RECLAMATION

Managing Water in the West

Technical Memorandum TM-85-833000-2015-07

2014 Annual Report
Paradox Valley Seismic Network
Paradox Valley Unit, Colorado

U.S. Department of the Interior
Bureau of Reclamation

June 2015

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

Technical Memorandum TM-85-833000-2015-07

2014 Annual Report Paradox Valley Seismic Network Paradox Valley Unit, Colorado

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Peer Review Certification

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

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1 Introduction

The Paradox Valley Seismic Network (PVSN) monitors earthquakes induced by injection operations at the Bureau of Reclamation's Paradox Valley Unit (PVU) deep disposal well, as well as local naturally occurring earthquakes. This report summarizes PVSN operations and the data recorded during calendar year 2014. We provide project background information in section 2.0, including the history of PVU injection operations and details of the seismic network. In section 3.0, we present PVSN network operations during 2014, including maintenance and upgrades of the seismic stations and data acquisition systems and annual network performance. The earthquake data recorded during 2014 are discussed in section 4.0 and compared to historical seismicity trends. In section 5, we include brief summaries of professional papers recently published in peer-reviewed journals by Reclamation staff and a discussion of Consultant Review Board activities.

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 8 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 9 shallow wells located within the valley near the 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 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.

2.2 PVU Injection Operations

Between 1991 and 1995, PVU conducted a series of seven injection tests, an acid stimulation test, and a reservoir integrity test. The purpose of these tests was to qualify for a Class V permit for deep disposal from the EPA. Continuous injection of brine began in July 1996, after EPA granted the permit. Since continuous injection began, PVU 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 rate, surface injection pressure, and downhole pressure (at a depth of 4.3 km) throughout the history of PVU injection operations are shown in Figure 2-5.

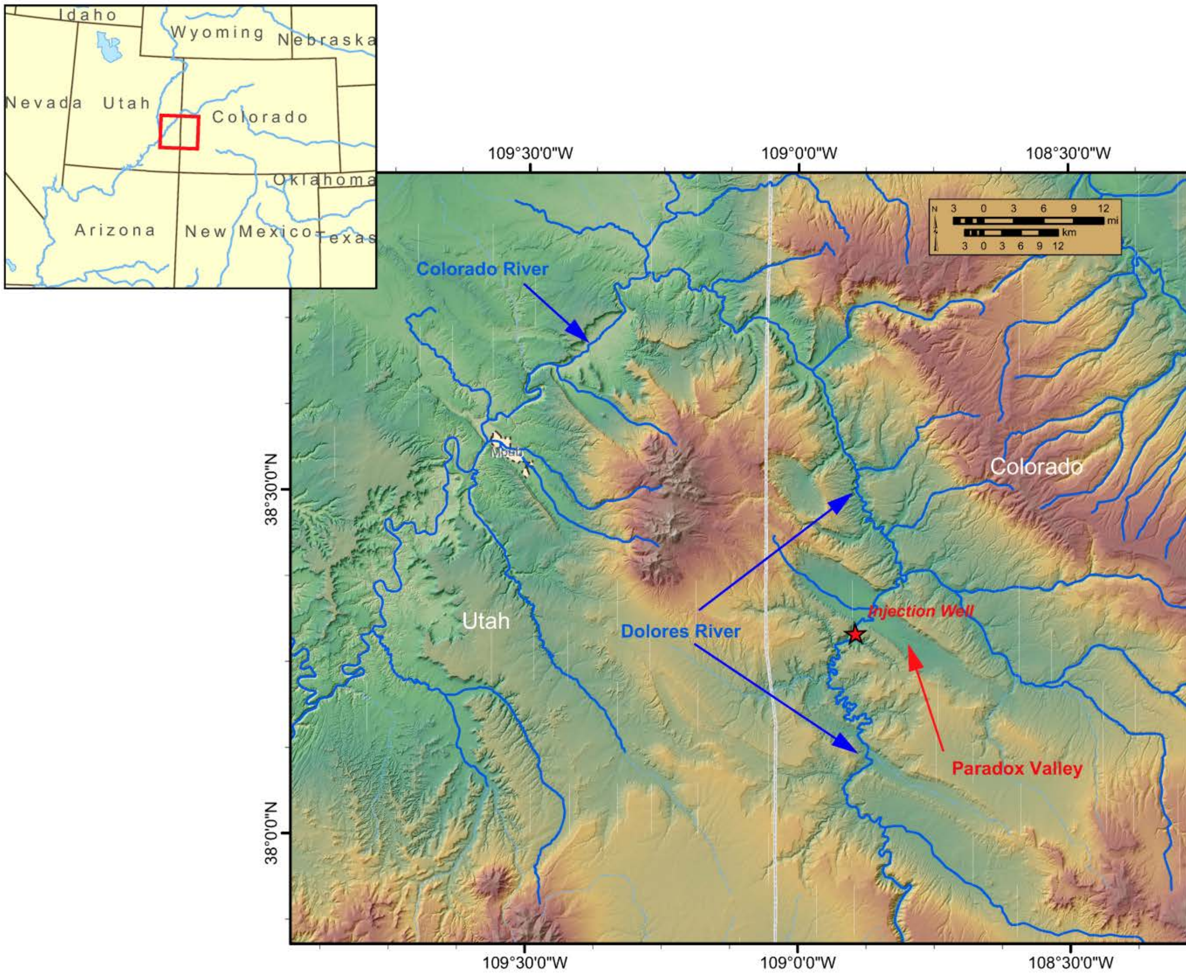


Figure 2-1: Location of the deep injection well at Reclamation's Paradox Valley Unit in western Colorado.

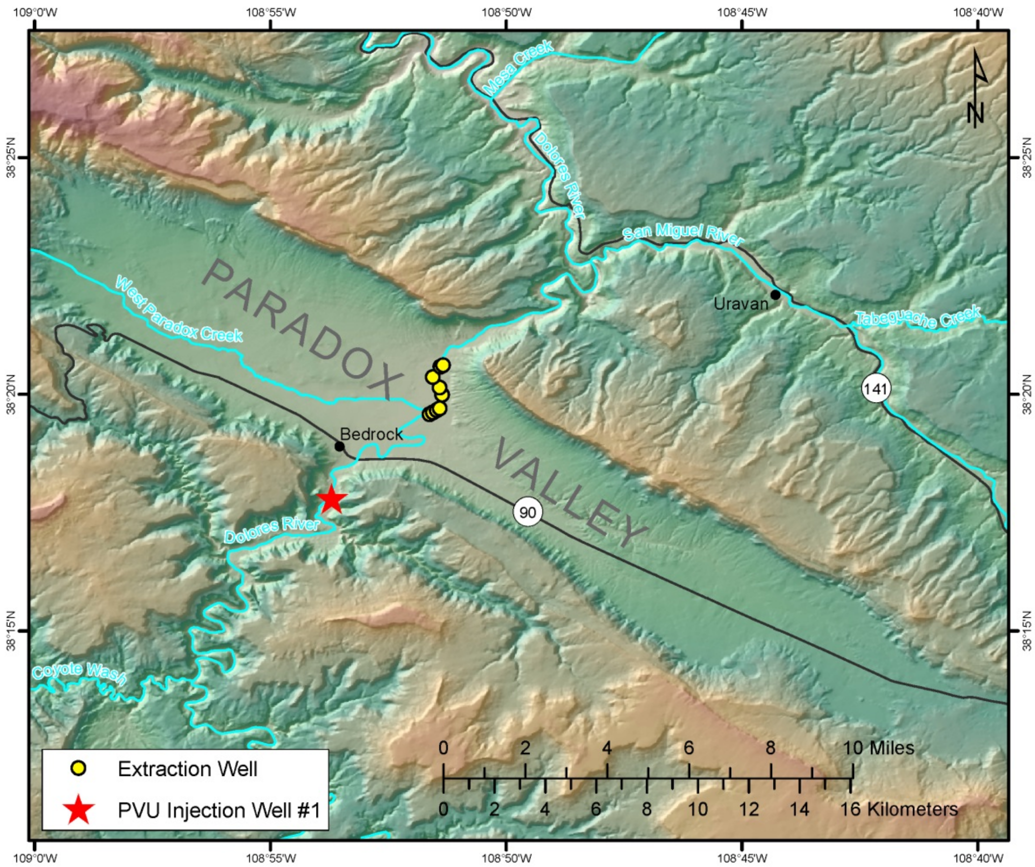


Figure 2-2: Location of the Paradox Valley Unit extraction wells (yellow circles) and injection well (red star).

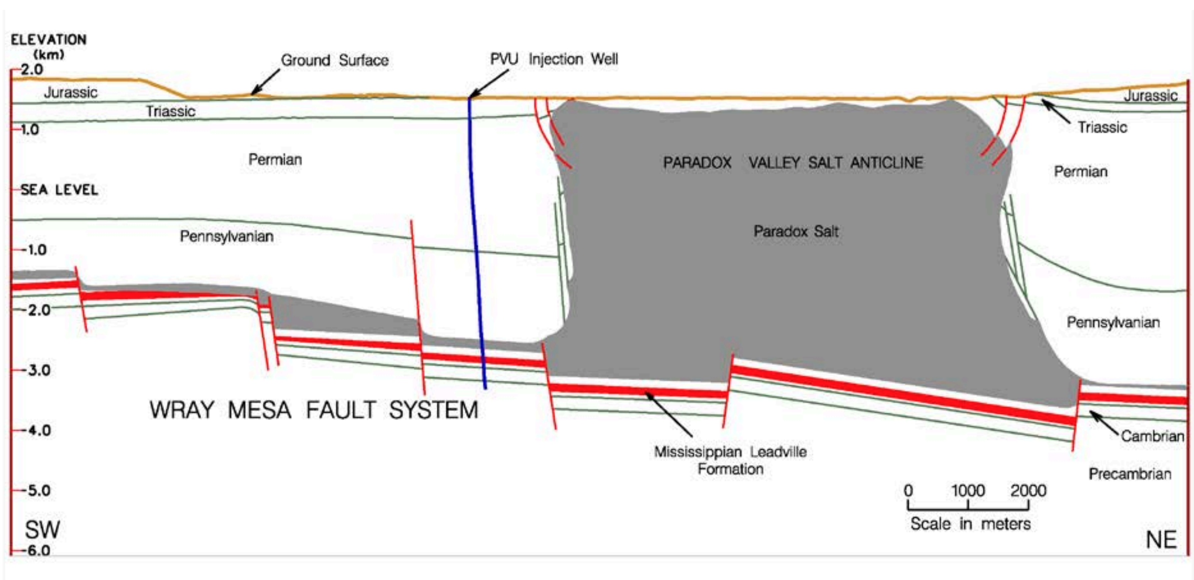


Figure 2-3: Vertical cross section roughly perpendicular to Paradox Valley, looking to the northwest. Based on figure from Bremkamp and Harr (1988).

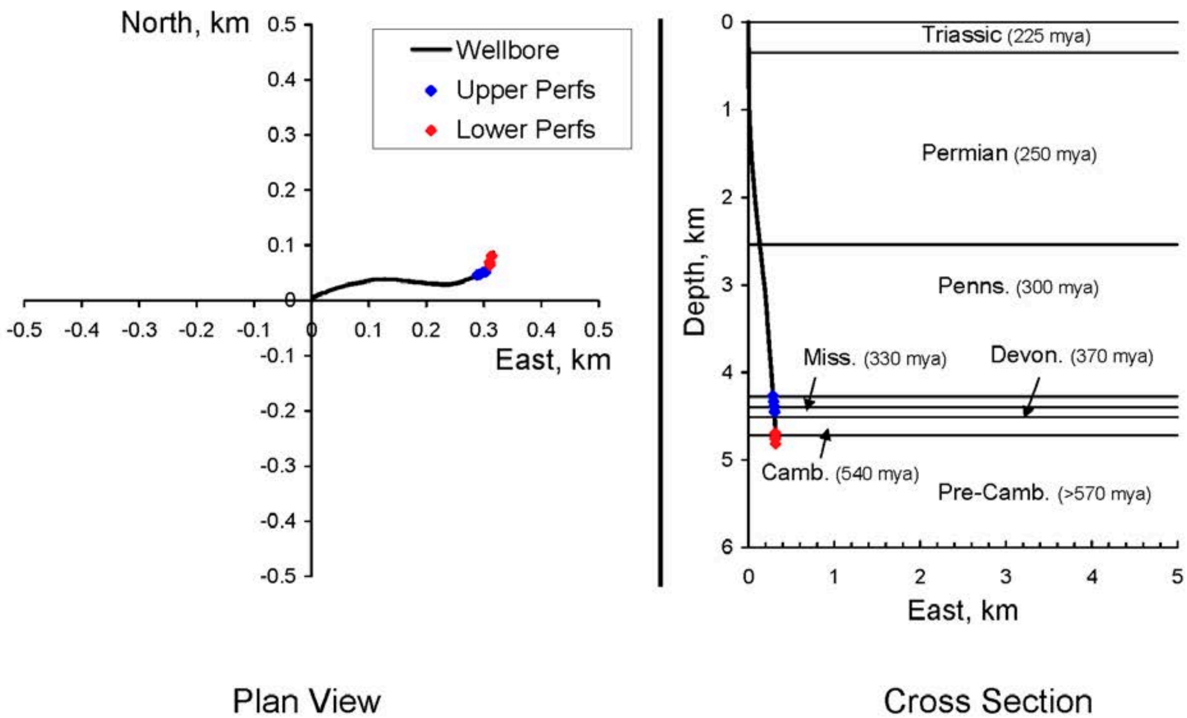


Figure 2-4: PVU injection well in plan view (left) and north-viewing vertical cross section (right). Figures include the near-wellbore stratigraphy and locations of the upper and lower casing perforations.

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, 3 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. At these times 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 3-pump operation. These shutdowns occurred frequently and lasted for minutes, hours, or a few days. 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). The injectate during phase I was a mixture of 70% Paradox Valley Brine (PVB) and 30% fresh water.

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

Following a local magnitude M_L 3.6 event in June, 1999, and a M_L 3.5 event in July, 1999, PVU altered the injection schedule to include a 20-day shutdown (i.e., a “shut-in”) every six months. Prior to these events, it was noted that the rate of seismicity in the near-wellbore region (i.e.,

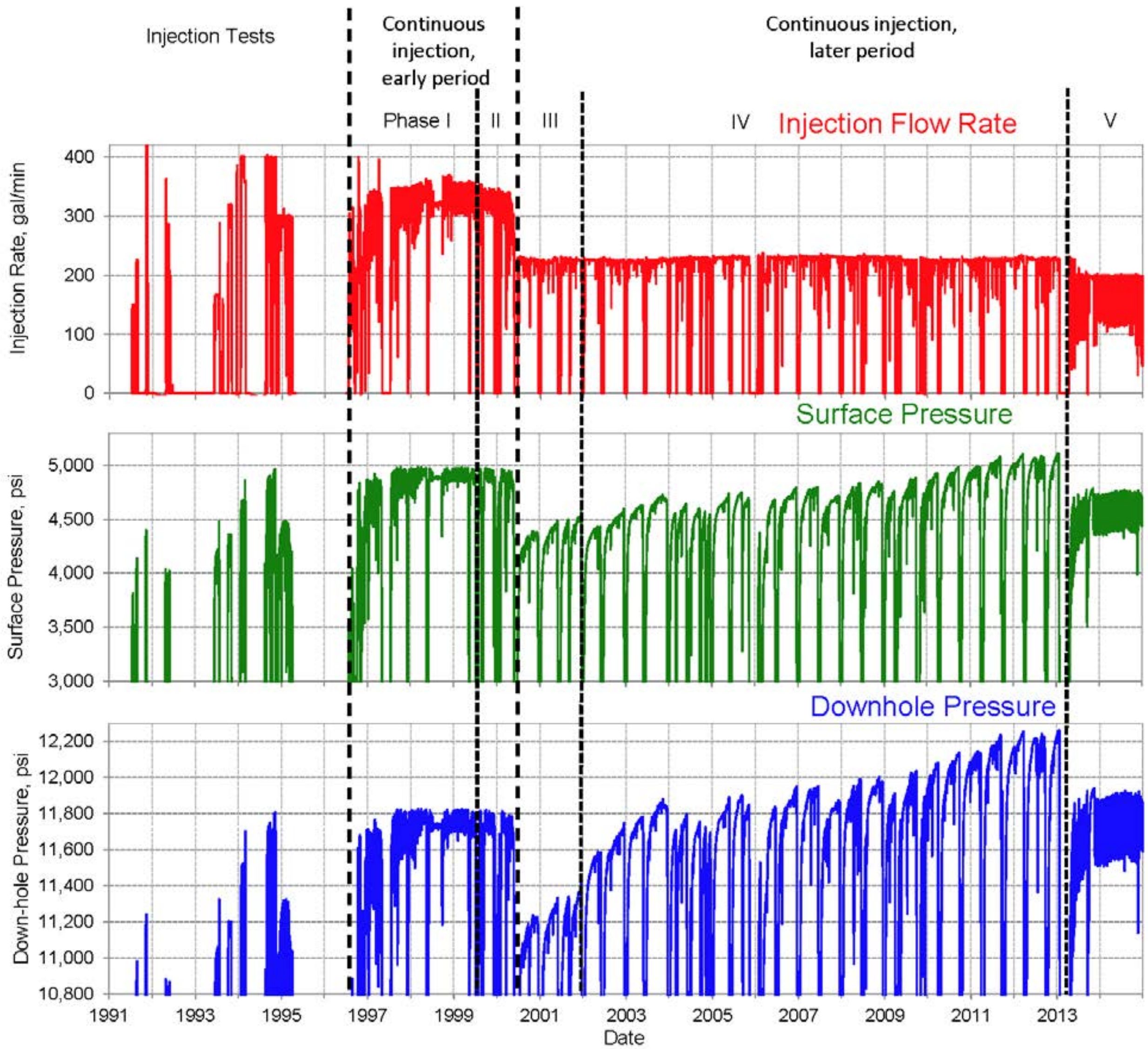


Figure 2-5: Daily average injection flow rate (top), daily average surface injection pressure (middle), and daily average downhole pressure at 4.3 km depth (bottom) during PVU injection operations.

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 injection pressure and flow rate were the same as during phase I.

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

Immediately following a M_L 4.3 earthquake on May 27, 2000, PVU shut down for 28 days. During this shutdown period, PVU evaluated the existing injection strategy and its relationship to induced seismicity. PVU decided to reduce the injection flow rate in order to 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.

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 volume 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 discussions 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. Injecting 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.

2.2.5 Phase V (April 17, 2013 – present)

A M_L 4.4 induced earthquake occurred about 8 km northwest of the injection well on January 24, 2013 (Block et al., 2014). In response to this earthquake, injection was halted while a reassessment of the seismic hazard associated with PVU injection was performed. Analyses of the seismic and injection data indicated that the potential for inducing large felt events could likely be reduced by decreasing the long-term average injection pressures (Block and Wood, 2009; Wood et al., 2015). 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., 2015). 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 178 gpm, which is ~9% less than the average flow rate of 196 gpm during the previous three years (2010-2012).

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. 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. 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 design and maintenance of the field instrumentation and telemetry.

Over the years, the original 10-station continuously telemetered, high-gain seismic network has been upgraded and expanded. Four stations (PV11-PV14) were added to this array in 1989 and another in 1999 (PV16). Station PV15 was installed in 1995 to replace PV06, which had been repeatedly vandalized and was finally removed the year before. Station PV08 was removed in

October 2003 to accommodate nearby construction activities, but was reinstalled in October 2007.

Between 2005 and 2011, upgrades to the high-gain seismic network focused on replacing the original analog short-period seismic equipment, which had become increasingly difficult to maintain, with modern digital broadband instrumentation. In November 2005, a new digitally telemetered station (PV17) was installed that employs a broadband triaxial seismometer. Thirteen existing stations have been converted from analog short-period to digital broadband instrumentation since 2005: PV12 in November, 2005; PV04 in May, 2007; PV14 in June 2007; PV02, PV03, PV10, and PV11 in October, 2008; PV01, PV05, PV07, PV13, and PV16 in May, 2010; and PV15 in July, 2011. 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 not to upgrade stations PV08 and PV09 at their original locations because of poor site conditions and resulting 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 is no longer maintaining the obsolete analog seismic stations. Three of the analog stations went permanently offline between 2002 and 2006 (PV04, PV12, and PV14; Table 2-1). Four additional analog stations have been offline since 2011 (PV02, PV07, PV08, and PV15). Another analog station (PV11) ceased functioning in late 2013. The remaining seven analog stations were taken offline 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 have been 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 would completely saturate the high-gain array.

The locations of the PVSN seismograph stations are shown in Figure 2-6. Details about the stations are provided in Table 2-1, including installation date, station type, and number of components. Table 2-2 lists the station location names.

