna test: NUCC AP2: GE iNetII SN# 1917962 with new antenna
  - VSWR : 1.26 (low)/1.51 (high)
  - % Match : 98.7% (low)/95.9% (high)
  - Return Loss : -18.9dB (low)/14.0dB (high)
  - Rho : 0.030 (low)/0.203 (high)
- Byrd Antenna test: NUCC AP3: GE iNetII SN# 1917973 with new antenna
  - VSWR : 1.30 (low)/1.70 (high)
  - % Match : 98.2% (low)/93.1% (high)
  - Return Loss : -17.5dB (low)/11.6dB (high)
  - Rho : 0.133 (low)/0.261 (high)

PVCC

- Station seemed to be in good condition. Sealant on enclosure applied last year seemed to have functioned well. No satellite and cellular signal on-site.
- Retrieved ADSL modem and replaced back phone line connectivity with TMC5 and US Robotics modem. Auxiliary cable has wrong pin, not connected. K2's LED blinking continuously at FAULT. Powered cycle K2, no change.
- Called C. Wood and M. Meremonte at A. Nicholas office to check on PVCC connection and availability of auxiliary cable with the right pin, respectively. Phone connection at PVCC only provided continuous ringing, not able to connect to modem; K2 auxiliary cable will be sent via FedEx. Borrowed phone from A. Nicholas.
- Checked phone line on-site, no dial tone. Will check with NNTC.
- <u>NOTE</u>: 1. Have a spare phone to check if phone line is active or not on-site. 2. Pins 1-10 setup on modem (ON, OFF, ON, OFF, OFF, OFF, ON, ON, ON, OFF).

PVPP

- Station in good condition. Checked connection of TMC5 (80202-224, TMC5-1H 980124h Ver 2.0), modem, K2 with internal sensor, serial number not visible. Pins 1-10 setup on

modem (ON, OFF, ON, OFF, OFF, OFF, ON, ON, ON, OFF). Connection remotely was successful.

- NOTE: 1. K2 is attached permanently on the concrete slab, needs cleaning on base to get SN. 2. Needs sealant on base to minimize elements inside the enclosure.

PVEF

- Station in good condition. Sealant on enclosure applied last year seemed to have functioned well.
- Checked connection of TMC5, modem, K2 (SN# 1382) and FBA-23 (46130). Remote connection from Denver data center was successful.

November 2, 2016

PVCC

- Dropped by NNTC to request phone connection at PVCC and borrowed a phone to check on-site.
- Checked phone line from junction box, now ON and had dial-tone inside enclosure.
- Accessed K2 thru laptop using serial cable. Put K2 on blockmode (was on streaming mode due to ADSL setup, hence the continuous LED blinking). Switched phone cable from phone to jack while baud rate changed from 19200 to 38400. Remote connection by C. Wood and by the dial-up system into PVCC now successful.
- NOTE: 1. Prepare complete cable set for K2-laptop access. 2. Print-out of procedure to access K2 via laptop. 3. Satellite signal on this site is about 50ft away towards north along the west side of the church. Check K2 settings (e.g. blockmode and baud rate).

PV04

- Station seemed to be in good condition. C. Wood and S. Cartwright working with team remotely.
- Power test on radio with Yagi antenna pointed to NUCC AP3 at PVHOP; PV04 GE iNetII SN# 1917965 0.4-.46W/ 0.02-0.05W (reflection).
- Byrd Antenna test: PV04: GE iNetII SN# 1917965
    - VSWR : 1.5 (low)/1.99 (high)
    - % Match : 96.3% (low)/91.3% (high)
    - Return Loss : -14.8dB (low)/-9.8dB (high)
    - Rho : 0.210(low)/ 0.375(high)
- Power test on radio with Omni antenna receiving remotes PV04-AP GE iNetII SN# 182934 0.5-0.52W/ 0.01W (reflection).
- Byrd Antenna test: PV04-AP: GE iNetII SN# 182934
    - VSWR : 1.07 (low)/1.26 (high)
    - % Match : 99.9% (low)/98.7% (high)
    - Return Loss : -29.8dB (low)/-17.7dB (high)

  - Rho : 0.037 (low)/0.121 (high)
- Cellular signal was indicated by 5 bars and laptop successfully connected to Reclamation's website. Moreover, call using cellular phone with Verizon provider went through without any problem, no dropouts.
- Climbed tower and checked orientation of Yagi antenna towards PVHOP (288°, within 3-4° of correct orientation: 291° back azimuth).
- Initial visual inspection of Omni antenna indicated connection between antenna and cable was not in good condition.
- Tower height lowered by 5ft, repositioned Yagi and Omni antennas to their pre-2016 configuration.
- Power test on radio with Yagi antenna at new height along 288° back azimuth; PV04 GE iNetII SN# 1917965 0.42-.46W/ 0.05W (reflection).
- Byrd Antenna test: PV04: GE iNetII SN# 1917965
  - VSWR : 1.28 (low)/1.60 (high)
  - % Match : 98.4% (low)/94.8% (high)
  - Return Loss : -17.9dB (low)/-12.9dB (high)
  - Rho : 0.105(low)/ 0.310(high)
- Power test on radio with original Omni antenna at new height; PV04 GE iNetII SN# 1829634 0.42-.44W/ 0.08W (reflection).
- Byrd Antenna test: PV04-AP: GE iNetII SN# 182934
  - VSWR : 1.56 (low)/1.71 (high)
  - % Match : 95.4% (low)/93.3% (high)
  - Return Loss : -13.2dB (low)/-11.6dB (high)
  - Rho : 0.219 (low)/0.259 (high)
- Based on the current condition of the Omni antenna and cable where connected, it was decided to replace the original Omni antenna. During this process, Omni and cable connection was already badly damaged wherein the antenna housing came out of the cable female connector. Also noted the damaged and twisted copper insulation as well as lack of water-proofing tape on cable-antenna connection.
- Omni antenna was replaced with the spare antenna that S. Trujillo brought from the Bldg. 54 with SN# FG 8966 connected to a new 25' heliax cable.
- Power test on radio with replacement Omni antenna; PV04 GE iNetII SN# 1829634 0.54-.50W/ .15W (reflection).
- Byrd Antenna test: PV04-AP: GE iNetII SN# 182934
  - VSWR : 1.4 (low)/1.48 (high)
  - % Match : 96.9% (low)/96.4% (high)
  - Return Loss : -15.0dB (low)/-14.5dB (high)
  - Rho : 0.163 (low)/0.199 (high)
- Attempted to install radio firmware upgrade to version 8.1 from laptop via cross-over cable, no success. Remote upgrade was also not a success, remote connection failed.

- NOTE: 1. Lowering the antenna was a 3-person job both for safety and efficiency. 2. Spare cables and Omni antenna are very important. 3. Spare radios programmed at the lab are preferred. 4. Bring a spare cross-over cable to connect from laptop to radio to implement on-site programming. 5. Redundancy on GE radio programming, software setup, and remote support are a must. 6. Skill set on proper antenna-cable installation would be a good advantage.

November 3, 2016

PV11

- Station seemed to be in good condition.
- Power test on radio with current Yagi antenna; PV11 GE iNetII SN# 1966643 0.3-.70W/ .18-.24W (reflection). RSSI -95dB
- Byrd Antenna test: PV11: GE iNetII SN# 1966643
    - VSWR : 3.87 (low)/4.63 (high)
    - % Match : 64.9% (low)/58.3% (high)
    - Return Loss : -4.5dB (low)/-3.7dB (high)
    - Rho : 0.601 (low)/0.657 (high)
- Change LMR-200 pigtail connected with TNC-male to N-female mating connector (digikey Molex).
- Byrd Antenna test on PV11 with new pigtail
    - VSWR : 4.64 (low)/6.58 (high)
    - % Match : 58.5% (low)/45.6% (high)
    - Return Loss : -3.8dB (low)/-2.8dB (high)
    - Rho : 0.666 (low)/0.761(high)
- Switched LMR-200 with N to TNC connector and another polyphaser inside the enclosure.
- Byrd Antenna test on PV11 with new pigtail and new polyphaser
    - VSWR : 3.78 (low)/4.24 (high)
    - % Match : 66.4% (low)/61.9% (high)
    - Return Loss : -4.7dB (low)/-4.2dB (high)
    - Rho : 0.580 (low)/0.620 (high)
- Installed the 25' LMR-400 (repaired from PV04) with new 5-element Yagi with original polyphaser and original LMR-200 pigtail.
- Byrd Antenna test on PV11 with original pigtail and polyphaser but with new antenna and new LMR-400
    - VSWR : 1.12 (low)/1.25 (high)
    - % Match : 99.7% (low)/98.9% (high)
    - Return Loss : -24.7dB (low)/-19.5dB (high)
    - Rho : 0.059 (low)/0.110(high)
- Climbed tower and setup old 5-element antenna at current orientation of 64° azimuth, new LMR-400 (repaired), through old polyphaser and old LMR-200 pigtail.