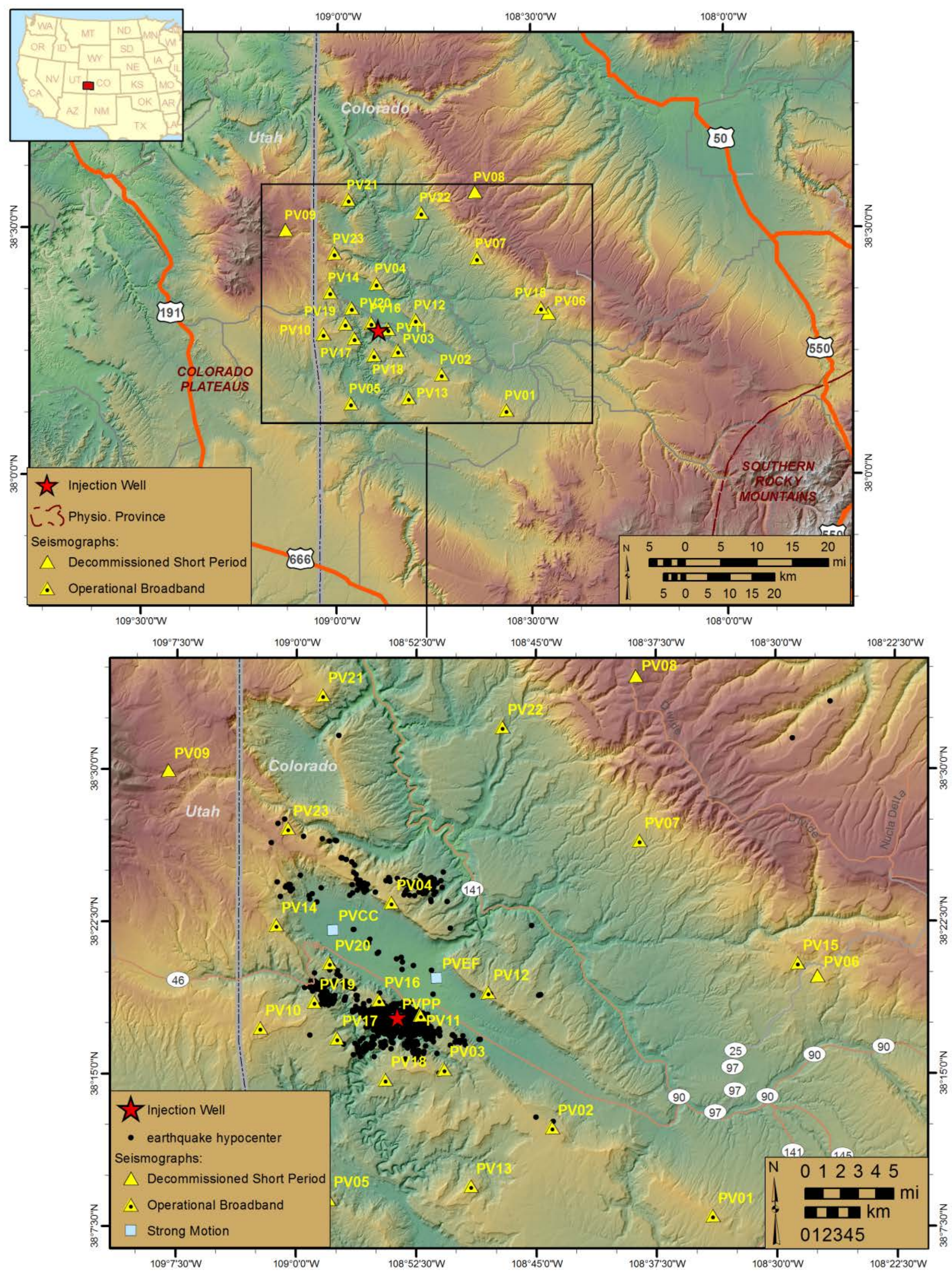


Figure 2-6: Locations of the PVSN seismic stations, PVU injection well, and epicenters of earthquakes less than 8.5 km deep. PVCC, PVEF, & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Physiographic provinces from Fenneman and Johnson (1946).

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 6,000 shallow (< 8.5 km deep) earthquakes have been recorded in the vicinity of Paradox Valley since injection began in 1991. No such 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 2-7). The initial earthquakes, detected four days after the start of the first injection test in July 1991, occurred very close to the injection well. As injection continued, earthquakes occurred at progressively increasing radial distances, and, by 2002, earthquakes were occurring nearly 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 2-7 strongly suggest that these earthquakes have been induced by PVU fluid injection.

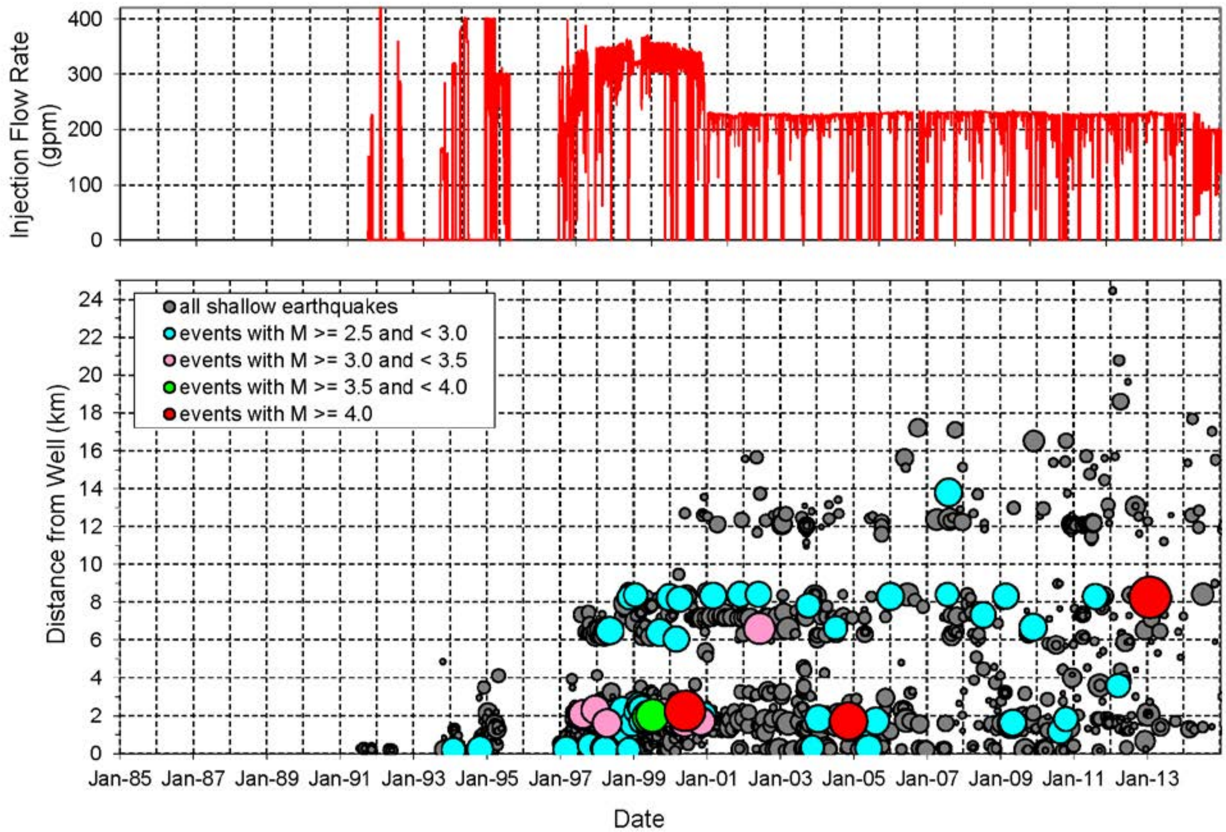


Figure 2-7: Lower plot: scatter plot of earthquakes having magnitude ≥ 0.5 and locating less than 8.5 km deep (relative to the ground surface elevation at the injection wellhead), plotted as a function of date and distance from the PVU injection well. Each circle represents a single earthquake, with 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 3 to 4 km from the well (Figure 2-8a). 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 2-8b). 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 2-8b). Several distinct clusters of earthquakes have occurred along the northern edges of the valley since 2000 (Figure 2-8c,d). The earthquakes occurring in all of these groups are referred to as “northern valley events”. An earthquake was first detected about 6 km southeast of the injection well in 2004 (Figure 2-8c), but the seismicity rate in this area markedly increased beginning in 2010 (Figure 2-8d). This tight group of earthquakes is referred to as the "southeast (SE) cluster". In recent years, a few isolated earthquakes have been detected in previously aseismic areas, including in the center of Paradox Valley (Figure 2-8d).

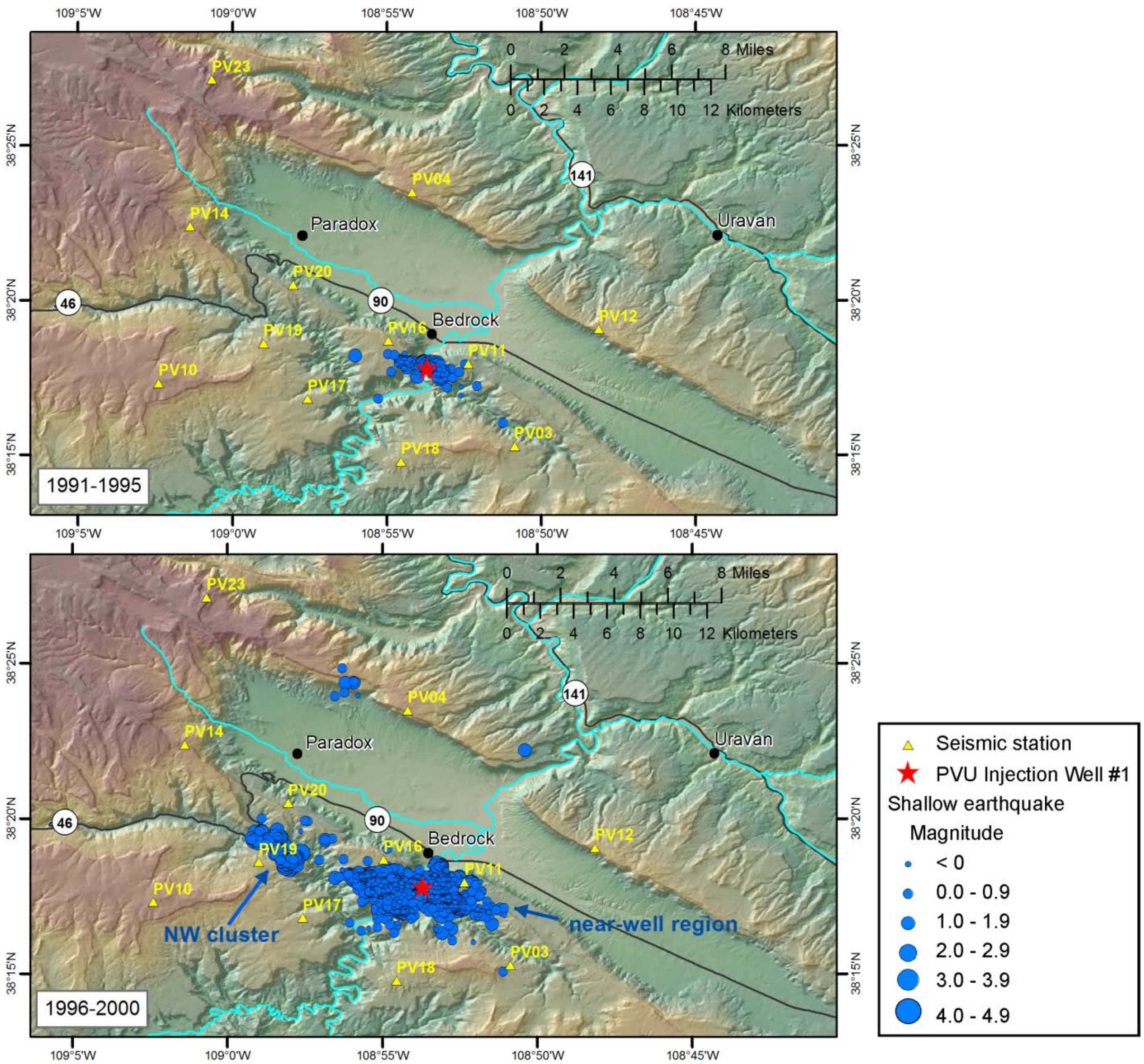


Figure 2-8: Maps showing the spatial distribution of shallow seismicity recorded in the Paradox Valley area over time: (a) injection tests, 1991-1995 (b) continuous injection,1996-2000 (c) continuous injection, 2001-2008 (d) continuous injection, 2009-2014. All detected earthquakes locating less than 8.5 km deep (relative to the ground surface elevation at the injection wellhead) are included.

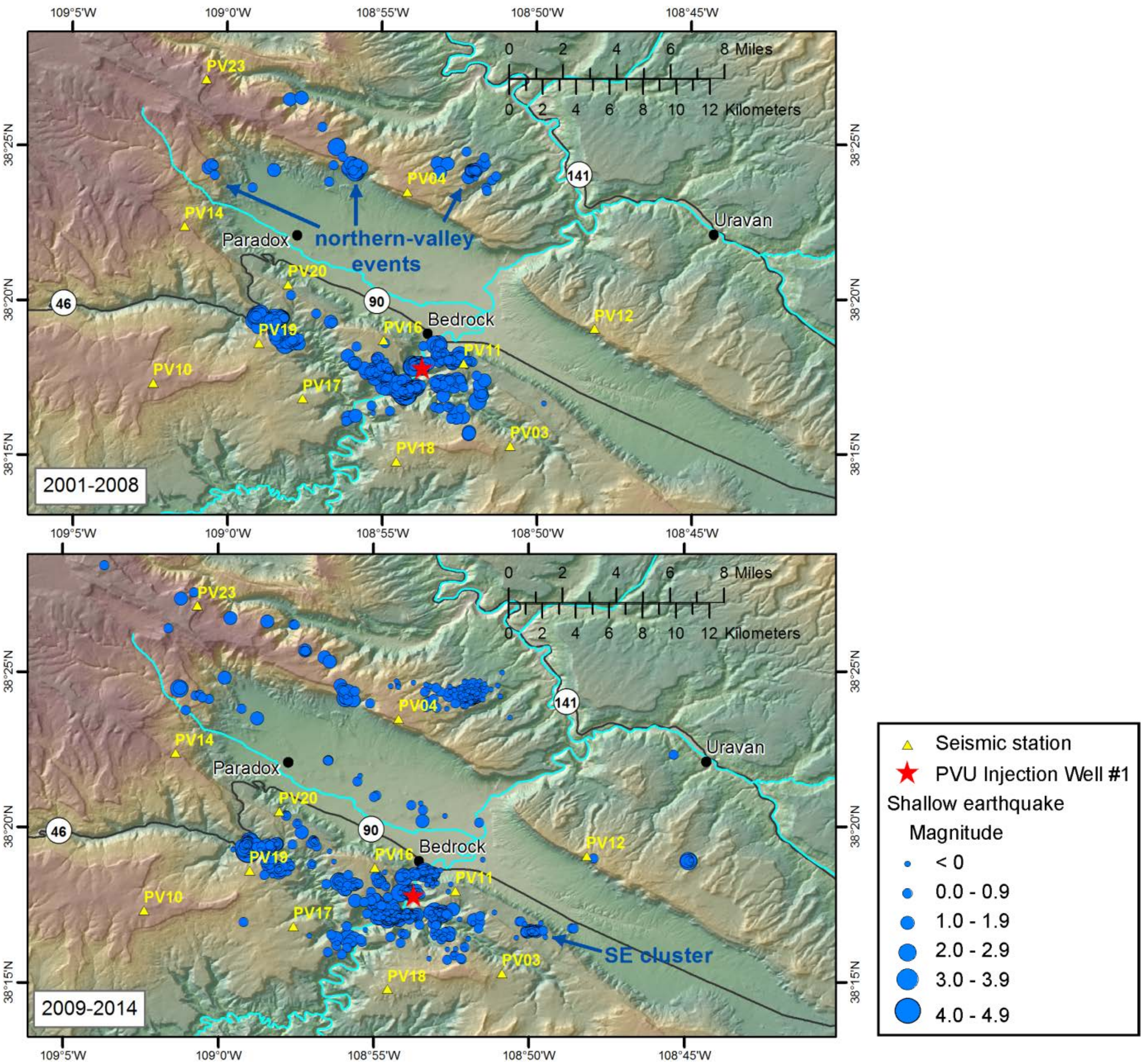


Figure 2-8, continued.

3 2014 Network Operations

3.1 Network Maintenance and Upgrades

Site visits in 2014 included the relocation and upgrade of the radio communications hub and data acquisition systems, seismograph station repairs in response to various electronic failures, updated GPS survey of seismograph vaults, and routine maintenance. See Appendix A for individual field trip reports which describe the work performed at each site.

The most significant field effort in 2014 was the transfer of the PVSN's communications and data acquisition hub (PVSN Comm Hub) from the Hopkins Field Airport terminal building to a separate, self-contained communications building. Moving the communication facility was mandated due to the FAA's decommissioning of the old Hopkins Field terminal and antenna tower, which was replaced with a new terminal and tower. Because the new terminal was not designed to accommodate a replacement PVSN Comm Hub, a separate self-contained electronic shelter built to PVSN's specification was designed, built, and installed at Hopkins Field near a new 50-ft antenna tower. The new electronics shelter provides PVSN with proprietary management and access to its radio communications and data acquisition systems. Features, such as an independent generator and battery backup systems, will help ensure the uninterrupted operations of the PVSN network. Multiple field trips were required to relocate the communication and data acquisition systems. Work performed included: installation of a state-certified lightning and grounding system, installation of a state-certified air conditioning and power generator system, installation of COAX cables and antennas following Motorola standards and guidelines on the new radio tower, and re-configuration of the PVSN data acquisition servers and communication computer systems.

Several stations required site visits to repair failed electronics. Stations PV01 and PV21 both required replacement of the DM24-BoB (noise suppression and surge protection electronics) due to failed fuses which were sized too small. PV21 also required replacement of the COAX cable due to wildlife damage. Station PV16 failed due to damage to the photo-voltaic panel wiring harness by wildlife. At station PV22, the GPS unit failed and required replacement. The effect of the electronic failures on the network performance is discussed in the following section.

Reclamation performed survey-grade GPS measurements at 14 PVSN broadband seismic stations and three strong motion (accelerometer) stations. The purpose of the GPS survey was to document the precise location of seismometer vaults as well as other seismic instrumentation. This data will improve Reclamation's ability to better determine accurate earthquake hypocenters and aid in field visits to remote stations. Stations surveyed include PV01, PV02, PV03, PV04, PV05, PV10, PV11, PV13, PV15, PV16, PV17, PV19, PV20, PV23, PVCC, PVEF, and PVPP, as well as the location of the PVSN Comm Hub major structural components at Hopkins Field Airport. Measurement accuracy was approximately 1/100 of a foot (about 1/8 inch) horizontally and 1/2 inch vertically. The GPS equipment included Trimble 4800 series receivers, which track GPS satellites on both the L1 and L2 frequencies to provide precise location data, and a Trimble Trimmark 3 Radio (450-470MHz) Repeater Base. The base station measurements were taken primarily to precisely determine the coordinates of the seismograph vaults. Likewise, the locations of the seismic station instrumentation enclosures (data logger, radio, power control box) and antenna towers were also measured.

3.2 Network Performance

PVSN performed fairly well during 2014. Network performance can be evaluated in two aspects: by the network data acquisition (the continuity of the data acquisition and recording systems) and the performance of individual seismic stations (the continuity of data gathering and transmission at individual stations).

The majority of individual seismic stations performed well throughout 2014 (Figure 3-1). Three digital seismic stations had temporary failures which required field visits to resolve: PV01, PV16, and PV21 (Table 3-1). In addition, the GPS clock at station PV22 malfunctioned, causing the absolute times to be unreliable until the unit was replaced. Also, station PV23 began having intermittent downtimes late in the year and has subsequently gone offline. Failed seismic stations were serviced as soon as feasible, but many stations are not accessible in the winter and therefore cannot be serviced immediately upon failure. These failures typically lasted 1-3 months and did not impact the ability of the network to detect and locate induced earthquakes.

Several stations had communication connectivity issues impacting their ability to transmit continuous near real-time data. In such cases, the daily average uptime (the time the instrument is connected) was reduced at these individual stations (Figure 3-1**Error! Reference source not found.**). The impact of such connectivity issues was generally small, reducing the daily average uptime by 5-10%. The stations most affected include PV02, PV05, PV13, PV20, and PV21. Station PV05 was the most severely affected by connectivity issues, and its poor line-of-site radio signal path may be a contributing factor. Although line-of-site issues may be of concern at PV05 and at the other stations, the connectivity issues began after the transition to the new communication hub and data acquisition system at Hopkins Airport in Nucla and therefore may be related to an unresolved problem at the hub. Presently, the cause of this problem is unclear and is under investigation. Considering both the hardware failures at individual seismic stations and the telemetry data drop-outs, the 2014 annual percent uptime for each station ranged from 65% to 98% (Figure 3-3).

The old analog seismic stations, comprised primarily of single-component short-period seismometers, are no longer considered active components of PVSN and were previously replaced with newer digital three-component broadband seismic stations. Reclamation continued to receive and record data from some of these analog stations, although they have not been maintained and their performance has degraded over time. The analog stations were taken offline on July 16, 2014, when the data acquisition system was moved to the new PVSN Comm Hub (Figure 3-4, Table 3-2).

Eight interruptions occurred to the PVSN data acquisition systems during 2014 (Table 3-3). Unplanned power outages occurred from January 20-22 (40.5 hours), February 27 – March 3 (88 hours), and from June 8-9 (23 hours). The relocation of the data acquisition system at Hopkins Field to the new PVSN Comm Hub on July 16-17 resulted in 22 hours of downtime. As part of this upgrade, the data acquisition computer systems were provided with a dedicated DC battery backup power supply and a natural gas AC generator, which should greatly reduce or eliminate future downtime due to commercial AC power outages. On August 28, the network was down for 12 hours, due to a hard drive failure on a data acquisition server at Hopkins Field. From September 22-24 (44.5 hours) the data acquisition systems were running, but event detection was substantially compromised due to an initialization problem with the *Scream* data acquisition software. Two outages occurred between October 20 and 22 (total 17.85 hours) as a result of upgrading the data acquisition server. In total, there were approximately 10.3 days when the PVSN data acquisition system was down. Therefore, PVSN data acquisition was up and functioning normally for 97.2 % of the year, which is comparable to the past few years of operations (Table 3-4).