- Byrd Antenna test on PV11 with original pigtail, original polyphaser, original antenna and new LMR-400
    - VSWR : 3.99 (low)/3.97 (high)
    - % Match : 64.3% (low)/64.7% (high)
    - Return Loss : -4.4dB (low)/-4.5dB (high)
    - Rho : 0.60 (low)/0.699 (high)
- Replaced the old Yagi antenna with new 5-element antenna (PCTEL BMOY 8905), switched back to original heliax cable, polyphaser and LMR-200.
- Byrd Antenna test on PV11 with original pigtail, original polyphaser, original LMR-400 and new antenna: setup currently installed at PV11.
    - VSWR : 1.18 (low)/1.41 (high)
    - % Match : 99.3% (low)/97.1% (high)
    - Return Loss : -21.7dB (low)/-15.4dB (high)
    - Rho : 0.072 (low)/0.172 (high)
- Checked cellular signal at the station: no signal.
- Left spare fuses (10 and 15 Amps).
- Left spare LMR-200 with TNC connector.
- NOTE: 1. Spare LMR-200 with right connector inside the bag of spare parts in the enclosure is very important. 2. Spare polyphaser on the enclosure is very important. 3. Spare polyphasers in the truck were not the correct model (should be IS-B50LN-C2). 4. Being able to fix an antenna cable on-site was critical to have a working cable when spare is absent. 5. Clear truck with unnecessary spares and bad parts.

PV12

- Station seemed to be in good condition.
- Came back to this repeater station to reorient Yagi antenna along correct azimuth.
- Climbed tower and reoriented antenna to 104° back azimuth towards PVHOP.
- Radio showing new RSSI -83 dBm and S/N ratio of 25dB.

November 4, 2016

PV15

- Station seemed to be in working condition.
- Remote connection by C. Wood was not successful. Will undertake radio diagnostics.
- Radio was working SN# 1968647 with SSH enabled and Telnet enabled.
    - RSSI : -76 -80 -74 dB
    - S/N ratio : 24 dB
    - Output : 30dB
    - Power cycled the radio. Remote access/connection still failed.
- Programmed another radio- same issue, can't SSH.

- Put back the old radio. C. Wood was able to connect, it was not the radio, Tectia setting had to be setup correctly. SSH was successful afterwards.
- NOTE: 1. Programmed spare radio for a remote station is important. 2. A print-out of procedure to program a radio will make on-site programming easier due to long paraphrase needed on the automatic connection and very numerous settings.

Lessons Learned

First, team meetings with lab practices and hands-on test on various components of the seismic stations provided immeasurable preparation for the field staff. Second, the full on-site assistance from A. Nicholas and complete remote support from Denver staff to on-site tests and monitoring system changes exemplified how efficient field maintenance work can be implemented. Third, an inventory of available spare parts and units would be critical for the succeeding field maintenance trip to Paradox Valley for the PVSN and the strong motion array. Last but not the least, redundancy on skillsets as well as complementary expertise must be achieved in a team to systematically maintain the network in the future.

Acknowledgment

We would like to extend our deep appreciation for their help and support to the following individuals and agencies who made this fieldwork possible and successful: Andy Nicholas, Lisa Block, Christopher Wood, Scott Cartwright, Mark Meremonte, Reclamation's IT Planning and Compliance for allowing S. Trujillo be part of this team, Al Baarson & Brendan Bono of Keysight Technologies, Kent Tomlinson and staff of NNTC, and Brad McKinney of the Nucla airport.

Paradox Valley Seismograph Network
December 2016 Maintenance Trip: Site Visit Summary Report

Site Visit No: PVSN-2016-5 Departure Date: 12/5/2016 Return Date: 12/10/2016

Prepared by: Lisa Block

Personnel: Mike Gilliam

Work Summary:

Dec. 5:

- Drove to Paradox, CO
- Stopped at Hopkin's Field and discovered that the alarm for the *Earthworm* data acquisition computer was on, indicating a failing disk drive. Called Denver to report the problem and have a replacement drive shipped.

Dec. 6:

- Hopkin's Field:
  - Moved radios and rerouted cables. Installed and tested new radio jumper cables.
- PV15:
  - Installed bladed fuses
- PV01:
  - Tested radios, cables, and antenna
  - Replaced LMR-200 pigtail cable.

Dec. 7:

- PV14:
  - Replace radio with unit having latest firmware installed.
  - Installed bladed fuses for batteries and solar panels
  - Tested radio, cables, and antenna.
- PV10:
  - Installed bladed fuses for batteries and solar panels
  - Tested radio, cables, and antenna.

Dec. 8:

- PV23:

    - Recycled power to restore GPS timing
    - Tested radio, cables, and antenna.

- PV16:
    - Tested radio, cables, and antenna.