Table 3-1: Performance of digital seismic stations during 2014

Station	Performance
PV01	The station was offline at the start of the year due to a failed DM24 breakout box. The electronics were replaced and the station was brought back online on March 20th 2014. Otherwise, the station was online and functioning normally throughout the year.
PV02	Online and functioning normally throughout the year.
PV03	Online and functioning normally throughout the year.
PV04	Online and functioning normally throughout the year.
PV05	Online and functioning normally throughout the year.
PV07	Online and functioning normally throughout the year.
PV10	Online and functioning normally throughout the year.
PV11	Online and functioning normally throughout the year.
PV12	Online and functioning normally throughout the year.
PV13	Online and functioning normally throughout the year.
PV14	Online and functioning normally throughout the year.
PV15	Online and functioning normally throughout the year.
PV16	The station was offline from May 26th 2014 – July 18th 2014 due to damage incurred from wildlife. Otherwise online and functioning normally throughout the year.
PV17	Online and functioning normally throughout the year.
PV18	Online and functioning normally throughout the year.
PV19	Online and functioning normally throughout the year.
PV20	Online and functioning normally throughout the year.
PV21	The station was offline from February 1st 2014 – March 21st 2014 due to a problem with the DM24 and power connection issues. The station went offline on December 14th for unknown reasons and remains down pending a field trip.
PV22	The GPS clock was replaced in late March to restore reliable timing. Otherwise online and functioning normally throughout the year.
PV23	Online and functioning normally until mid-December, when intermittent downtimes began occurring, most likely due to problems with the power supply.

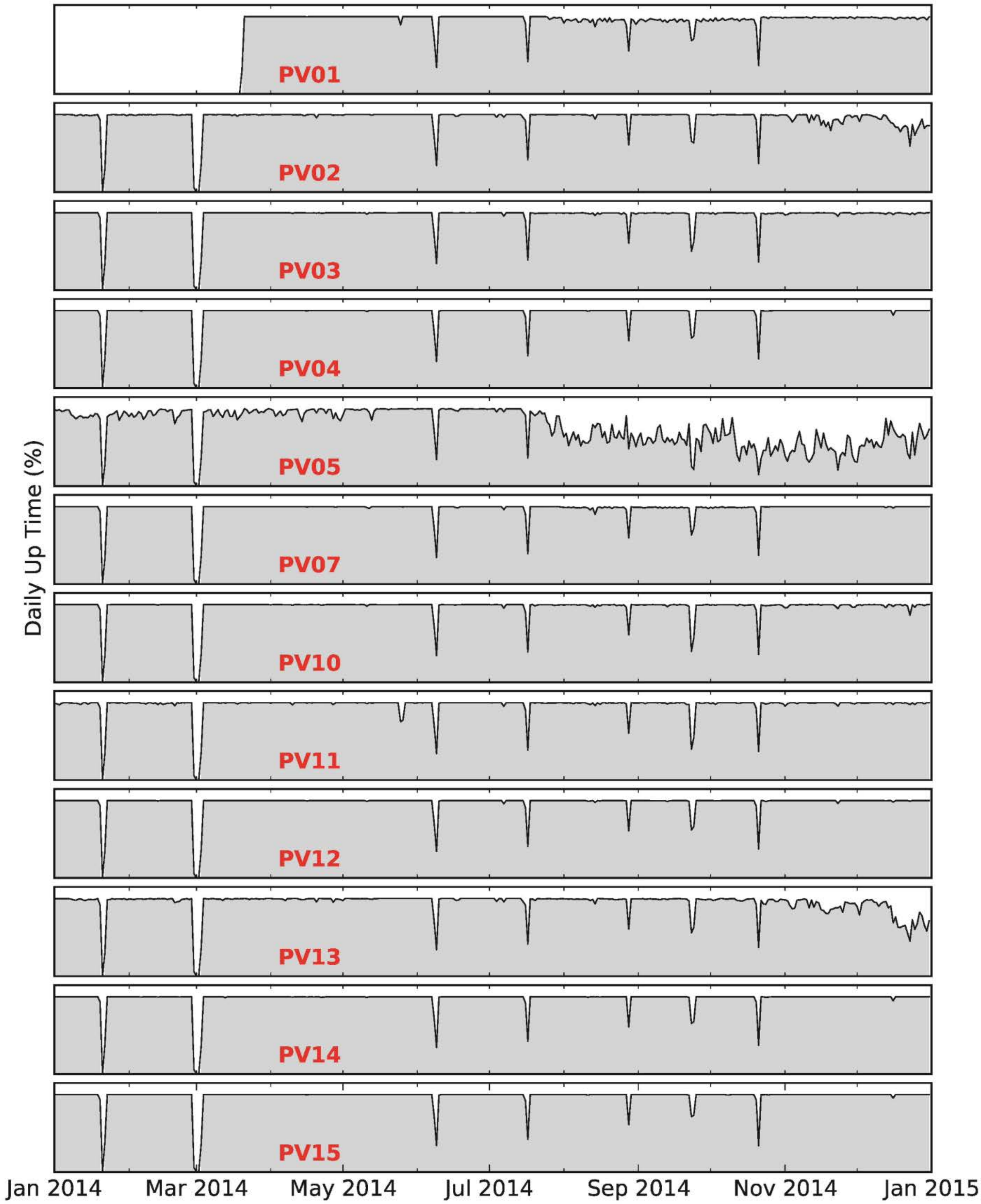


Figure 3-1. Daily uptime (%) for each digital PVSN seismic station during 2014 . Filled gray areas represent uptime, while dips in the filled volume show decreases in uptime. Vertical axes on plots are scaled from 0 to 115%. Coeval dips in performance are the result of failures in the central data acquisition systems. A long period of zero uptime at a single station is commonly the result of a hardware failure at that station. Daily variance in uptime is generally the result of poor radio communications with a given station.

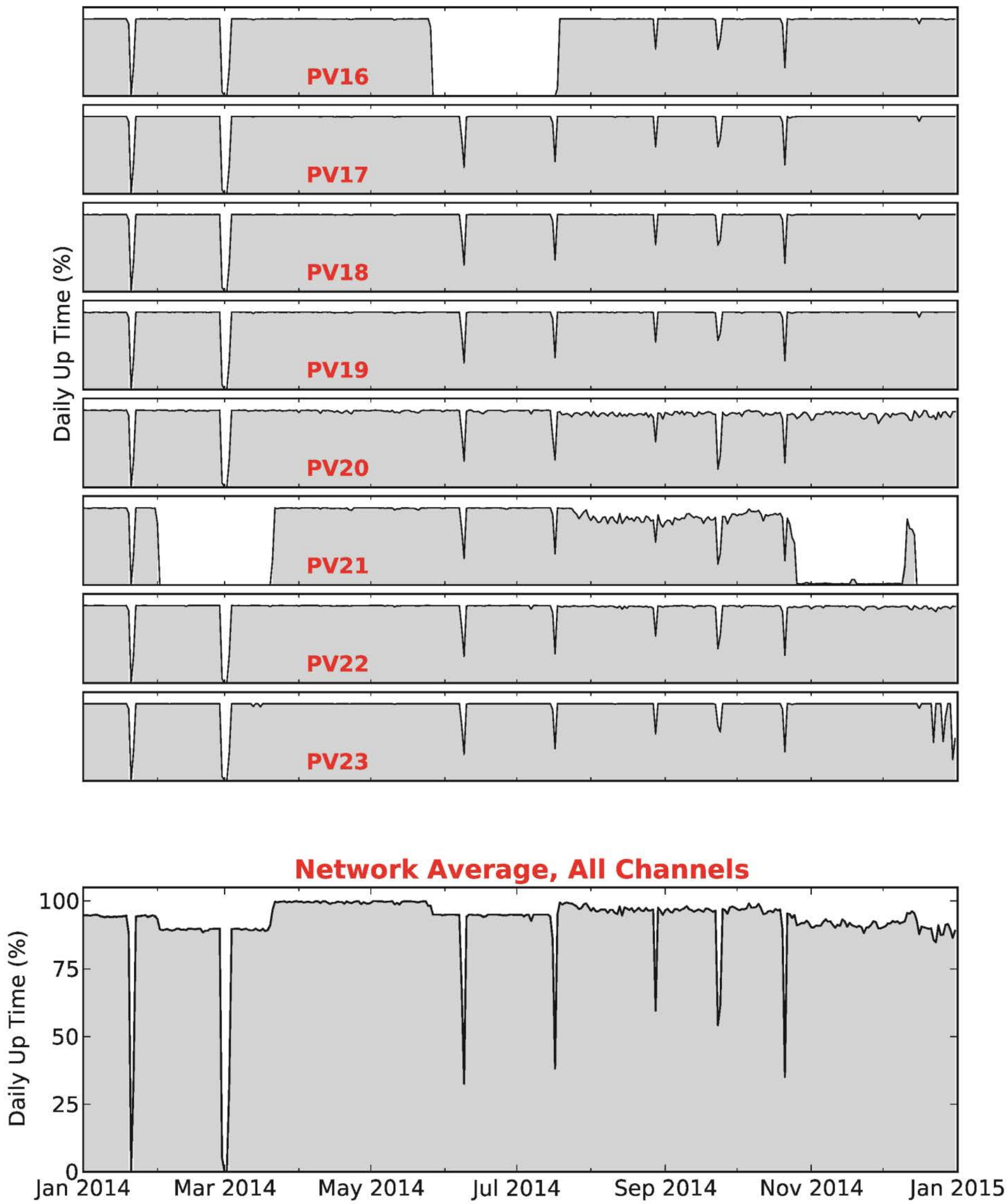


Figure 3-2. Same as Figure 3-1 for the rest of the PVSN stations. Bottom plot shows the daily average performance for all digital PVSN stations.

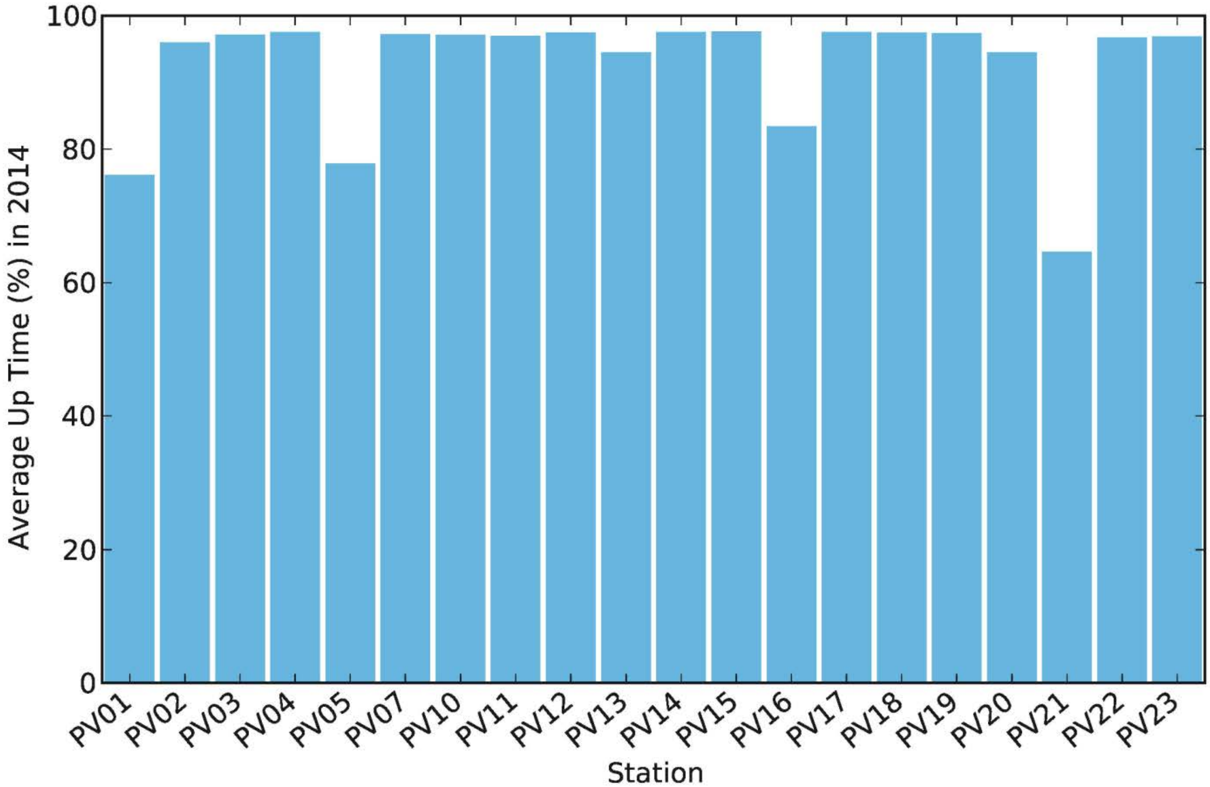


Figure 3-3. Annual (2014) uptime (%) for each digital PVSN seismic station.

Table 3-2: Performance of analog seismic stations during 2014

Station	Performance
PV01	Taken permanently offline on July 16th 2014. Previously functioning normally.
PV02	Permanently offline since 2011.
PV03	Taken permanently offline on July 16th 2014. Previously functioning normally.
PV05	Taken permanently offline on July 16th 2014. Previously functioning normally.
PV07	Permanently offline since 2011.
PV08	Permanently offline since 2011.
PV09	Taken permanently offline on July 16th 2014. Previously functioning normally.
PV10	Taken permanently offline on July 16th 2014. Previously functioning normally.
PV11	Permanently offline since 2013.
PV13	Taken permanently offline on July 16th 2014. Previously functioning normally.
PV15	Permanently offline since 2011.
PV16	Taken permanently offline on July 16th 2014. Previously functioning intermittently.

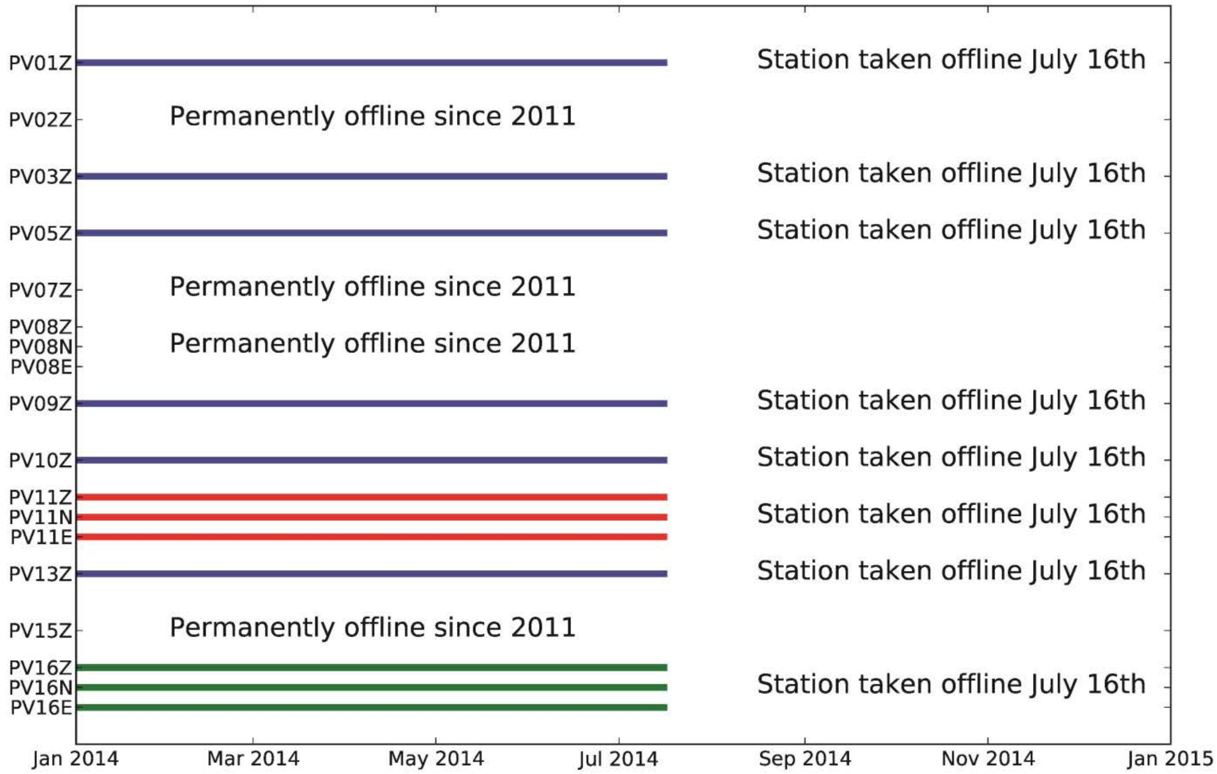


Figure 3-4: Annual (2014) performance of PVSN analog seismic data channels. Trace components are labeled as: Z = vertical component, N = north-south horizontal component, E = east-west horizontal component. Blue lines indicate that the channel was functioning adequately. Red lines indicate that the channel was offline. Green lines indicate that the channel was operating intermittently. (Three analog stations not shown here (PV04, PV12, and PV14) were taken permanently offline between 2002 and 2006.)

Table 3-3: Data acquisition downtimes during 2014

Down Period (UTC)	Reason
1/20 22:25 to 1/22 14:55	Power failure at Hopkins Field Airport
2/27 16:20 to 3/3 8:14	Power failure at Hopkins Field Airport
6/8 17:04 to 6/9 15:49	Power failure at Hopkins Field Airport
7/16 16:04 to 7/17 13:49	Transfer of data acquisition system to new building.
8/28 5:30 to 8/28 17:30	Hard drive failure in data acquisition system
9/22 22:25 to 9/24 19:00	Systems running, but event detection was compromised due to software issues
10/20 22:15 to 10/21 14:00	Server upgrade
10/21 21:54 to 10/22 00:00	Server upgrade

Table 3-4: Annual PVSN data acquisitions uptime

Year	Annual Number of Down Days	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%
2011	12.2	96.7%
2012	2.2	99.4%
2013	4.6	98.8%
2014º	10.3	97.2%
**not tabulated in 2001 º includes 40.5 hours of downtime in September when network was operating but event detection was severely degraded.		

4 Seismic Data Recorded in 2014

4.1 Annual Summary

Forty-five earthquakes were recorded within or near the perimeter of PVSN during 2014. 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 circles). During 2014, 28 earthquakes were detected in the near-well region of induced seismicity (within 5 km of the injection well, magenta circles in Figure 4-1), two earthquakes were detected in the northwest (NW) cluster (6 to 9 km northwest of well, blue circles), two earthquakes were detected in the southeast (SE) cluster (6 to 7 km southeast of well, green circles), and five earthquakes were detected in areas of recurring seismicity around the northern edge of Paradox Valley (yellow circles). In addition, four earthquakes occurred beneath north-central Paradox valley, in areas that have been seismically active since 2010 (red circles in Figure 4-1; three of the events occurred at the same location near the northern end of Paradox Valley). The remaining four earthquakes occurred in areas that have experienced little to no previous seismic activity. Two of these events occurred 15.5 to 17 km southeast of the injection well, close to seismic station PV02 (white circles in Figure 4-1). No events had previously been detected in this location. The depths of these events are 6.2 and 4.6 km, relative to the ground surface elevation at the injection well. An additional shallow event occurred 8.7 km east of the injection well, near seismic station PV12 (white circle); its estimated depth is 5.9 km. One deep event (depth ≥ 8.5 km) was recorded in the vicinity of Paradox Valley during 2014. This event occurred about 19 km northeast of the injection well and has an estimated depth of 10.8 km. The numbers and magnitudes of the earthquakes in each of the location categories are summarized in Table 4-1, and the average daily seismicity rates are listed in Table 4-2. The date and time of occurrence, latitude, longitude, elevation, depth, and computed duration magnitude of each earthquake are listed in Appendix B.

The local earthquakes recorded by PVSN during 2014 are plotted as a function of date, earthquake magnitude, and location category in Figure 4-2. This graph shows that the northern-valley events occurred during the first half of the year (in February, March, and May), whereas the central-valley events and the isolated events around the southern edges of Paradox Valley (in the “other” location category) occurred late in the year (in September to November). The near-well area, NW cluster, and SE cluster exhibited low rates of seismicity with no distinct temporal trends.