Dec. 9:

- Hopkin's Field:
    - Replaced failing disk drive in *Earthworm* data acquisition computer
    - Cleaned and re-organized data acquisition shelter
    - Updated log book

Dec. 10: Returned to Denver

Appendix B

PVSN 2016 Local Earthquake Catalog

Table B-1: Local earthquakes recorded by PVSN during 2016

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
1/1/16	18:47:38	38.3048	-108.9080	-2.7	4.2	0.2	1.46
1/4/16	21:40:40	38.3273	-108.9722	-2.5	4.0	-0.1	7.56
1/6/16	11:11:56	38.4045	-108.8818	-2.8	4.3	0.2	12.04
1/9/16	8:12:09	38.2848	-108.9104	-1.6	3.2	0.3	1.87
1/12/16	7:38:04	38.2040	-108.7300	-6.2	7.7	1.5	17.72
1/12/16	10:44:38	38.2227	-108.7815	-2.2	3.8	0.3	12.88
1/12/16	12:12:53	38.2909	-108.9117	-2.5	4.0	0.6	1.59
1/15/16	7:51:27	38.2792	-108.9298	-0.3	1.9	0.1	3.61
1/20/16	21:57:59	38.2620	-108.8697	-1.0	2.6	-0.7	4.43
1/21/16	4:35:34	38.2762	-108.8283	-2.9	4.4	-0.5	6.25
1/23/16	11:06:47	38.2833	-108.9052	-2.0	3.5	0.1	1.72
1/23/16	11:09:57	38.2843	-108.8997	-2.0	3.6	0.7	1.42
1/23/16	11:18:47	38.2843	-108.8998	-2.0	3.6	0.4	1.42
1/31/16	4:14:46	38.4118	-109.0095	-4.5	6.1	1.6	16.25
2/3/16	17:27:28	38.2859	-108.9034	-2.1	3.6	1.4	1.39
2/3/16	18:13:20	38.2858	-108.9035	-2.1	3.6	-0.3	1.40
2/4/16	5:34:41	38.3167	-108.9735	-2.1	3.6	0.1	7.22
2/4/16	16:48:11	38.2859	-108.9033	-2.1	3.6	-0.1	1.39
2/5/16	7:21:18	38.3066	-108.9165	-2.7	4.2	2.1	2.18
2/9/16	3:23:41	38.4593	-108.9622	-3.5	5.0	1.0	19.00
2/9/16	10:24:09	38.4582	-108.9610	-3.0	4.5	0.2	18.85
2/10/16	15:37:06	38.4553	-108.9595	-2.0	3.6	0.2	18.51
2/10/16	18:16:13	38.4053	-108.9334	-4.4	5.9	1.8	12.53
2/10/16	22:24:13	38.4580	-108.9595	-2.7	4.2	-0.1	18.79
2/10/16	22:25:27	38.4637	-108.9552	-2.3	3.9	-0.8	19.28
2/12/16	23:24:47	38.4417	-108.9680	-1.0	2.5	0.5	17.33
2/13/16	18:53:43	38.4595	-108.9618	-3.0	4.5	0.2	19.01
2/13/16	19:01:41	38.4600	-108.9603	-2.8	4.3	-0.1	19.02
2/15/16	16:09:53	38.2939	-108.9224	-2.5	4.0	1.8	2.42
2/19/16	0:30:44	38.3236	-108.9706	-2.3	3.8	0.0	7.26
2/19/16	11:38:54	38.4128	-109.0155	-5.6	7.1	1.9	16.67
2/19/16	12:05:39	38.4157	-109.0142	-5.1	6.6	1.2	16.84
2/21/16	7:55:14	38.2748	-108.8507	-1.9	3.4	-0.4	4.57
2/25/16	13:31:10	38.1678	-108.8220	-5.1	6.6	-0.1	15.65
2/26/16	14:08:29	38.2849	-108.9105	-1.6	3.1	0.5	1.87
3/3/16	14:24:12	38.2991	-108.9309	-2.7	4.2	0.2	3.15
3/3/16	20:55:09	38.3393	-108.8899	-5.7	7.2	-0.1	4.77
3/6/16	2:48:49	38.2822	-109.0317	-1.1	2.6	-0.5	12.06
3/6/16	2:49:15	38.2947	-109.0397	-1.6	3.1	-1.0	12.66
3/6/16	2:49:35	38.2970	-109.0420	-1.8	3.3	-1.2	12.86
3/6/16	6:16:01	38.2880	-109.0368	-1.5	3.0	-0.2	12.44
3/6/16	6:16:53	38.2817	-109.0333	-1.3	2.8	-0.4	12.21
3/6/16	6:17:21	38.2817	-109.0327	-1.3	2.9	-0.9	12.16
3/9/16	2:40:20	38.2825	-108.8678	-2.0	3.5	0.0	2.85

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
3/10/16	11:40:37	38.3007	-108.9359	-2.4	3.9	-0.1	3.61
3/11/16	4:45:02	38.2790	-108.8781	-5.2	6.8	-0.4	2.44
3/11/16	9:13:36	38.2791	-108.8783	-5.2	6.8	0.0	2.42
3/11/16	10:52:45	38.2791	-108.8783	-5.2	6.8	-0.5	2.43
3/11/16	11:07:54	38.2791	-108.8784	-5.2	6.8	-0.2	2.42
3/11/16	13:48:10	38.2792	-108.8784	-5.2	6.8	0.6	2.41
3/12/16	3:07:20	38.2791	-108.8784	-5.3	6.8	-0.4	2.42
3/12/16	4:13:47	38.2793	-108.8785	-5.2	6.8	0.5	2.39
3/12/16	9:19:52	38.2793	-108.8785	-5.3	6.8	0.3	2.39
3/15/16	15:42:02	38.2717	-108.9378	0.2	1.3	0.1	4.66
3/16/16	19:54:22	38.2851	-108.8983	-2.0	3.5	0.4	1.30
3/16/16	19:55:09	38.2851	-108.8984	-2.0	3.6	-0.7	1.30
3/16/16	20:06:27	38.2852	-108.8983	-2.0	3.6	-0.1	1.30
3/16/16	20:08:06	38.2852	-108.8983	-2.0	3.6	-0.7	1.30
3/16/16	20:52:56	38.2852	-108.8984	-2.0	3.5	0.5	1.30
3/16/16	20:53:32	38.2851	-108.8982	-2.0	3.5	-0.7	1.30
3/16/16	20:59:50	38.2852	-108.8985	-2.0	3.6	0.1	1.29
3/16/16	21:26:24	38.2853	-108.8985	-2.0	3.6	0.5	1.29
3/17/16	0:13:45	38.2851	-108.8983	-2.0	3.5	0.2	1.30
3/17/16	4:34:14	38.2854	-108.8987	-2.0	3.6	-0.3	1.28
3/18/16	11:30:59	38.2864	-108.9092	-1.6	3.1	0.1	1.68
3/18/16	13:38:40	38.2853	-108.8983	-2.1	3.6	-0.4	1.29
3/20/16	5:35:57	38.2850	-108.8820	-2.3	3.8	-0.7	1.72
3/20/16	6:17:07	38.3032	-108.9351	-2.5	4.0	-0.1	3.59
3/20/16	7:49:51	38.2704	-108.8653	-1.2	2.7	0.1	3.90
3/21/16	20:20:38	38.2848	-108.9088	-1.3	2.8	-0.7	1.78
3/22/16	13:01:32	38.2563	-108.9512	-0.9	2.4	-0.2	6.64
3/22/16	13:53:16	38.3062	-108.9365	-2.3	3.9	-0.9	3.79
3/26/16	19:21:48	38.3057	-108.9170	-2.7	4.2	-0.2	2.17
3/27/16	19:54:18	38.2866	-108.9074	-1.8	3.3	0.1	1.55
3/28/16	5:21:17	38.2847	-108.8837	-2.4	3.9	0.0	1.64
3/28/16	8:41:34	38.2866	-108.9075	-1.8	3.3	-0.1	1.56
3/30/16	23:22:04	38.2704	-108.8655	-1.2	2.7	-0.1	3.88
3/31/16	1:52:44	38.3033	-108.9355	-2.5	4.0	1.5	3.62
4/5/16	3:39:30	38.4019	-108.8630	-4.2	5.8	0.0	12.02
4/17/16	12:29:58	38.3064	-108.9167	-2.7	4.2	1.1	2.19
4/20/16	6:00:44	38.2940	-108.9222	-2.5	4.0	0.0	2.40
4/23/16	12:30:37	38.3032	-108.9359	-2.4	3.9	0.4	3.65
4/24/16	3:01:07	38.3067	-108.9147	-3.0	4.5	-0.4	2.06
4/24/16	8:47:23	38.3067	-108.9146	-3.0	4.5	-0.4	2.05
4/26/16	20:19:39	38.4188	-108.9625	-2.6	4.1	-1.0	14.80
4/27/16	13:13:28	38.4262	-108.9378	-5.3	6.8	1.3	14.87
4/27/16	23:22:12	38.3033	-108.9346	-3.9	5.4	-0.2	3.54
4/29/16	7:45:12	38.2594	-108.8698	-1.2	2.8	0.1	4.67
4/29/16	7:47:15	38.3070	-108.9333	-3.1	4.6	-1.0	3.55
4/29/16	15:48:03	38.3215	-108.6963	-11.9	13.4	0.2	17.60