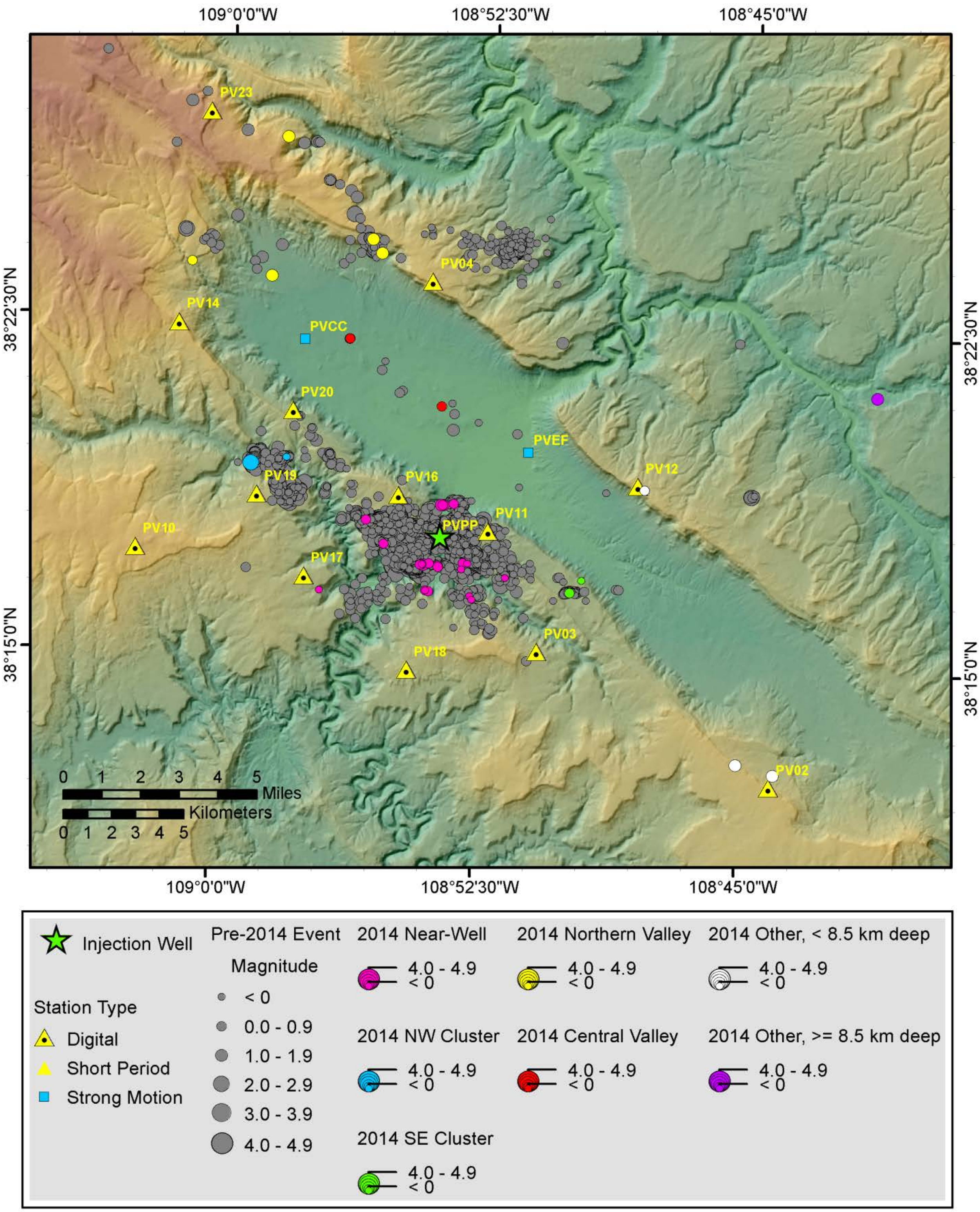


Figure 4-1: Locations of local earthquakes recorded by PVSN during 2014 (colored circles) and previous years (gray circles).

Table 4-1: Summary of events recorded during 2014 by location category

Location Category	Number of Earthquakes	Magnitude Range	Median Magnitude
near-well	28	-1.2 – 1.7	0.1
NW cluster	2	-0.2 – 2.3	1.1
SE cluster	2	-0.5 – 0.5	0.0
central valley	4	0.1 – 0.8	0.2
northern valley	5	0.7 – 1.5	1.1
other	4	0.1 – 1.8	1.1
TOTAL	45	-1.2 – 2.3	0.3

Table 4-2: Average daily seismicity rates of local earthquakes recorded by PVSN during 2014. These rates were computed using the number of days the network was operational, 354.7, as discussed in section 3.

Earthquake Category	All Magnitudes		Magnitude ≥ 0.5	
	Number of Events Recorded	Average Daily Rate	Number of Events Recorded	Average Daily Rate
near-well	28	0.079	7	0.020
NW-cluster	2	0.006	1	0.003
SE cluster	2	0.006	1	0.003
central valley	4	0.011	1	0.003
northern valley	5	0.014	5	0.014
Other	4	0.011	3	0.008
TOTAL	45	0.127	18	0.051

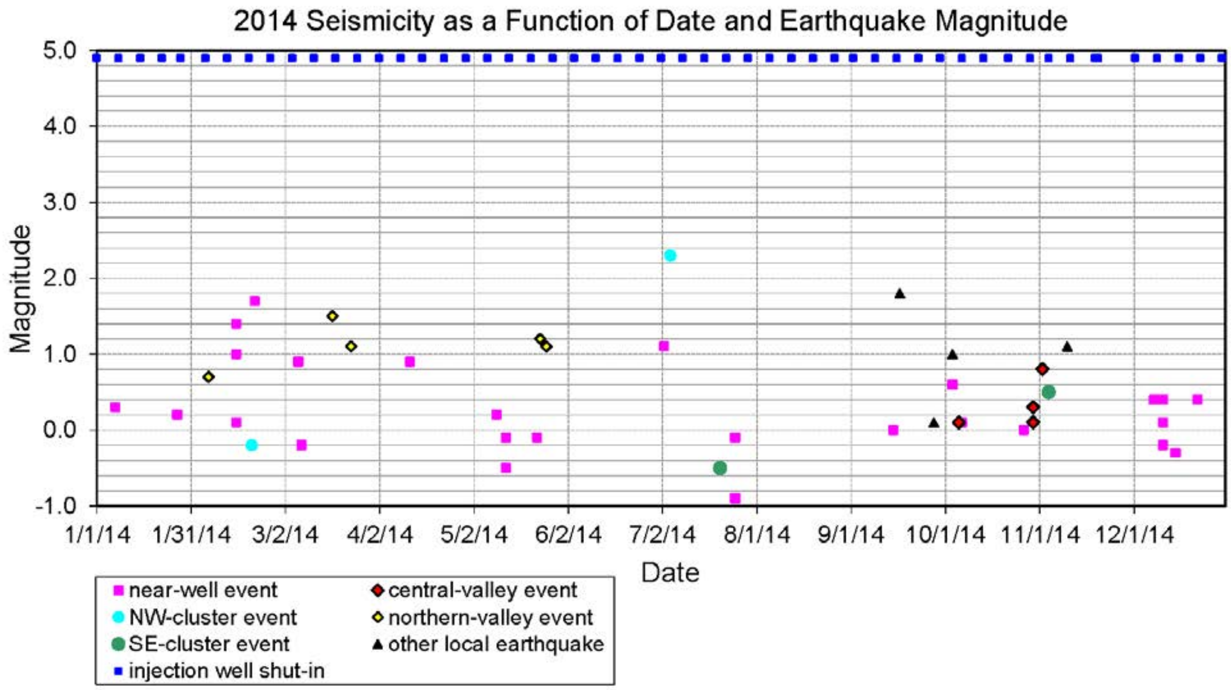


Figure 4-2: Earthquakes recorded by PVSN during 2014, plotted as a function of date, magnitude, and event location category. The dates of injection well shut-ins are included as indicated by the legend.

4.2 Shallow Earthquakes Locating within 10 km of the Injection Well

4.2.1 2014 Seismicity

The earthquakes induced within 10 km of the injection well during 2014 occurred in areas of previous seismic activity. The hypocenters of the earthquakes that occurred in 2014 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 2014 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 using an algorithm employing manually-determined absolute arrival times, because the waveform data were not of sufficient quantity or quality to include these events in the relative location.

Four shallow, likely-induced earthquakes occurred beneath Paradox Valley in 2014. One of these events occurred 5.5 km from the injection well (white circle, Figure 4-3), at an estimated depth of 6.8 km (relative to the ground surface elevation at the injection well). Its duration magnitude is 0.1. The other three events have nearly identical epicenters 9.1 km from the well (red circle,

Figure 4-3) and identical estimated depths of 5.4 km. Their duration magnitudes range from 0.1 to 0.8. Earthquakes were first detected beneath Paradox Valley in 2010. Three such events were recorded in 2010, two in 2011, five in 2012, and five in 2013.

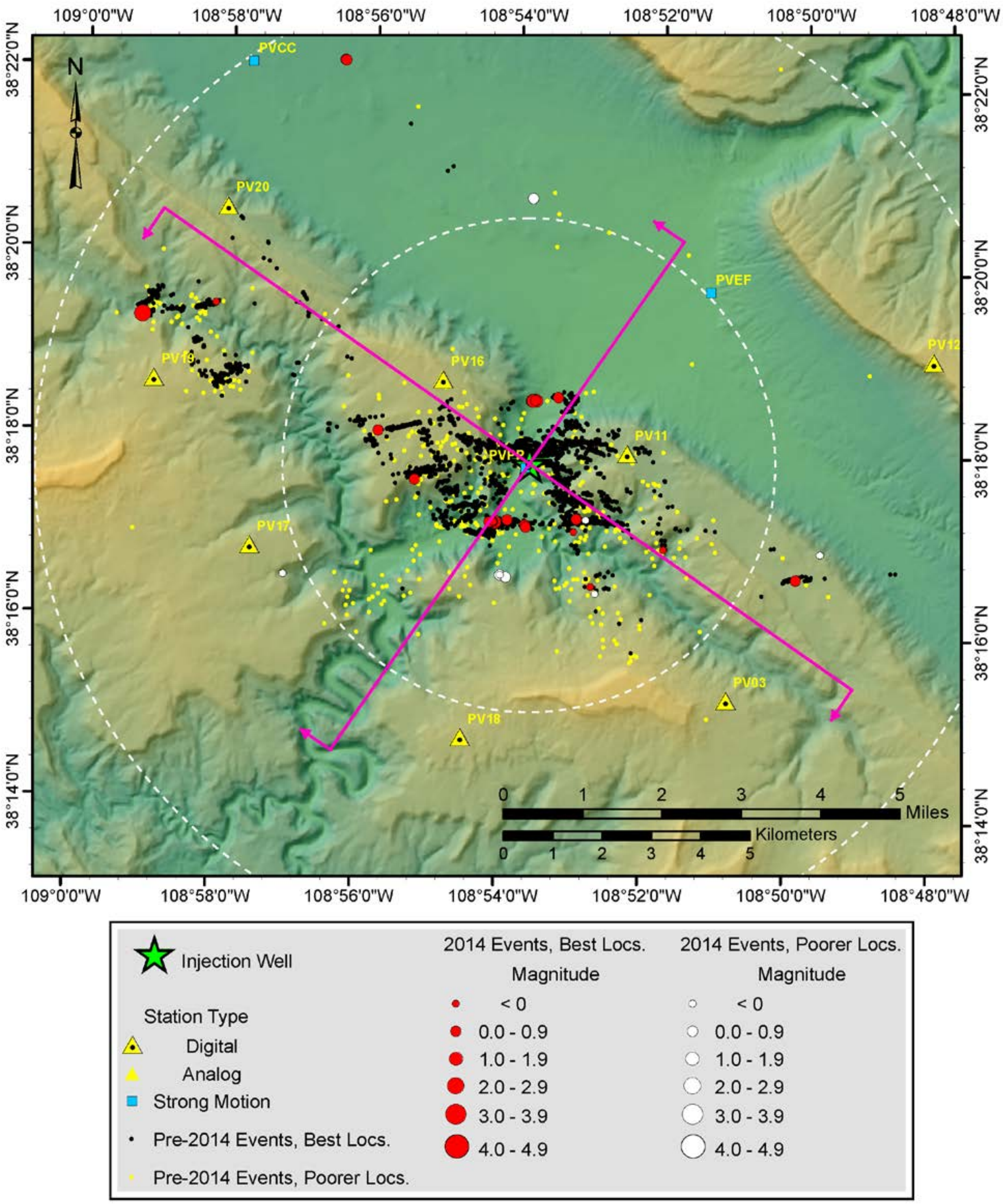
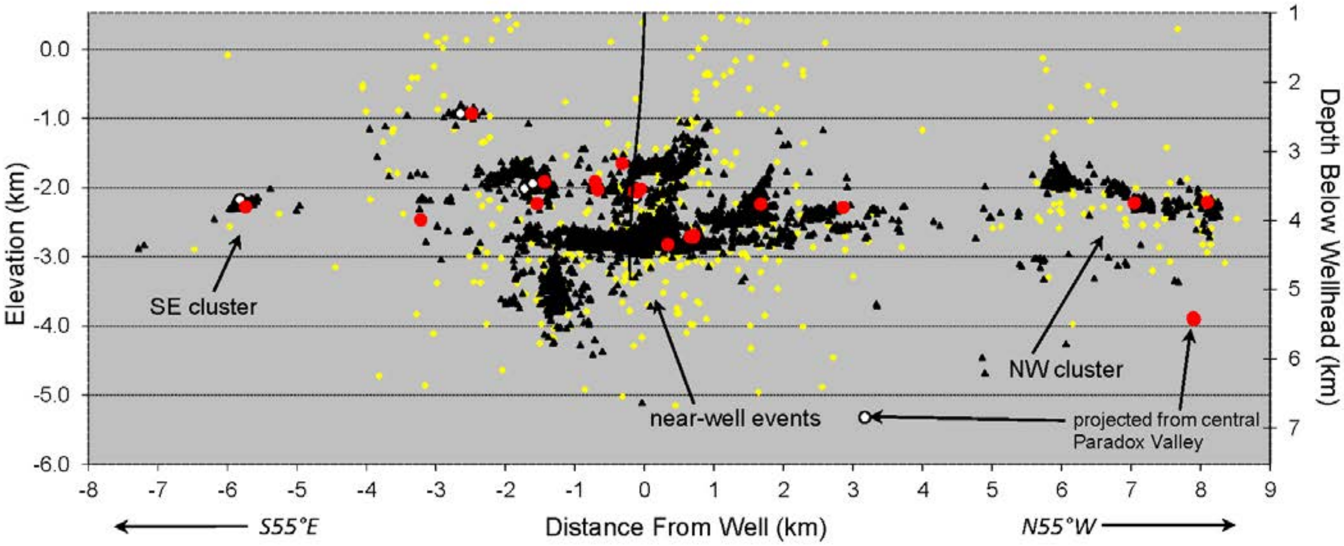


Figure 4-3: Map showing the epicenters of shallow earthquakes (< 8.5 km depth) in the vicinity of the injection well in 2014, compared to the locations of previously-induced events. The white dashed circles indicate radial distances of 5 and 10 km from the injection well. The magenta lines indicate the 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

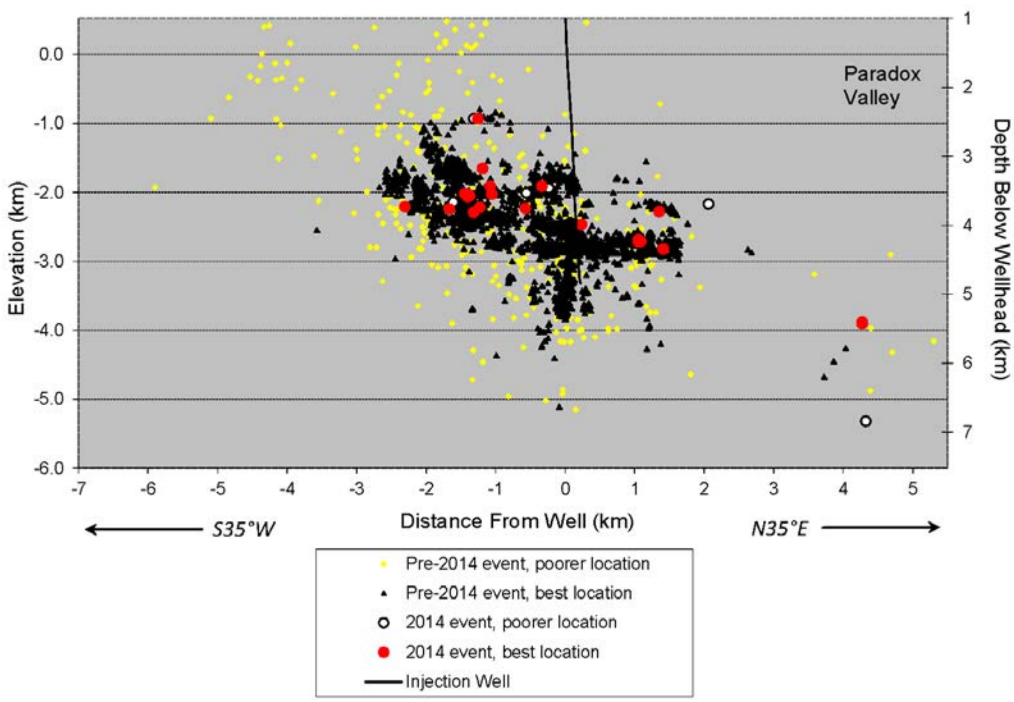


Figure 4-4: Vertical cross sections showing the hypocenters of earthquakes occurring within approximately 10 km of the injection well in 2014, compared to the locations of previously-induced events: (a) section parallel to Paradox Valley (b) section perpendicular to Paradox Valley. The orientations of the cross sections are indicated by the magenta lines in Figure 4-3.

4.2.2 Comparison to 2013 Seismicity

The number of earthquakes observed within 10 km of the injection well decreased by 67% in 2014 (37 events) compared to 2013 (112 events). Some of this decrease, particularly for the smallest-magnitude events (< ~M 0.5), may be due to variations in PVSN's event detection capabilities over time. In particular, the reliably of detecting the smallest-magnitude events may have decreased during the last few months of 2014, due to potential missed real-time triggering of these events caused by increased radio telemetry delays at several seismic stations. (Changes were made to a data acquisition parameter on May 1, 2015 to compensate for such telemetry delays in the future.) Although the effect of the telemetry delays on event triggering was still being investigated at the time of this report, it is unlikely that the decreased seismicity rate during 2014 is due mostly to changes in event detection capabilities. Rather, it is more likely that most of the decrease in seismicity rate is related to decreased reservoir pore pressures following the PVU operational changes made in 2013 (section 2.2.5).

In the absence of observation wells, spatiotemporal variation in seismicity rates is the only available indicator of changes in subsurface pore pressures. In addition, changes in rates of small-magnitude events often precede changes in the rates of larger-magnitude events (see, for example, Block and Wood, 2009). For these reasons, we include events of all magnitudes in the comparison of the 2014 and 2013 seismicity rates presented below. (In a later section (4.4), we perform a more robust examination of the variation in the seismicity rate throughout the history of PVU operations by including only events above the historical event completion threshold of ~M 0.5.)

The numbers of earthquakes recorded during 2014 and 2013 are plotted as a function of magnitude in Figure 4-5. Individual histograms are shown for earthquakes within 5 km of the injection well (the near-well region), for those at distances of 5 to 10 km from the well (the NW and SE clusters and the events in Paradox Valley), and for all events within 10 km of the well. These radial distances are indicated by the white dashed circles on the map in Figure 4-3. Cumulative magnitude-frequency plots of the same data are presented in Figure 4-6.

The seismicity rate for earthquakes locating within 5 km of the injection well decreased by 65% in 2014 (28 events) compared to the previous year (79 events). However, this decreased rate occurred only for earthquakes with duration magnitudes between -1.0 and 1.0 (Figure 4-5, top). The rates of events with magnitude ≥ 1.0 were identical for the past two years: 4 events per year. The largest near-well earthquake recorded during 2013 had a duration magnitude of M 2.4. The largest near-well earthquake recorded during 2014 had a smaller magnitude, M 1.7.

The seismicity rate for earthquakes at distances of 5 to 10 km from the injection well decreased by 73% in 2014 (9 events) compared to the previous year (33 events). This decreased rate occurred for earthquakes with nearly all magnitudes (Figure 4-5, middle). The maximum earthquake magnitude in this region decreased in 2014 compared to 2013. The largest event in this region recorded during 2013 had a local magnitude of 4.4, whereas the largest event recorded during 2014 had a duration magnitude of 2.3 (both events occurred in the NW cluster).

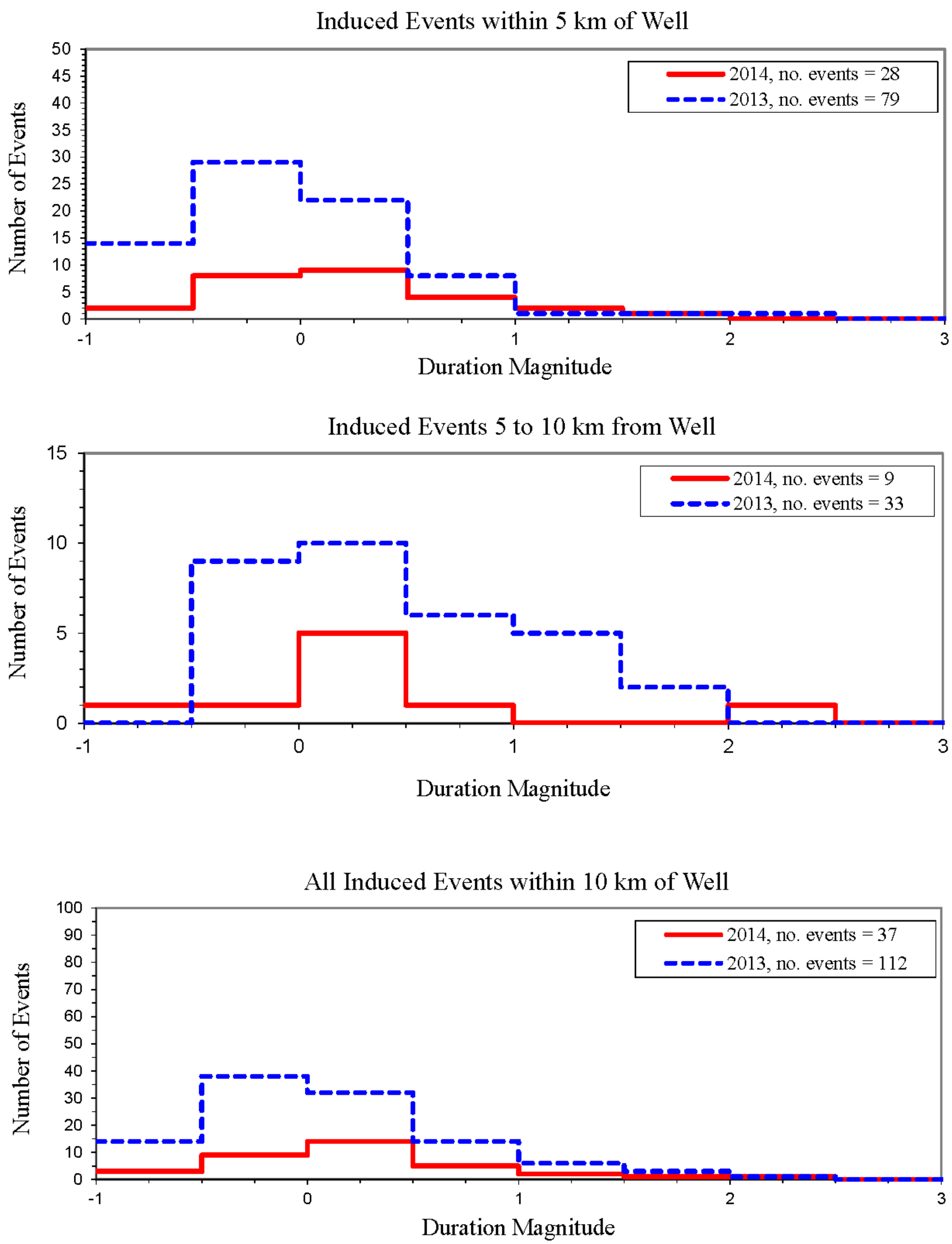


Figure 4-5: Magnitude histograms of events within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and in both regions (bottom) during 2014 (solid red lines) and 2013 (dashed blue lines).