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
5/1/16	17:21:04	38.5282	-109.0033	-12.3	13.8	1.3	27.40
5/2/16	18:25:23	38.2595	-108.8699	-1.2	2.8	-0.3	4.66
5/2/16	18:52:47	38.2595	-108.8699	-1.2	2.8	0.1	4.66
5/4/16	1:42:06	38.3021	-108.9267	-2.4	3.9	0.2	2.84
5/4/16	2:17:52	38.3019	-108.9266	-2.4	3.9	-0.1	2.83
5/4/16	6:29:07	38.3248	-109.0058	-1.1	2.6	-0.8	10.19
5/8/16	15:19:33	38.2779	-108.8306	-2.3	3.8	-0.5	6.00
5/8/16	22:50:26	38.3059	-108.9173	-2.7	4.3	1.4	2.21
5/9/16	12:18:51	38.2778	-108.8302	-2.2	3.8	1.4	6.03
5/9/16	14:48:13	38.2777	-108.8303	-2.2	3.8	0.5	6.03
5/9/16	19:44:51	38.2813	-108.8600	-1.4	2.9	-1.0	3.50
5/9/16	20:56:12	38.2789	-108.8601	-1.1	2.7	-0.2	3.62
5/10/16	5:28:20	38.2735	-108.8735	-1.0	2.6	-0.8	3.17
5/10/16	5:28:59	38.2743	-108.8750	-0.8	2.4	-0.1	3.02
5/10/16	7:24:29	38.2935	-108.9097	-2.2	3.7	-0.6	1.33
5/10/16	8:31:31	38.2743	-108.8751	-0.8	2.4	0.5	3.02
5/12/16	2:26:29	38.2776	-108.8305	-2.3	3.8	-0.2	6.02
5/13/16	0:02:19	38.2668	-108.8832	-1.3	2.8	-0.3	3.46
5/13/16	0:02:23	38.2682	-108.8823	-1.5	3.0	-0.5	3.34
5/27/16	6:41:03	38.2978	-108.9153	-2.3	3.8	-1.2	1.78
5/27/16	6:41:03	38.3071	-108.9196	-2.3	3.8	-0.5	2.45
6/5/16	5:09:10	38.2882	-108.9045	-1.8	3.4	-0.2	1.25
6/5/16	19:01:01	38.2852	-108.8984	-2.0	3.6	-0.1	1.30
6/5/16	19:02:43	38.2852	-108.8984	-2.0	3.5	-0.2	1.29
6/5/16	19:03:15	38.2852	-108.8984	-2.0	3.6	-0.7	1.29
6/9/16	3:06:29	38.2852	-108.8983	-2.0	3.5	0.1	1.29
6/12/16	15:58:29	38.2118	-108.7398	-7.1	8.6	1.4	16.51
6/12/16	20:31:06	38.2873	-108.9153	-4.1	5.6	-0.8	2.05
6/12/16	20:37:15	38.2859	-108.9031	-2.1	3.6	0.6	1.38
6/12/16	21:21:06	38.2859	-108.9031	-2.1	3.6	0.3	1.38
6/12/16	22:09:36	38.2859	-108.9030	-2.1	3.6	0.4	1.37
6/13/16	3:20:01	38.2859	-108.9032	-2.0	3.6	-0.5	1.38
6/13/16	3:27:03	38.2859	-108.9031	-2.1	3.6	0.1	1.38
6/13/16	5:28:41	38.2994	-108.9067	-2.7	4.2	0.1	1.07
6/14/16	14:17:06	38.2859	-108.9030	-2.1	3.6	-0.5	1.37
6/14/16	14:48:10	38.2860	-108.9029	-2.1	3.6	-0.2	1.36
6/14/16	14:54:55	38.2859	-108.9030	-2.1	3.6	1.1	1.37
6/14/16	15:13:42	38.2859	-108.9029	-2.1	3.6	-0.9	1.37
6/15/16	9:46:33	38.2860	-108.9030	-2.0	3.6	-0.4	1.37
6/15/16	14:45:29	38.2859	-108.9029	-2.1	3.6	-0.6	1.37
6/17/16	7:36:18	38.2860	-108.9031	-2.0	3.6	0.0	1.37
6/17/16	11:17:15	38.2860	-108.9031	-2.0	3.6	0.2	1.37
6/19/16	20:04:48	38.2773	-108.8283	-2.4	3.9	-0.6	6.21
6/24/16	6:38:23	38.3145	-108.9745	-2.0	3.5	-0.1	7.24
6/27/16	7:48:17	38.3189	-108.9404	-2.8	4.3	0.0	4.68
6/27/16	13:05:59	38.2785	-108.8781	-0.8	2.3	-0.3	2.49