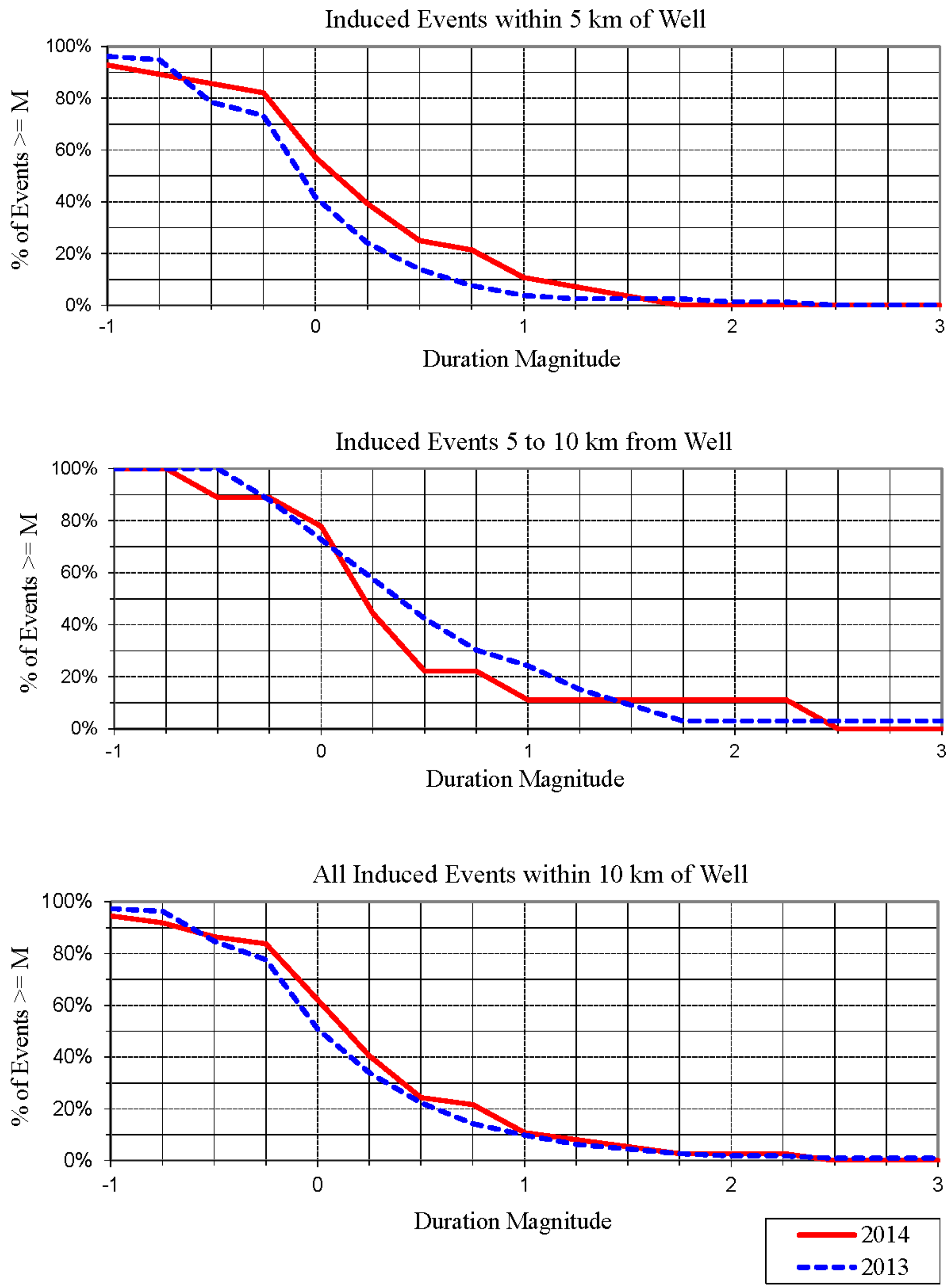


Figure 4-6: Cumulative magnitude-frequency plots of events within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and in both areas (bottom) during 2014 (solid red lines) and 2013 (dashed blue lines).

4.3 Northern Valley Earthquakes

The magnitudes and estimated depths of the five northern-valley earthquakes recorded during 2014 are comparable to the magnitudes and depths of northern-valley events recorded in previous years. Magnitudes of the northern-valley earthquakes recorded from 2000 (when they were first detected) through 2013 range from M -0.8 to M 2.9, with all but one event having duration magnitude ≤ 2.3. Magnitudes of the earthquakes that occurred during 2014 range from M 0.7 to M 1.5. Estimated depths of the northern-valley earthquakes recorded in 2014 range from 5.2 to 6.2 km (relative to the ground surface elevation at the injection wellhead), with a median value of 5.5 km. These values are comparable to estimated depths of previous northern-valley earthquakes having reasonably well-constrained hypocenters.

4.4 Historical Seismicity Trends

The rates and magnitudes of earthquakes that occurred during 2014 are compared to the historical seismicity trends in three plots described below. Only events with duration magnitude ≥ 0.5 (M 0.5+) are included in these plots, since the detection capability for earthquakes with magnitude less than this threshold has varied considerably over the history of PVSN. First, the bubble plots in Figure 4-7 show the historical occurrence of shallow seismicity (< 8.5 km depth) as a function of date and earthquake magnitude during long-term injection at PVU (1996-2014). The area of each circle in these plots is scaled by the number of earthquakes occurring in a given quarter-year and magnitude range. Individual bubble plots are included for earthquakes occurring within 5 km of the injection well (near-well region), between 5 and 10 km from the well (NW and SE clusters and events occurring beneath north-central Paradox Valley), and along the northern edge of Paradox Valley (northern-valley events). The downhole injection pressures, averaged over varying lengths of time, are included in Figure 4-7 for reference. In order to better observe the trends in recent years, similar plots that only include data from 2008-2014 are presented in Figure 4-8. Lastly, we show the annual seismicity rates for 2008-2014, for the different distances from the well, in Figure 4-9.

These plots show that both the seismicity rates and maximum earthquake magnitude for the near-well area (within 5 km of the well) were low in 2014 compared to most previous years. The decrease in near-well seismicity rate during 2014 continues a trend of decreasing near-well rates that has been observed since 2009 (Figure 4-9). The rate of M 0.5+ earthquakes observed in the near-well area during 2014 was 21% of the average rate observed during the previous 6 years (2008-2013).

The seismicity rate observed at distances of 5 to 10 km from the injection well was also low during 2014 compared to previous years. This change in seismicity rate appears to be more abrupt than for the near-well region, as we do not observe any consistent decrease in rates over the last several years (Figure 4-9). The rate of M 0.5+ earthquakes observed at distances of 5 to 10 km from the well during 2014 was 17% of the average rate observed during the previous 6 years. Most of the decrease from 2013 to 2014 occurred in the NW cluster, whereas rates in the SE cluster had decreased abruptly about a year earlier (Figure 4-10). Despite the substantially decreased seismicity rates, the maximum earthquake magnitude observed during 2014 at these radial distances was only slightly lower than maximum magnitudes observed during most previous years (Figure 4-7). The largest 2014 event, an M 2.3 event that occurred in the NW cluster, appears to have occurred on the same fault plane as the January 2013 M_L 4.4 event and may have been an aftershock of that larger event.

The seismicity rate of northern-valley events, which have occurred around the northern edges of Paradox Valley since 2000, remained low in 2014. Such low rates of northern-valley seismicity have been typical in the past, with the exception of occasional brief swarms of increased activity (in 2003, 2010, and 2011). The maximum northern-valley event magnitude in 2014 was M 1.5, which is comparable to maximum magnitudes in previous years.

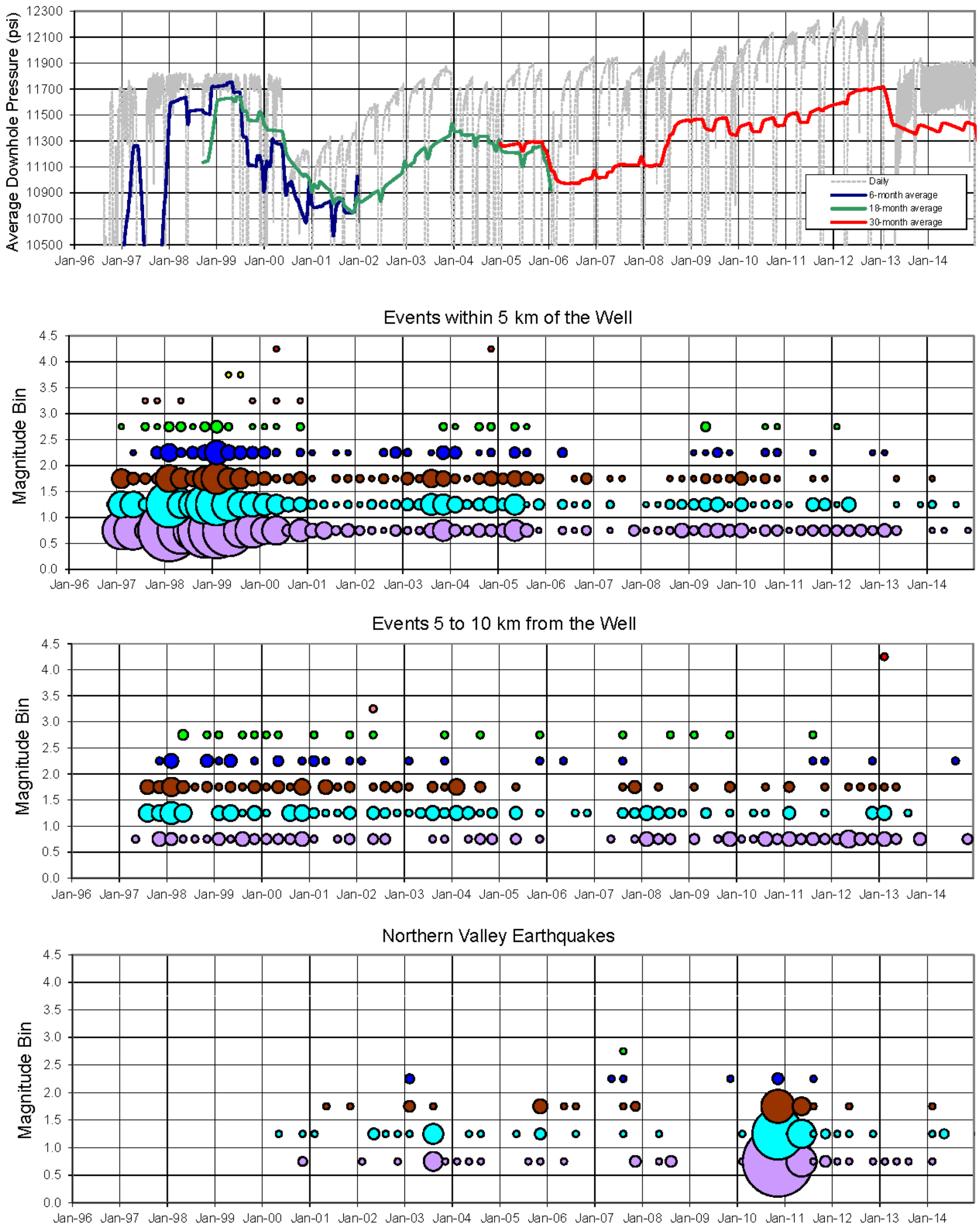


Figure 4-7: 1996-2014 injection well downhole pressure data averaged over daily, 6-month, 18-month, and 30-month time periods (top) and occurrence of shallow seismicity as a function of date and magnitude within 5 km of the injection well, at distances of 5 to 10 km from the well, and in the northern valley region. In the seismicity plots, the area of each circle is scaled by the number of earthquakes occurring in a given quarter-year and magnitude range; each plot is scaled separately.

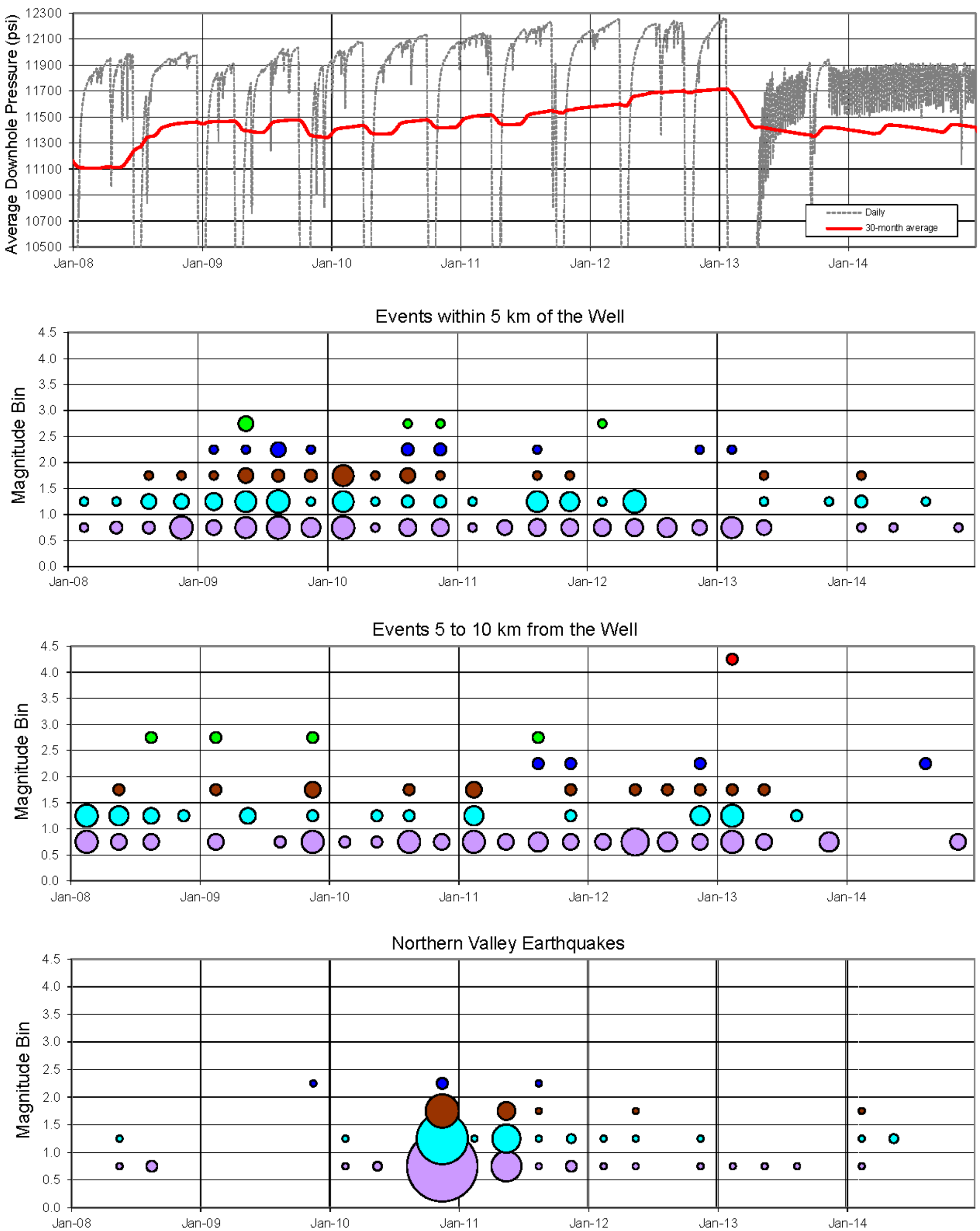


Figure 4-8: 2008-2014 injection well downhole pressure data averaged over daily and 30-month time periods (top) and occurrence of shallow seismicity as a function of date and magnitude within 5 km of the injection well, at distances of 5 to 10 km from the well, and in the northern valley region. In the seismicity plots, the area of each circle is scaled by the number of earthquakes occurring in a given quarter-year and magnitude range; each plot is scaled separately.

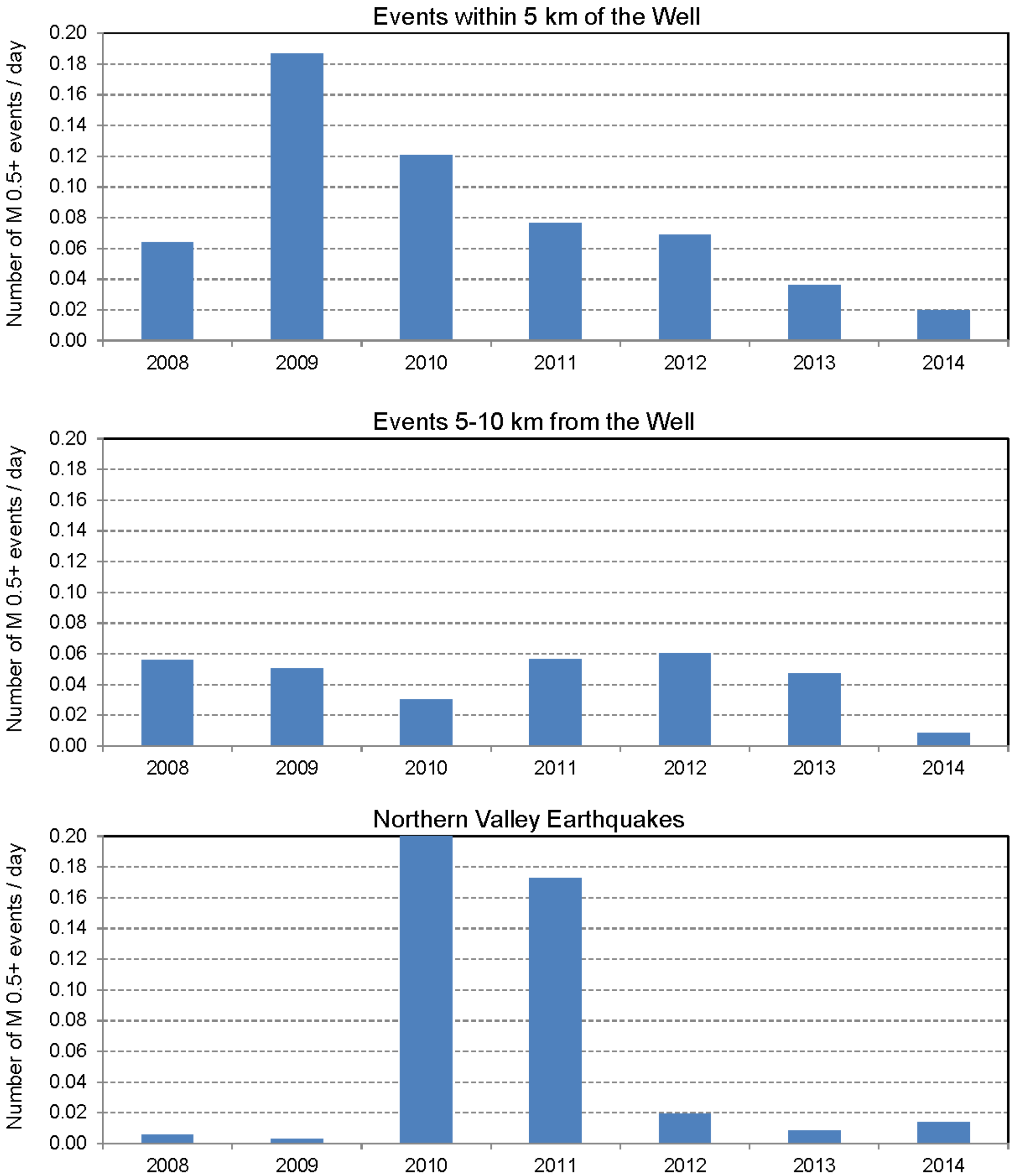


Figure 4-9: Annual rates of earthquakes with magnitude ≥ 0.5: within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and in the northern valley region (bottom). Data from 2008-2014 are shown.

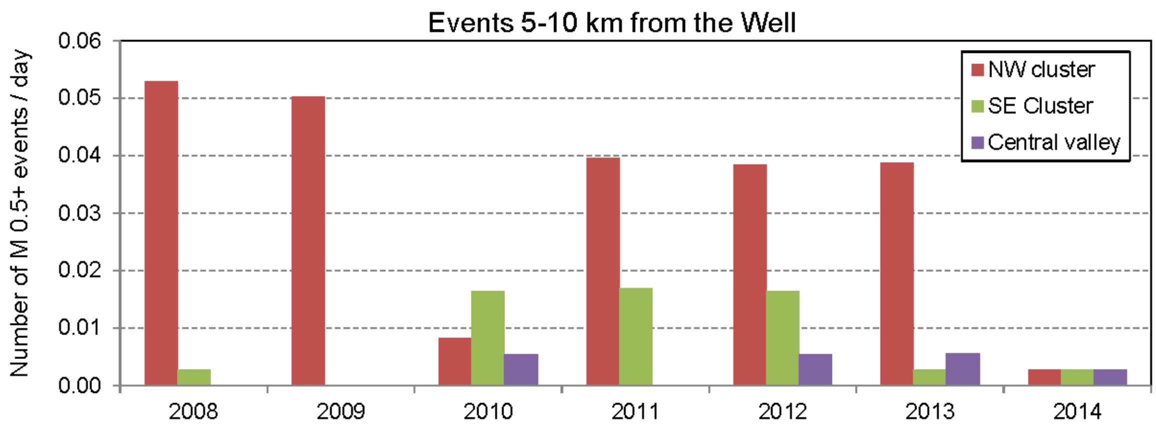


Figure 4-10: Annual rates of earthquakes with magnitude ≥ 0.5 occurring in the NW cluster, SE cluster, and north-central Paradox Valley. Data from 2008-2014 are shown.

5 Other Activities

5.1 Publications

In 2014, four manuscripts were accepted by peer-reviewed scholarly journals for publication. These manuscripts contain scientific analyses of geologic and seismic data from PVSN. The material in these manuscripts covers a wide range of topics relevant to PVU operations, including: the regional subsurface geologic structure, the relationship between injection operations and induced earthquakes, source mechanisms of induced earthquakes and their relation to preexisting faults, and induced earthquake maximum magnitude estimations over time. Each paper is briefly described in the sections below; the section headings correspond to the titles of the papers.

5.1.1 The 24 January 2013 M_L 4.4 Earthquake near Paradox, Colorado and its Relation to Deep Well Injection

This paper was published in the June 2014 issue of *Seismological Research Letters*, a publication of the Seismological Society of America (Block et al., 2014). The paper presents basic information about a felt earthquake that occurred in 2013, including: date and time of occurrence, location, magnitude, and fault plane characteristics. It compares the characteristics of the January 2013 event to those of previous earthquakes in the area. The paper compares observed ground motions to those predicted using standard empirical ground motion prediction equations. The major conclusions are: the January 2013 earthquake was induced by PVU fluid injection; most of the characteristics of the earthquake are similar to those of previous events, with the only significant difference being its distance from the injection well for an event of its magnitude; and that the ground motions observed from the earthquake were larger than what would be predicted using standard ground motion prediction equations.

5.1.2 Geological Structure of the Paradox Valley Region, Colorado, and Relationship to Seismicity Induced by Deep Well Injection

This paper was published in the *Journal of Geophysical Research, Solid Earth*, a publication of the American Geophysical Union, in June 2014 (King et al., 2014). The paper presents geologic models of the subsurface in the vicinity of the PVU injection well based on interpretations of deep seismic reflection and well log data. The geologic models were developed in the 1980s by two groups of consultants retained by Reclamation. The paper summarizes and compares the models from these earlier investigators. The paper also discusses how the spatial patterns of the PVU-induced seismicity that have developed over time might be controlled by the deep geologic structure. The major conclusion is that the spatial distribution of the seismicity is largely consistent with existing geologic models, although some seismicity patterns remain unexplained by the current models.

5.1.3 Maximum Magnitude Estimations of Induced Earthquakes at Paradox Valley, Colorado, from Cumulative Injection Volume and Geometry of Seismicity Clusters

This paper was published in *Geophysical Journal International*, a publication of The Royal Astronomical Society, in January 2015 (Yeck et al., 2015). The paper evaluates the observed maximum magnitude (M_{max}) earthquakes at Paradox Valley as a function of time, and compares these with estimates of M_{max} using two distinct methodologies. The first method relies on the correlation of observed M_{max} earthquakes and the cumulative volume of injected fluid. The second method relies on fitting the largest possible fault plane into areas of assumed pore-pressure alteration, delineated by the presence of induced earthquakes. The paper shows that both the observed and estimated M_{max} increased quickly until the year 2000, but have since remained relatively constant. The paper also shows that the estimated M_{max} (~M 5) is slightly larger than the observed M_{max} (~M 4), suggesting that either constrains from geologic structures further limit magnitudes or that insufficient time has occurred to observe the M_{max}.

5.1.4 Induced Seismicity Constraints on Subsurface Geologic Structure, Paradox Valley, Colorado

This paper was published in *Geophysical Journal International* in February 2015. The paper presents geologic structural models of the subsurface in the vicinity of the PVU injection well based on the interpretation of precise earthquake locations and focal mechanisms (direction of fault slip) (Block et al., 2015). The locations and vertical offsets of faults previously identified from seismic reflection surveys are refined, and the presence of new faults is inferred. Analyses of fault orientations and stress models are used to evaluate which faults are most likely to experience induced seismicity. Results suggest local stress orientations near the well that are different from the regional average. The detailed subsurface model produced by this analysis provides important insights for anticipating spatial patterns of future induced seismicity and for evaluation of possible additional injection well sites that are likely to be seismically and hydrologically isolated from the current injection well.

5.2 Consultant Review Board

In January, 2015, Reclamation convened a consultant review board (CRB) of outside technical experts to review analyses of PVU injection and seismic data. The objective of the CRB was to provide review and recommendations on analyses related to: the maximum allowable surface injection pressure (MASIP), causes of the injection pressure increase over time, and the relation between injection and induced seismicity. The board consisted of five experts in the fields of rock mechanics, geomechanical and finite element modeling, induced seismicity, and deep well injection.

The CRB reviewed the four publications described above, three recent internal Reclamation reports in draft form (Wood et al, 2015; King and Block, 2015; and Yeck and Block, 2015), and numerous older Reclamation documents. The final report from the CRB containing their comments and recommendations was completed in March, 2015 (Wang et al., 2015). An accountability report detailing Reclamation's response to the CRB's recommendations is in progress.

The major conclusions of the CRB are:

- The current MASIP for the PVU injection well (5350 psi) is conservative. The CRB provided a recommendation for a method to compute a more realistic estimate of the maximum injection pressure that may be safely adopted without danger of breaching the confining layer. Use of this recommended computational method is expected to result in a substantially higher potential MASIP than the current value.

- The pressure increase in the PVU injection well over time is the result of long-term injection into a formation with relatively low permeability, resulting in far-field reservoir pressurization, and is not related to near-wellbore flow impairment. (Hence, a work-over of the well or near-wellbore reservoir stimulation is not expected to provide a long-term solution to the issue of increasing injection pressures.)

- Shallow earthquakes observed within ~20 km of the injection well since the start of PVU operations have likely been induced by injection. This includes the events occurring on the opposite side of Paradox Valley.

- The hypothesis that the induced earthquakes are triggered by increased pore pressure (resulting in decreased effective normal stress across preexisting faults and shear slip on those faults) is a reasonable working model. Hence, areas with induced seismic activity can be assumed to have increased reservoir pore pressures. However, lack of seismicity in an area does not necessarily mean that pore pressures have not been affected in that location. The CRB recommended analyzing radar satellite data (INSAR analysis) to see if surface deformation can be used to further delineate areas of subsurface pore pressure increase.

- A magnitude of ~M 4.4 to ~M 5.2 is a good estimate of the largest earthquake that could be induced at PVU over the next 5 to 10 years.

6 Conclusions

The Paradox Valley Seismic Network performed well during 2014. The data acquisition systems were online and functioning normally approximately 97% of the year. The most significant network upgrade in 2014 was the transfer of the communication and data acquisition hub from the Hopkins Field Airport terminal building to a separate communications building. The new building has independent generator and battery backup power systems, which will help ensure the uninterrupted operation of the network. Additional field work is anticipated (in 2015) to optimize the radio telemetry communications at the new hub. The seven analog short-period seismic stations that were still operational in 2014 were taken permanently offline when the hub was relocated (July, 2014). Hence, PVSN now consists of twenty 3-component broadband seismometers, with no short-period stations.

The rate of PVU-induced seismicity decreased in 2014 compared to previous years. The total number of earthquakes (of all magnitudes) observed within 10 km of the injection well decreased by 67% in 2014 (37 events) compared to 2013 (112 events). The rate of M 0.5+ earthquakes observed within 10 km of the well during 2014 was 20% of the average rate observed during the previous 6 years (2008-2013). The observed decrease in seismicity rate is likely related to the PVU operational changes made in 2013 (decreased flow rate and more frequent shut-in schedule) and the associated decreased injection pressures (section 2.2.5).

No induced events with magnitude ≥ 2.5 were recorded during 2014, and no events were reported as felt by the public. The largest earthquake induced in 2014 had a duration magnitude of 2.3 and occurred approximately 8.4 km northwest of the injection well.

7 References

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Appendix A

2014 Site Visit Reports

Paradox Valley Seismograph Network
Site Visit Summary PVSN-2014-1

Departure Date: 3/17/2014 Return Date: 3/21/2014

PURPOSE:

Prepare new data acquisitions system including: electronics, shelter, and radio tower. Repair stations PV01, PV21, and PV22.

WORK SUMMARY:

Installed electronics shelter grounding ring, installed cable/ice bridge, and repaired stations PV01, PV21, and PV22.

PERSONELLE:

1. Mark Maremonte (USBR)
2. Dave Copeland (USBR)
3. Mike Gilliam (USBR)
4. William Yeck (USBR)

ACTIVITIES BY SITE:

- **Hopkins Field / Communications Hub**
  - **Overview:**
    - We installed a lightning & grounding ring around electronics shelter. The ground-ring was composed of eight 3/4" x 10' ground rods connected to a continuous stranded copper cable by thermowelds. The shelter ground-ring was spliced to the radio towers pre-existing ground-ring. Additionally, we installed stranded copper extension cable between the ground-ring, the shelter's internal ground system, the radio tower's ground bus bar, and the cable bridge. We installed an ice bridge to facilitate COAX cable spanning the distance from tower to shelter and to protect COAX cable from ice and other objects falling from tower.
    - Digging the grounding trench was much more difficult than expected due to large rock cobbles in the soil the necessity dig around existing utilities and the tower ground ring. Thank you to Reams Construction of Naturita, CO, for their work trenching.
  - **Communication Hub work:**
    - On Thursday evening at ~6:30 pm MST, we replaced the bank of batteries in the ABC Backup. This required a shutdown of the computer system. On power up, we forgot that Scream does not automatically start on a system power up but Earthworm does. However, we did not realize this until that evening, at about 9:30 pm MST. Thus the network was down for about 3 hours from 6:30 - 9:30 pm. I inquired with Guralp as to if Scream can be run as a service but apparently it cannot.
- **PV01**
  - **Symptom:**
    - No communication to station.
  - **Diagnosis and Repair:**
    - Inside datalogger control box, the DM24 fusible link very hot to the touch.

        - Replace the datalogger power control box (Figures 4 & 5).
    - **Comment:**
        - Apparently, fusible links were sized too low.
    - **Other:**
        - Visually inspected station instrumentation, cabling, and vault. Everything appears ok with no signs of bear marks on PVC tubing.

- **PV22**
    - **Symptom:**
        - No GPS timing. GPS LED on Guralp control board indicated no pulse and Scream GPS status showed no GPS link or status update packets.
    - **Diagnosis and Repair:**
        - Replaced GPS and verified LED pulse.
    - **Comment:**
        - Verified GPS lock and sync by logging onto Scream back at motel.
- **PV21**
    - **Symptom:**
        - No communication to station.
        - Not all batteries charging.
    - **Diagnosis and Repair:**
        - Inside the datalogger control box, the DM24 fusible link very hot to the touch. Therefore, replaced datalogger power control box.
        - The battery is still in good condition. The wire was being stretched which caused it to disengage. Created some slack and reinserted into Wago block terminal. All 3 batteries are again charging and providing backup power supply properly.
    - **Comment:**
        - Apparently, fusible links were sized too low.
        - It was obvious a bear had interfered with the station. There were paw prints on front of the shelter's door, bite/tooth marks on all PVC coated flex-steel tubing (protecting seismograph, GPS, & solar cables) with PVC coating ripped off in spots, and deep tooth marks in 3 places on the COAX cable. Checking radio remotely earlier, I had noticed that the radio signal strength from this station was low with data packets being dropped. The deep tooth-marks (see attached photos) are likely contributing to this because the integrity of the COAX (wave guide) cable has been affected. There is likely moisture entering into cable as well. All cables were sealed with electrical tape to protect exposed area.
    - **Work needed at site:**
        - On next site visit, the COAX cable needs to be replaced to ensure the long term health of station. Although there were several problems with this site, the site is back online and operating.
        -

Remaining Work:

- **Hopkins Field / Communications Hub**

- Finish installing the COAX cable and install a lightning protection system on the radio tower and cable bridge.
- Complete modifications of generator concrete pad to accommodate state code regulations of AC mains power circuit box which require no objects within several feet in front and to side of the mains box. In short, the generator has to be moved about 2.5' northward. Reams Construction slated to make those changes. Wings Electric slated to complete AC power hookup and connection to generator. Statement of Work in preparation to contract and schedule Source Gas to install natural gas tap. Local Heating and A/C company scheduled to attach A/C before mid-April and slated to perform natural gas hookup to generator from gas tap. Nucla Naturita Telephone Company slated to install phone/IT cables to phone box on shelter.
- Complete COAX grounding/lightning protection system inside shelter and finish tying shelter internal ground system to ground-ring extensions. Then the final move of instrumentation from old communication hub to the new hub. I took detailed photo record of current instrumentation of old communication hub to help understand and plan the move.



Shelter/Tower photos left to right: Ground ring trench around shelter; Ground rod & copper stranded cable in trench; Thermoweld of cable to rod;



PV21 photos left to right: Bear tooth marks on conduit and stripping of PVC off of conduit; Bear tooth mark/hole in COAX cable, occurs in several spots; 3rd phot shows bear paw marks on shelter door, best paw mark within blue circle

Paradox Valley Seismograph Network

Site Visit Summary PVSN-2014-2

Departure Date: 5/5/2014 Return Date: 5/7/2014

PURPOSE:

Install antennas and lightning protection on radio tower. Work on infrastructure of new data acquisitions building.

WORK SUMMARY:

We Installed T-mounts and antennas on top of the tower, lightning protection spline balls, and 3 ground cables from each spline ball to the ground. We also completed the installation of shelter tie-down brackets to stabilize shelter in high winds onto the pad, discussed final needs to complete AC power and generator hookup, swapped out failing hard drive on earthworm system and reviewed battery backup systems on current computer rack to design new battery backup systems in new shelter.

PERSONNEL:

1. Mark Maremonte (USBR)
2. Dave Copeland (USBR)

ACTIVITIES BY SITE:

- **Hopkins Field / Communications Hub**
  - **Work Preformed / Comments:**

Before working too around the FAA antennas, we called FAA's NOC to verify wattage and system's operation. We found out that we are not allowed to work on the tower without the FAA's authorization. I was able to obtain authorization and to power down system for 5 hours to allow us to work safely without RF heating exposure. I do not know the wattage output and frequency of FAA Omni antennas but suspect it is not > 500 watts & around 100 MHz. Next time I call I will see if I can find that information for our records.

We were not able to install the antenna COAX cables and connect the 3 ground cables together at top of tower. This will need to be done on next trip.

We completed the installation of shelter tie-down brackets to stabilize shelter in high winds onto the pad, discussed the final needs to complete AC power and generator hookup, swapped out a failing hard drive on the earthworm system and reviewed battery backup systems on the current computer rack to design new battery backup systems in new shelter. We were not able to make contact with local phone company to further discuss the transition schedule of T1 line and phone line over to the new shelter. However, I spoke with Rosini Russell, who is a BOR IT projects manager who may be able to facilitate that transition.

As far AC power and generator hookup, we have a couple of roadblocks to overcome:
1. Electric inspector will not approve shelter without a certificate of inspection. According to local electrician and his experience with installing communication shelter such as this one, the certificate is usually affixed by manufacturer inside the shelter. This one does not have one. I have contacted manufacturer, PQ Shelters, in order to find out procedure for obtaining certificate and awaiting their response. We may have to schedule and pay for a state inspection to receive certificate.

2. Linking the generator to the shelter is problematic due toa broken wire terminal on one of two solenoids on the transfer switch. I have contacted manufacturer, Generac, to find out if solenoid can be replaced under warranty but unfortunately neither the transfer switch or generator have been registered. I am unable to register them because I do not have purchase date of items (I do have serial numbers though). These items were installed by PQ Shelters. I have contacted them and am awaiting their response. However, Generac has advised me that if I cannot prove that wire terminal was broken on delivery, then they will not cover it. It may be best to order part and pay for it outright to facilitate its repair in a timely manner.

3. The electric inspector has inquired why we have 30A, 125V ,twist receptacles in the shelter in addition to the standard 20A, 125V receptacles. I have explained that these are not required for our instrumentation power usage and believe they were installed as part of the manufacturer's standard configuration. I have contacted manufacturer to find out original requirements issued to build the shelter.

4. The fluorescent ceiling lights in the shelter do not have safety plastic, protective coverings to help protect from falling glass. I contacted the manufacturer to resolve issue and awaiting response.

5. I am still in the process of resolving funding issues to complete the natural gas tap for the generator which costs about $6k. Once the gas tap is installed we can schedule the linkup from the tap to the generator.

6. The 2 500lb A/C units have been mounted on the outside of the shelter. Once the AC power is hooked up, we we will do a final power up to verify its operation.

FUTURE WORK:

We need to complete AC hookup and inspection, gas hookup, T1 line, phone line, and A/C verification by mid-June (before July). We then need to make the final push to move old hub into the new building in early to mid-July including , schedule a bucket truck to complete tower installation and complete vault GPS locations. However, we may have to make an obligatory trip in June to finish coordinating AC, gas, T1, and phone connections.

PHOTOS:

Paradox Valley Seismograph Network

Site Visit Summary PVSN-2014-3

Departure Date: 7/14/2014 Return Date: 7/19/2014

PURPOSE:

Complete installation of new communication hub at Hopkins Field and repair station PV16.

WORK SUMMARY:

Moved communication equipment from the old hub in the old airport facility to the new electronics shelter and tower, and repaired station PV16.

PERSONNEL:

1. Mark Maremonte (USBR)
2. Dave Copeland (USBR)
3. Glenda Besana-Ostman (USBR)
4. Mike Gilliam (USBR)
5. Brandon Baker (USBR)

ACTIVITIES BY SITE:

- **Hopkins Field / Communications Hub**
  - **Commercial Work on Shelter/Tower:**
    - Finished installing COAX and lightning protection system on tower and cable bridge with bucket truck from Jim Forney.
    - REAMS Construction modified generator pad to accommodate state code regulations of AC mains power circuit box which require no objects within several feet in front and to side of the mains box.
    - Source Gas in conjunction with REAMS Construction and Wilson Refrigeration completed installation of natural gas tap and connection to generator.
    - Wings Electric completed AC power hookup, connection to generator, and transfer switch tests.
    - Nucla Naturita Telephone Company completed installation of phone/IT cables to D-marc box on shelter; and Verizon successfully installed Cisco Router to complete T1 link between Nucla and Denver.
  - **Preparation Work Inside Shelter and Tower:**
    - Completed installing ground system for COAX cables on tower and reviewed/verified antenna alignments to repeater sites PV02, PV04, & PV12.
    - Completed COAX grounding/lightning protection system inside shelter and finished tying shelter internal ground system to ground-ring extensions.
    - Tested/configured HVAC system (72 deg), lighting system, and power/circuit systems inside shelter as well as tested transfer switch and generator operation. All systems operating at this time.
  - **Communication Hub Transfer and Setup:**
    - Completed transfer of digital communication and recording equipment from old comm hub in Hopkins Airport Facility to the new PVSN Electronics / Communication shelter. This included Scream and Earthworm computers, 3 MDS wireless radios, Linksys router, Avocent KVM, Cisco Switch, US-Robitics modem, TMC-5 comm module, Netbotz environmental monitor system, and

APC/NewMar power/battery backups systems. All systems installed and reconfigured onto computer rack and interfaced with new Cisco-2951 T1 Router.

- The network was down for about 24 hours from morning of 7/16/14 @ 16:00 to about 7/17/14 @ 16:00 UTC the next morning. No network data was recorded during this time period.
- System is operational but PV05, PV21, and PV20 seem to have more gaps than prior to the communication hub move. Presently investigating.

- **Communication Hub Additional Needs:**
  - Investigate the new Netbotz environmental & shelter state of health device to connect and support various alarms built into the shelter including: AC power failure/on alarm, generator failure/on alarm, HVAC power, smoke alarm, door alarm, temperature. These alarms are not implemented yet. However, the old Netbotz device is activated and monitoring temperature, humidity, dew point, & noise.
  - Install better mount system for wireless radios. Their mounting location needs a larger 1' x 3' metal plate to create better support base.
  - Ice bridge needs to have its grounding system installed and connected to tower/shelter ground ring.
  - Complete labeling equipment and cables; most labeled already but good to complete to facilitate identifying equipment and cable line connections.
  - Organize manuals and warranties especially warranties.
  - Place log book in shelter to date & monitor access (comings and goings of personnel) and activities at shelter including local utility & contract personnel.

- **PV16**
  - **Symptom:**
    - No communication from station. Unable to ping MDS wireless radio.
  - **Diagnosis and Repair:**
    - A review of waveforms previous to station drop out showed no unusual activity or noise. On arrival at station, a visual review showed bear tooth marks on COAX cable and other conduits. Opening shelter showed no power to any instruments or to solar regulator. Batteries measured 6.4V (very low) and 15A solar panel fuse was blown. Subsequent review of solar panel revealed main cable was pulled out of the circuit box (j-box) with negative wire disconnected from terminal. Apparently the bear had climbed tower and yanked on solar power cable.
    - Initially swapped out the solar regulator to verify regulator's operation especially with battery voltage at 6.4V. Discovered the regulator needs at least 8V for its operation. Fortunately the nearby analog station, which is still running, had 2 good batteries at 13.5V. Therefore, we swapped them into the digital station to bring regulator and station back to life more quickly. Otherwise it would have taken several days for batteries to recharge while simultaneously supplying power to load. However, the remaining 3rd battery is still at low voltage pulling good batteries down a bit but should recover and equalize in time even though 6.4V is low even for a deep cycle battery. Need to monitor voltage remotely to verify battery integrity. Once power returned it was evident all other components were operating and verification of data receipt completed by Scott at Denver office. Also, replaced damaged COAX cable installing it in such a manner the other PVC steel coated conduits protect it better from direct access say from a bear.