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
7/2/16	10:24:09	38.3685	-108.7803	-3.5	5.0	-0.1	12.82
7/5/16	16:30:53	38.2710	-108.8717	-1.3	2.8	-0.2	3.49
7/12/16	7:49:45	38.2767	-108.8349	-2.2	3.7	1.1	5.70
7/12/16	22:56:44	38.2766	-108.8347	-2.1	3.6	-0.2	5.72
7/12/16	22:59:25	38.2768	-108.8352	-2.2	3.7	0.0	5.68
7/14/16	4:00:32	38.2835	-108.9077	-1.6	3.1	-0.5	1.82
7/16/16	13:12:33	38.2851	-108.9117	-1.6	3.1	-0.2	1.94
7/16/16	13:24:29	38.2856	-108.9118	-1.5	3.1	0.5	1.91
7/20/16	15:42:10	38.2855	-108.9120	-1.7	3.2	-0.5	1.93
7/21/16	9:50:34	38.3151	-108.9757	-2.0	3.5	-0.2	7.35
7/21/16	17:32:41	38.2859	-108.8916	-1.8	3.3	0.7	1.22
7/29/16	3:36:22	38.2776	-108.8270	-2.4	3.9	0.3	6.31
7/29/16	4:07:12	38.3778	-108.8408	-2.9	4.4	0.2	10.19
7/29/16	4:08:17	38.3835	-108.8270	-3.1	4.6	-0.3	11.34
7/29/16	4:17:45	38.3691	-108.8484	-1.6	3.1	0.9	9.03
7/29/16	6:17:16	38.3448	-108.8909	-4.9	6.4	0.1	5.37
7/29/16	15:05:17	38.3778	-108.8325	-2.4	3.9	0.0	10.55
8/2/16	6:15:19	38.2992	-108.9307	-2.6	4.2	0.3	3.14
8/3/16	2:44:30	38.2829	-108.8393	-2.0	3.6	0.6	5.10
8/3/16	6:32:24	38.3159	-108.9715	-2.0	3.6	0.0	7.03
8/18/16	22:51:57	38.3234	-108.9837	-2.3	3.8	-0.7	8.31
8/21/16	1:41:00	38.4623	-108.9845	-3.1	4.6	0.1	20.00
8/23/16	8:08:32	38.2827	-108.9157	-1.4	2.9	-0.5	2.38
8/26/16	8:14:01	38.2670	-108.8702	-0.5	2.1	0.7	3.93
8/27/16	5:25:29	38.3127	-108.8495	-3.9	5.5	-0.2	4.36
9/11/16	0:00:27	38.2752	-108.8837	-0.2	1.7	1.2	2.57
9/20/16	15:47:57	38.3505	-108.8843	-5.4	6.9	0.8	6.06
9/26/16	19:06:40	38.3683	-108.9397	-4.1	5.6	0.1	8.87
9/27/16	5:46:27	38.3256	-108.9745	-2.4	3.9	-0.2	7.67
10/12/16	11:56:59	38.2885	-108.9060	-1.8	3.3	-0.7	1.31
10/13/16	12:04:01	38.3697	-108.8457	-3.8	5.3	0.7	9.19
10/17/16	23:52:48	38.3449	-108.8924	-4.4	5.9	-0.1	5.37
10/18/16	3:09:36	38.3234	-108.9719	-2.2	3.7	1.1	7.36
10/18/16	23:32:53	38.3117	-108.8570	-3.5	5.1	-0.2	3.72
10/20/16	3:30:32	38.3453	-108.8903	-4.3	5.9	-0.2	5.43
10/20/16	16:49:03	38.3037	-108.9364	-3.8	5.3	0.5	3.71
10/23/16	6:25:35	38.2836	-108.9055	-1.8	3.3	0.1	1.70
10/23/16	7:31:54	38.2403	-108.8255	-1.8	3.3	0.1	8.71
10/24/16	6:02:54	38.4625	-108.9632	-3.3	4.8	0.2	19.36
10/29/16	15:37:21	38.2682	-108.8692	-0.6	2.1	-0.4	3.87
11/5/16	7:42:00	38.4368	-108.9599	-4.4	5.9	0.5	16.57
11/7/16	17:20:59	38.4065	-108.9327	-4.8	6.3	0.1	12.64
11/8/16	23:18:06	38.2940	-108.9220	-2.5	4.0	-0.2	2.38
11/11/16	1:32:01	38.3585	-108.7178	-7.4	9.0	1.2	16.95
11/11/16	3:30:47	38.3553	-108.7160	-7.4	8.9	1.3	16.96
11/14/16	0:33:18	38.3169	-108.9709	-2.1	3.6	0.3	7.01

Date[1]	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Magnitude[4]	Horizontal Distance from Injection Well (km)
11/16/16	1:31:22	38.2843	-108.9046	-2.0	3.5	-0.2	1.60
11/16/16	6:52:05	38.3712	-108.8453	-2.9	4.4	0.2	9.35
11/16/16	21:56:10	38.4037	-109.0020	-2.0	3.5	0.1	15.13
11/20/16	10:57:39	38.2741	-108.8770	-0.9	2.4	0.4	2.95
11/20/16	10:59:24	38.2740	-108.8772	-0.9	2.5	0.0	2.94
11/20/16	11:11:54	38.2741	-108.8773	-0.9	2.4	0.5	2.94
11/20/16	20:17:37	38.2741	-108.8775	-0.9	2.4	1.0	2.92
11/23/16	2:56:05	38.3160	-108.9712	-2.0	3.6	-0.2	7.01
11/23/16	17:01:15	38.2742	-108.8777	-0.9	2.4	0.5	2.91
11/23/16	17:55:11	38.3160	-108.9709	-2.0	3.6	0.0	6.98
11/24/16	0:22:20	38.4081	-108.9345	-4.6	6.1	-0.1	12.85
11/28/16	22:10:21	38.3448	-108.8909	-4.9	6.5	1.2	5.37
11/29/16	18:30:11	38.3067	-108.9146	-3.0	4.5	-0.5	2.05
11/30/16	18:07:10	38.2733	-108.8747	-1.0	2.5	-0.5	3.13
11/30/16	20:14:47	38.3069	-108.9146	-3.0	4.5	1.0	2.07
11/30/16	21:33:50	38.2706	-108.8754	-1.5	3.0	-0.3	3.36
12/5/16	15:00:32	38.4371	-108.9600	-4.4	5.9	0.7	16.60
12/5/16	16:33:00	38.3521	-108.8818	-5.3	6.8	0.4	6.27
12/9/16	8:20:40	38.2773	-108.8317	-2.2	3.8	-0.1	5.94
12/9/16	16:46:28	38.4058	-108.9327	-4.8	6.3	1.6	12.57
12/10/16	16:44:53	38.3170	-108.9708	-2.1	3.6	0.1	7.01
12/13/16	23:51:17	38.3092	-108.8897	-2.6	4.1	-0.4	1.48
12/14/16	7:56:23	38.2857	-108.9170	-1.3	2.8	1.1	2.27
12/14/16	10:16:49	38.3067	-108.9147	-2.9	4.5	-0.1	2.06
12/15/16	10:19:09	38.2938	-108.9229	-2.5	4.0	0.4	2.46
12/16/16	20:32:03	38.4682	-108.9840	-4.1	5.6	-0.2	20.58
12/16/16	20:55:07	38.4610	-108.9867	-1.4	2.9	-0.5	19.94
12/16/16	21:47:32	38.4637	-108.9822	-3.3	4.8	0.4	20.06
12/16/16	21:48:35	38.4742	-108.9807	-3.1	4.6	-0.8	21.09
12/16/16	21:58:37	38.4462	-109.0448	-2.0	3.5	-0.3	21.16
12/18/16	9:57:13	38.2868	-108.9074	-1.8	3.3	0.4	1.53
12/18/16	17:54:12	38.3521	-108.8815	-5.3	6.8	0.8	6.28
12/21/16	22:27:16	38.2852	-108.8985	-2.0	3.6	-0.1	1.30
12/22/16	5:09:47	38.3522	-108.8815	-5.3	6.8	-0.3	6.29
12/22/16	16:11:41	38.3138	-108.9750	-1.9	3.5	-0.3	7.26
12/24/16	1:55:43	38.3522	-108.8815	-5.3	6.8	1.3	6.29
12/26/16	7:01:05	38.3522	-108.8814	-5.3	6.8	1.1	6.29
12/26/16	20:40:09	38.3032	-108.9359	-2.5	4.0	-0.5	3.66
12/28/16	6:17:53	38.3520	-108.8812	-5.3	6.8	1.5	6.27
12/28/16	15:35:57	38.3519	-108.8813	-5.3	6.8	-0.5	6.25
12/29/16	6:01:26	38.2770	-108.8764	-1.0	2.5	0.0	2.71
12/31/16	6:00:24	38.3522	-108.8811	-5.3	6.8	1.3	6.29

[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