        - In addition, replaced the DM-24 power control box with larger fusible links which have been problematic at other stations causing DM-24 system to hang and cease communications.
    - **Comment:**
        - To provide additional battery support for digital station, we swapped the low batteries into the analog shelter to afford them the capability of being recharged and available onsite; and removed the analog instrumentation load because analog network decommissioned.
    - **Action Items:**
        - Bring blue and yellow ring terminals to repair solar cable connections in j-box and to repair lose ground wire on spare polyphaser. Also bring flex-tube Al conduit to protect COAX cable.



Shelter/Tower photos left to right:
1st photo - Top of tower showing lightning protection system, PVSN antennas and FAA two large Omni antennas and their relationship to each other;
2nd photo - Similar to first but from a ground perspective and shows our three COAX cables running up tower;
3rd photo - Electronics shelter, AC main power, D-marc T1/Phone box, generator, natural gas meter, and ice bridge.

Top: Shelter inside photos left to right:
1st photo - Computer rack with installed components; COAX copper ground trapez system is on upper right with radios installed on cable ladder just to its left;
2nd set of photos - Upper shows Cisco router, Switch, TMC-5, & modem; Lower photo shows Earthworm Penquin server, Scream Dell server, Avocent KVM;
3rd set of photos - Upper shows COAX cable ground trapeze with radios just to its left; Lower shows closeup of the three MDS wireless radios.

Bottom: PV16 photos left to right:
1st photo - View of station on arrival with analog station just barely in view on the left;
2nd set of photos - Upper shows COAX cable punctured by bear tooth; Lower shows solar panel cable pulled out of j-box;
3rd set of photos - Upper shows PV16 digital electronics with 2 good batteries (dated August 2007) replaced from analog station; Lower shows analog station with low voltage batteries (dated October 2009) installed and charging.

Paradox Valley Seismograph Network

Site Visit Summary PVSN-2014-4

Departure Date: 9/22/2014 Return Date: 9/28/2014

PURPOSE:

To perform a high quality GPS survey of seismic and strong motion stations.

WORK SUMMARY:

The location of each PVSN station vault locations: PVHOP, PV01, PV02, PV03, PV04, PV05, PV10, PV11, PV13, PV15, PV16, PV19, PV20, and PV23 and Strong Motion stations: PVCC, PVEF, and PVPP was measured with a survey grade GPS.

PERSONNEL:

1. Glenda Besana-Ostman
2. Matthew Jones

ACTIVITIES:

- The location of each PVSN station was measured using a base station composed of Trimble 4800 GPS antenna-receiver unit and a Trimble Trimmark 3 Radio (450-470MHz) Repeater Base. During measurements, the baseline distance from the PVSN station relative to the base station was within 6 miles to maintain radio link. However, whenever radio communication was not established between base and the rover antenna-receiver at the PVSN site(s), a 20min static survey was undertaken to preserve the same level of accuracy for each station. GPS measurements were done on the following PVSN stations: PVHOP, PV01, PV02, PV03, PV04, PV05, PV10, PV11, PV13, PV15, PV16, PV19, PV20, and PV23) and Strong Motion stations: PVCC, PVEF, and PVPP.

COMMENTS:

- In regard of the PVSN station maintenance check, ocular investigation and documentation of equipment on each stations were completed for the following: PVHOP, PV01, PV02, PV03, PV04, PV05, PV10, PV11, PV13, PV15, PV16, PV19, PV20, PV23, PVCC, PVEF, and PVPP. All stations are in good working condition. It was noted, however, that some of the stations have some evidence of physical disturbance from wildlife, disconnected frame, open, rusty and dysfunctional locks; and ground erosion and missing sensor markers that needs some attention. A plastic bag containing spare parts (cable, nuts and bolts and fuses) is present in each PVSN stations. Based on this initial inspection, some stations will need spare fuses, screw drivers, new locks; and new batteries particularly for PV01, PV02, PV04, PV05, PV10, PV12, PV13, and PV16 stations, and frame repairs. A logbook was placed inside the fiberglass enclosures in each of the PVSN stations visited. Lastly, prior to this field survey, seismic signal form PV05 had immensely deteriorated. A suspect source of intermittent signal was either antenna or radio malfunction. Evaluation of the station and on-site investigation during this survey showed no antenna blockage from foliage and/or no apparent equipment damage. On the other hand, with regard to the Strong Motion stations, only PVPP enclosure was inspected due to limited access. Hence, lock won't open at PVCC and area is fenced with high security at PVEF. However, based on the very limited access, the stations would require cleaning and some insect repellant (beehive on PVCC). For detailed information and references for future inspections, please see the online logbook available on Google Drive.

- Among the stations scheduled for measurements and inspection, the survey team were not able to reach PV21, 22, PV07, and PV17 due to bad road conditions, weather, and time limitations. At least 5 more days of survey is most probably needed to measure the location of the four remaining stations. Moreover, most of the stations were accessed by a vehicle combined with 1-2mile hike due to the unexpected road conditions, where in a few number cases were very dangerous and risky for the survey team. Thus, to undertake a similar survey in the future, it is highly recommended that it be undertaken during a 2-week long fieldwork and usage of a 4X4 vehicle (ATV or Jeep) with high clearance. As a precaution, please DO NOT use RD 6 to access PV04; instead, use RD 0371 and RD Q3 to access PV23 and PV04.

Paradox Valley Seismograph Network

Site Visit Summary PVSN-2014-5

Departure Date: 10/20/2014 Return Date: 10/25/2014

PURPOSE

Install spare Scream server running Windows-OS, repair GPS receiver at PV22, replace damaged COAX cable at PV21, and review wireless communication issues with PV01, PV07, PV05, PV21, and PV20.

WORK SUMMARY

We were able to successfully install and configure spare Dell Scream server running Windows Server 2008 and with current supported V4.5 edition of Scream data acquisition system. PV22 GPS receiver has returned to operational status. PV21 COAX cable replaced and cable protected from future bear bites. Realignment of directional antennas and reorientation of Omni antenna was performed at Hopkins Field communication Hub (Communication Hub) and onsite review and analysis of instrumentation and hardware performed at stations PV05 and PV21 and their access points at stations PV02 and PV04. Resultant modifications resolved communication issues at PV07, much improved communication issues at PV01, slightly improved communication issues for PV05, and worsened communication issues at PV21.

PERSONNEL:

- **Mark Meremonte**
- **Glenda Besan-Ostman**

ACTION ITEMS:

1) Confirm generator fan blades replaced, battery replaced, upgrade of battery charger, and installation of engine block heater (Gunn's Generator Service).
2) Stations PV02, PV05 need DM24-BOB fuse upgrades: PV02 has upgrade but PV05 does not
3) PV05: Review ground system to finalize ground rod configuration and connections
   See #5 in "Work by Site" on site visit report 2013-2_PVSN-SiteVisit_30JUL2013.xls for details
4) PV16: See PVSN-2014-2 "Work by Site" PV16 "Return trip activities" for more info

EQUIPMENT DETAILS:

Item	Model	S/N
Certificate 8/13/14	Bldg. Inspection Certificate, Wings Electric	7865 AIC by SMPA
Generator	Generac 25kw, 60Hz, 1.5L N. Gas; QT02515ANSX	7665940
Generator Battery	Group 26, 12V, 525 CCA	-----
Transfer Switch	120/240, RTSX200	7700424
Gas Meter	Source Gas	42418998
Electric Meter	San Miguel Power	106 883; 113 890 553
Comm Hub Phone	Nucla Naturita Telephone Co	970-864-7578
T1: Router	Cisco 2951	FTX1724AJ02
T1: Circuit ID	Verizon; GW – 140.215.65.253	BCBK48CX0001/0001/00
T1: Circuit LEC	Nucla Naturita Telphone Co	24/HCGS/749380/MS

ACTIVITIES BY SITE:

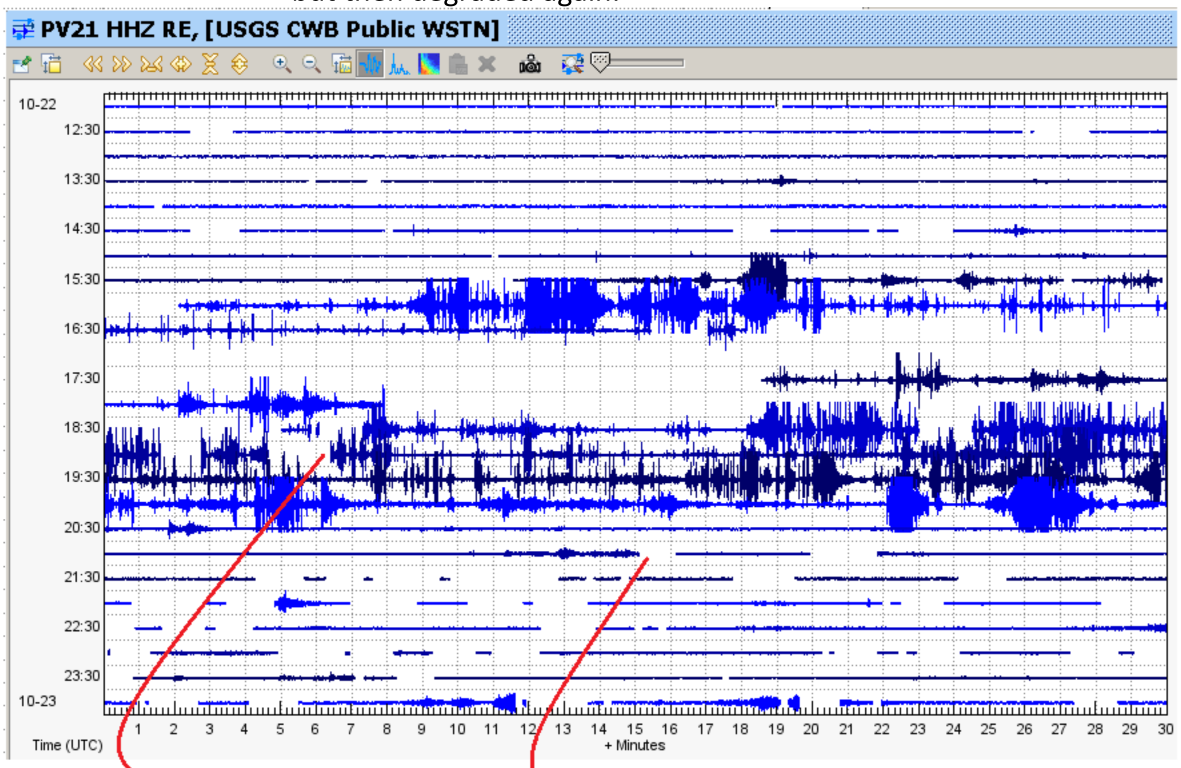
- **Hopkins Field / Communication Hub**
  - Installed temporary replacement Dell Scream server with Scream V4.5. However, we may convert Scream V4.5 back to V4.4 to provide compatibility with current legacy Earthworm. Any case, this spare Scream server is being prepared to replace the current aging Scream V4.4 server, which only has one disk of the RAID-1 disk configuration operating, before it fails. We are currently configuring a permanent server with Raid 5 or 6 running Windows 2012 server with supported versions of Scream (V4.5) and Earthworm (V7.7) as long term replacement. Tests are currently in process to verify triggers and waveforms recorded and processed on current production Scream 4.4/Earthworm V6x system are equally being recorded and processed on the new production Scream 4.5/Earthworm 7.7 system.
  - We also reviewed directional and Omni antennas on tower to verify orientation to remote Access Points (AP) and to remote stations (See Figure 1 at bottom: Current state of PVSN radio communications). Using Handheld GPS we slightly adjusted directional antennas to APs PV02, PV04 & PV12. Ultimately, this appeared to have no effect on signal quality from Aps. The Omni's horizontal arm was also adjusted and rotated to N to provide a better line-of-site to station PV07. Tower, itself, was somewhat in the line-of-site to PV07 which is located NE of Hopkins Field Comm Hub. Indeed, this did have an effect on PV07's signal quality and to a slight degree with PV01's signal quality (See Figure 2 at bottom: Summary of communication issues). We may have to extend the horizontal arm of the Omni antenna a bit further out from tower to provide better signal coverage.
  - Scream/Earthworm down times due to Comm Hub activities:
    - October 20 @ 22:15 to October 21 @ 14:00 UTC
    - October 21 @ 21:54 to October 22 @ 00:00 UTC

- **PV21**
  - **Symptom:**
    - COAX cable has deep bear tooth mark possibly causing a weak communication signal resulting in numerous gaps.
  - **Diagnosis and Repair:**
    - Yes, identified bear tooth mark when last visited station in March 2014 and wrapped with electrical tape to prevent moisture entering into cable. A review of waveforms previous to visit indeed showed gaps present. Thinking was the deep tooth mark may be causing reflections in COAX cable preventing good signal transmission through cable. On our arrival all systems looked healthy including batteries. The electrical tape bandage looked in good shape but possibly moisture was able to penetrate under tape and caused additional signal degradation.
    - We swapped out the COAX cable, trimmed dead tree directly in line-of-site, replaced 5-element 9 dB directional with 6-element 9 dB antenna, and protected COAX antenna from future bites in a flex-steel tube to resolve issues.

Action	Power (dB)	RSSI (dBm)	SNR (dB)
Before	30	-85 to -87	23, 24
After	30	-79	25

Note: RSSI of -86 to -91 is borderline; SNR of 25 is desirable

- At this point, figured problem resolved. However, when we reviewed waveforms later, the signal was fine for about 2 hours after we left site but then degraded again:



Left station after repairs; time signal degraded once more

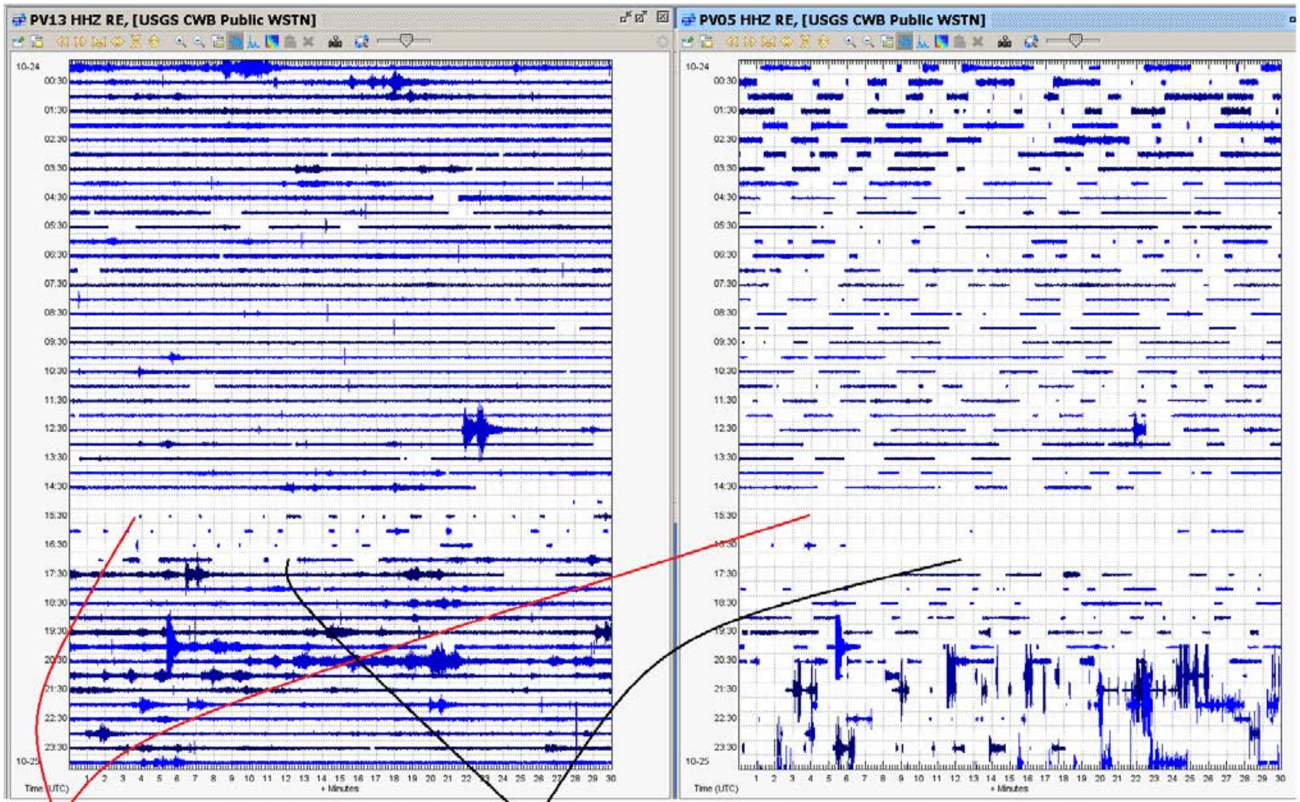
- Subsequently we returned to station. This time we swapped out lightning protection polyphaser with thought it may be degrading and interrupting signal, swapped out the antenna with higher gain (10 and 13 dB) antennas with thought that higher gain may be required to travel the 13 mile distance to its AP , and changed radio power output as well. Fact is, no change made a significance difference in signal strength/quality where RSSI bounced between -86 to -94 dBm and SNR was steady at 23 dB. Interesting, once we installed the 13 dB, 12-element directional antenna the signal RSSI dropped below -100 dB which is no signal. We attempted to compensate the higher gain antenna with lowering radio output power from 30 to 20 dB but no help. Finally, we returned all cable and Hardware back to its original configuration. A check indicated that RSSI was stabilizing at -83,-84 dBm, and signal to noise ratio stabilizing at 23, 24 dB. We did not expect these measurements on return to original configuration and with radio output power at the low level of 20 dB. Therefore, because these signal strength/quality measurements looked good, we left this configuration with low radio power.

- **Comment:**
  - Just before we left station to drive home to Denver, I did a quick antenna orientation review to be confident that original orientation was correct with the new Handheld GPS and noticed that the antenna may be off 10-12 degrees to the East from where it ought to point. I climbed tower to verify but it was too dark to visually verify. Some trees limbs may still need to be removed. On return to office, a check of PV21 showed that signal has degraded more than previously.

- **Return Trip Activities:**
  - Because there may be a possibility of current radio failing, bring a new radio to test. We may also need to trim additional tree limbs and check orientation of directional antenna. Also, need to complete grounding installation with possibility of installing a spline ball.

- **PV22**
  - **Symptom:**
    - No GPS timing.
  - **Diagnosis and Repair:**
    - GPS LED on Guralp control board indicated no pulse and Scream GPS status showed no GPS link and status update packets. Power cycled GPS-BoB and verified LED pulse. The GPS, itself, did not need replacing.
  - **Comment:**
    - Verified GPS lock and sync by logging onto Scream back at motel that evening to review log. Note that the GPS did not need to be replaced but only a power cycle was required. I have discussed this with GPS-BoB manufacturer and we may need to make mods to all GPS-BoBs. We have several sites now where only a GPS-BoB power cycle was required to rectify GPS timing loss.
  - **Return Trip Activities:**
    - Need to complete grounding installation with possibility of installing a spline ball and square Cu plates. Presently grounding system here is weak.
- **PV17**
  - **Symptom:**
    - No symptoms.
  - **Diagnosis and Repair:**
    - Visited station to complete a comprehensive GPS Static survey of station seismometer location using Trimble and to review DM24-BoB status because older models have a problem with under-sized fusible links resulting in DM24 communication failures. Indeed, review of station indicated the BoB is an older model.
    - Replaced DM24-BoB with upgraded model with larger fusible links.
  - **Comment:**
    - Successful gathering GPS data to complete Trimble GPS Static survey. Station is in good shape. No visible damage to any components.

- **Return Trip Activities:**
  - May need upgrade of grounding system.
- **PV04**
  - **Symptom:**
    - No symptoms.
  - **Diagnosis and Repair:**
    - Visited station to attempt to increase radio signal quality from PV21 and to review DM24-BoB status because older models have a problem with under-sized fusible links resulting in DM24 communication failures. Indeed, review of station indicated the BoB is an older model.
    - We raised Omni antenna about 3' but still below top of tower where directional antenna resides. The interest was to provide better line-of-site to station PV21 but to others as well. However, there was no effect upon PV21's signal strength. Currently other stations received by this AP have RSSI values > -80 dBm but PV21 is still < -86 dBm. Also, Replaced DM24-BoB with upgraded model with larger fusible links.
  - **Comment:**
    - Station is in good shape. No visible damage to any components.
  - **Return Trip Activities:**
    - May need upgrade of grounding system including 2 spline balls.
- **PV02**
  - **Symptom:**
    - No symptoms.
  - **Diagnosis:**
    - Visited station to attempt to increase radio signal quality from PV05 and to check on status of the chem-rod grounding system.
    - Here we temporarily installed an Omni antenna on tower top and removed both spline balls to prevent radio interference to increase line-of-site characteristics and improve signal quality of radio signal from PV05 to PV02 access point. Overall the Omni was raised about 5'. However, the signal strength/quality degraded rather than improved and, unexpectedly, signal degraded from PV13 as well:

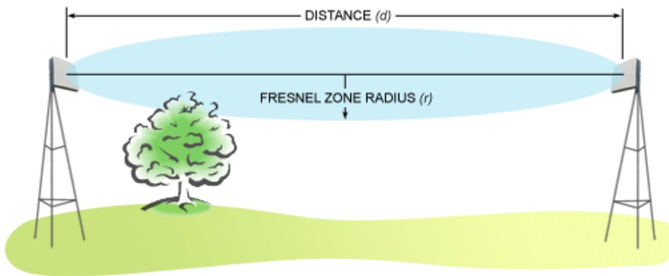


- We do not know why this occurred. Line-of-site to PV13 is unobstructed even before raising antenna; and should have improved from PV13. Unless the analog antenna nearby somehow is interfering but its frequency is in the 100 MHz range vs 900 MHz range for the MDS radios. Consequently, PV02's Omni antenna was returned to original configuration along with spline balls returned to tower top. The chem-rod grounding system required about 8 gallons of water before water stopped receding down tube.

- **Comment:**
  - Station is in good shape. No visible damage to any components.

- **Return Trip Activities:**
  - May need to trim several tree limbs to provide better signal line-of-site to PV05. Jury still out whether Omni antenna needs to be raised in addition.

- **PV05**
  - **Symptom:**
    - The signal strength and quality of signal are below acceptable levels causing a weak communication signal resulting in numerous gaps.
  - **Diagnosis:**
    - A review of waveforms previous to visit indeed showed gaps, many and long gaps, present. Thinking was that the AP Omni antenna at PV02 is too low on tower contributing to poor line-of-site characteristics as defined by the Fresnel Zone shown in simple model below:



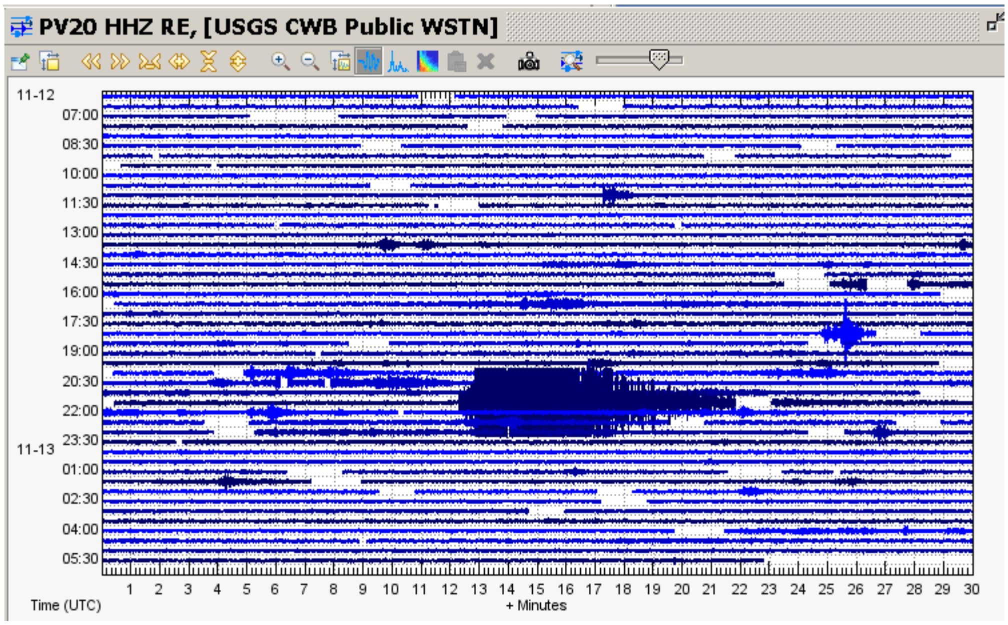
(www.wlanantennas.com)

- Initially, I thought the tops of trees close to PV02 were contributing to weak signal. Hence the reason to raise Omni antenna described above under PV02 station entry. The distance from PV05 to PV02 is ~ 14 miles. Because raising antenna at PV02 did not resolve signal/quality issue from PV05, we have come to PV05 to experiment with radio/antenna configuration here to attempt resolution of signal degradation.
- We tried several iterations of configuration changes replacing one by one: COAX cable, lightning protection polyphaser, directional 9 dB antenna, and radio. Then we replaced the communication system with all new components including radio with no clear improved results. In addition, checked orientation of antenna there by rotating it clockwise and then counter-clockwise over 180 degrees with no improved results over initial orientation towards PV02 AP. In general, we were not able to improve signal strength > -92 dBm – not very good. We returned to original communication configuration including the radio. Interesting there was slight improvement in RSSI signal strength amongst couple of RSSI Zones that make up the RSSI dBm statistic. However, a review later of the data revealed more degradation of signal resulting in more gaps and longer gaps.

- We tried reconfiguration of communication system both at PV02 with no affect and here at PV05 with a further degradation of signal even though RSSI indicated slight improvement. From PV05's vantage, which is close to a steep bluff and no trees, the line-of-site is clear with deep canyon of Dolores River to within 200 meters of PV02's Omni. There is a slight incline with tall Junipers whose tree tops may be still problematic on that side of the signal and representative of the Fresnel Zone figure above. It was interesting that raising Omni at PV02 did affect PV13 adversely as well. However, line-of-site from PV02 to PV13 appears to be better than to PV05 and distance is < 6 miles. I have thought of possibility the AP radio at PV02 is not able to handle the data bandwidth from both PV13 and PV05 but both the other APs at PV04 and PV12 handle at least twice the data flow as PV02 AP radio.

- **Return Trip Activities:**
  - Need to complete grounding installation. Copper rods need to be connected with copper braided cabling to tower to provide adequate grounding.

- **PV20**
  - **Symptom:**
    - The signal strength is low resulting in an unreasonable number of data gaps as compared to the average station.



  - **Comment and Return Trip Activities:**
    - We were unable to venture to PV20 in the allotted time span for field work. Therefore, we will need to return to review communications at a later date. Also, may need to upgrade grounding system to include a spline ball.

Figure 1: Current state of the PVSN radio communications. The green lines indicate good communications from remote stations to access points; the orange lines show good communications from access points to Hopkins Field Communication Hub; and the red lines show problematic communications to access points.

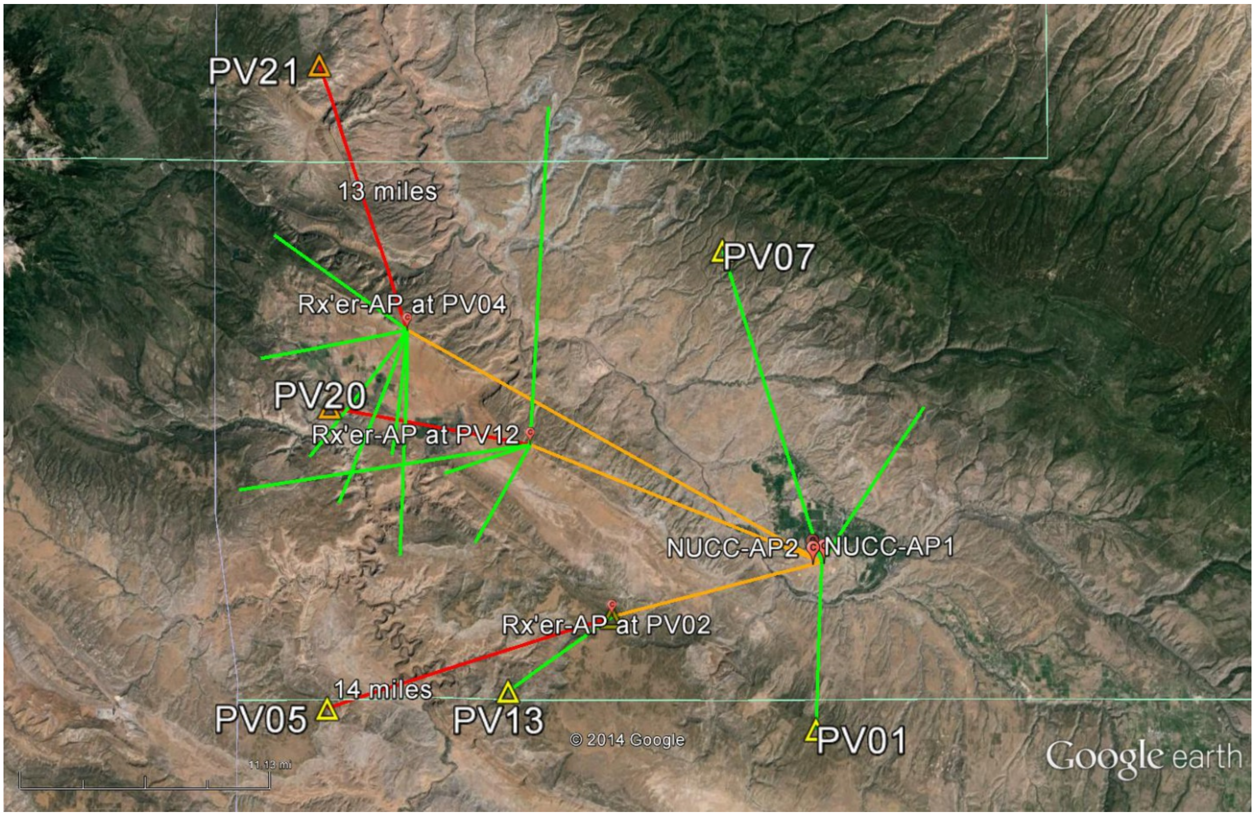
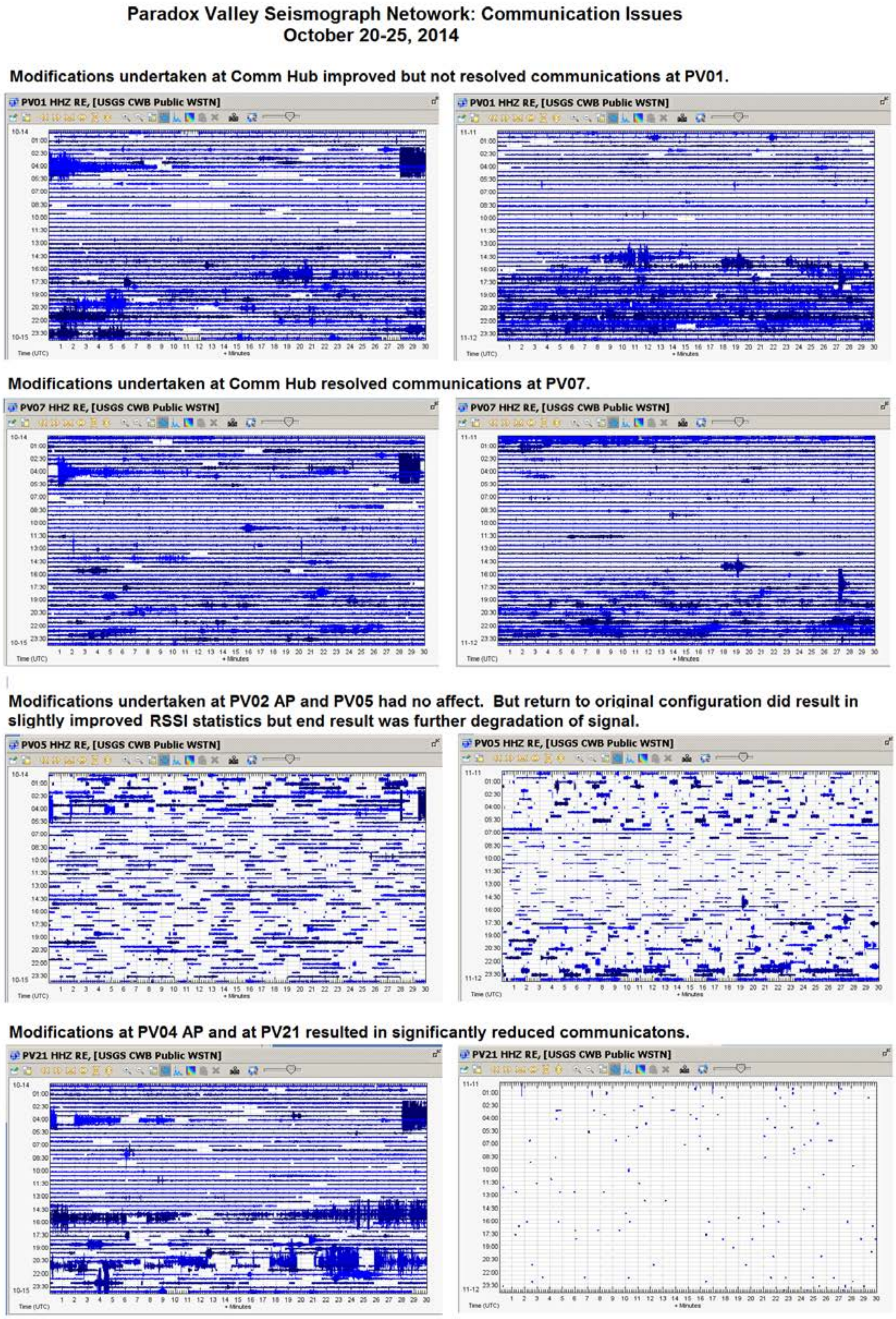


Figure 2: Summary of communication issues. Left side of figure is 24 hour record before mods/tests undertaken and right side is 24 hour record after mods/tests performed.



Paradox Valley Seismograph Network
Site Visit Summary PVSN-2014-6

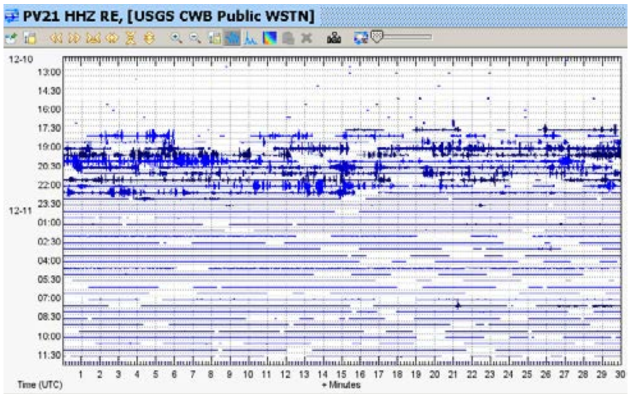
Departure Date: 12/9/2014   Return Date: 12/13/2014

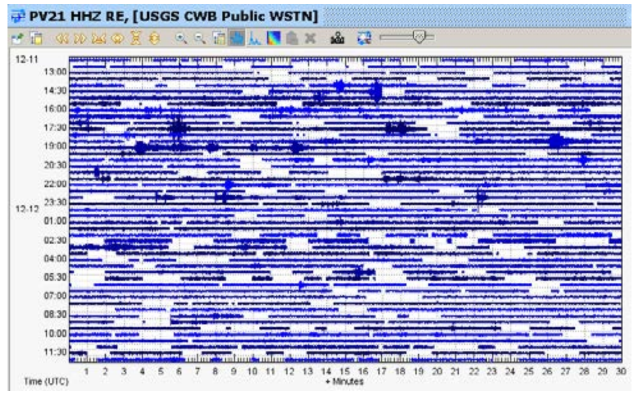
PURPOSE:
Review radio configurations, statistics, and line of site characteristics for stations PV21 & PV05 which have weak wireless communication links.

WORK SUMMARY:

PERSONELLE:
- **Mark Meremonte**

ACTIVITIES BY SITE:
- **PV21**
  - **Symptons:**
    - Degradation of the radio communications to this site.
  - **Diagnoisis and Repair**
    - Radio power setting was set to low (20 dB). The setting of 20 db was the result of a successful communication configuration change during previous maintenance trip in October 2014 but, as we found out later, the comm link degraded several hours after team's final departure.
    - Increased radio power to 30db.
    - Communication from PV21 to hub statino PV04 was still weak. Therefore we considered it likely that line of site issues exisited between the two radios.
    - Removed vegitation which may have been interfeing with radio communcation.
    - Results were favorable as indicated in figures below but intermittent communications still exist. Figure A below shows at about 19:30 UTC on December 10 the comm link robustness increasing as mitigation continues till its completion at about 22:45 UTC. Figure B shows the comm link status 13 hours later for a 24 hour period. Although there is still intermittent communications, the radio signal strength is much better producing more continuous data than previous.





Left, Figure A: PV21 comm link status before and after mitigation. Right, Figure B: PV21 comm link status 13 hours after mitigation.

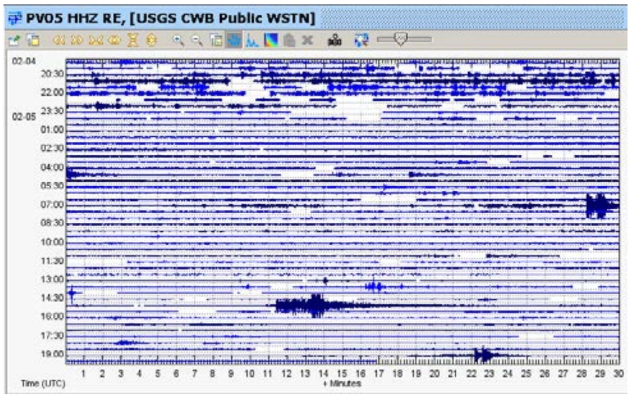
- **Comments:**
  - With respect line-of-site Fresnel Zone characteristics, the radio signal is skirting the top of Sewemup Mesa above Sinbad Valley possibly contributing to signal interference.

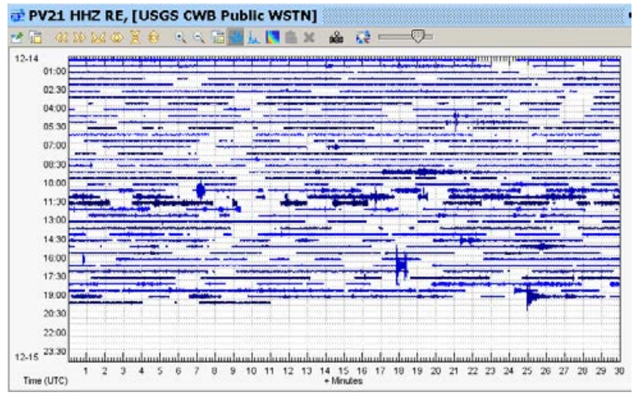
- **Return Trip Activities:**
  - More mitigation at PV21and/or equipment reconfiguration at PV04 access point may still need to be performed.

- **PV05**
  - **Symptons:**
    - Radio signal link to its access point (PV02) was weak.

  - **Diagnoisis and Repair:**
    - Examined orientation of antenna to its access point, tested using larger gain antennas, and swapped the radio to affect change to signal with no results.
    - Reviewing the line-of-site characteristics with respect to Fresnel Zone, it was decided that vegetation mitigation was necessary at PV05's access point located at PV02. Therefore removed interefering plants.

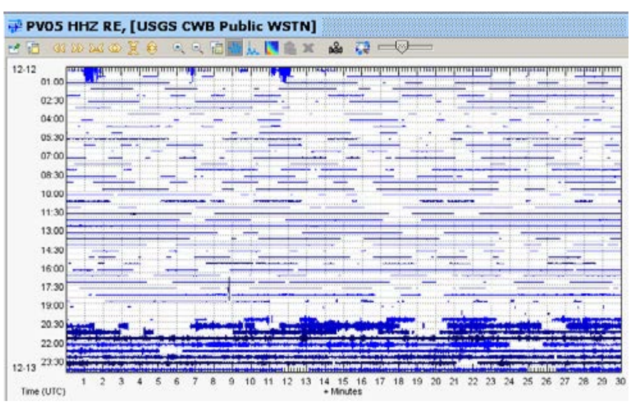
  - **Comments:**
    - Currently, PV05's comm link status as of February 5, 2015, is in a comparatively similar state as it was on December 13, 2014 (see Figure C). Unfortunately, at PV21, the comm link was lost completely about 4 days later on December 14, 2014. Figure D shows its comm link integrity was maintained since mitigation was performed but shows no unusual activity before total loss of contact. Therefore, the reason for the station going dead is unknown at this time.

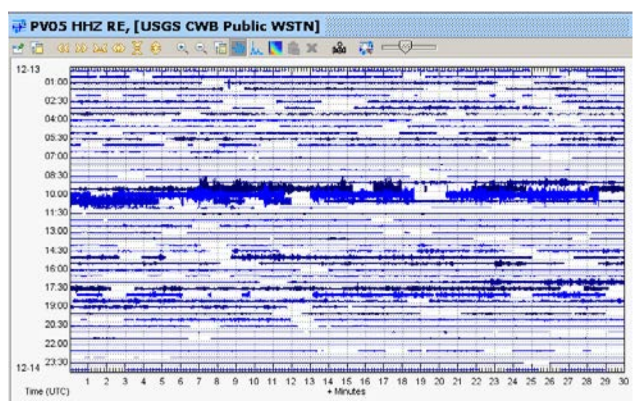




Left, Figure C: PV05 current comm link status as of February 4, 2015. Right, Figure D: PV21 contact loss on December 14, 2014. Note these figures are from after mitigation at PV02, below.

- **PV02**
  - **Symptons:**
    - Poor communications with station PV05.
  - **Diagnoisis and Repair:**
    - Vegetation mitigation at PV02 was carried out with favorable results. Figure E below shows the comm link robustness increase soon after mitigation completion at about 22:00 UTC on December 12, 2014. Figure F shows comm link status 2 hours later for 24 hours with a much improved link but still intermittent drop outs are occurring. Further vegetation mitigation may be necessary and/or re-configuration of PV02 access point may be required.





Left, Figure E: PV05 comm link status before and after mitigation. Right, Figure F: PV05 comm link status 2 hours after mitigation.

Appendix B

PVSN 2014 Local Earthquake Catalog

TABLE B-1: Local earthquakes recorded by PVSN during 2014.

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	M[4]	Location Category[5]
1/7/14	10:05:48	38.2849	-108.8954	-1.9	3.4	0.3	near-well
1/27/14	19:22:14	38.3016	-108.9304	-2.3	3.8	0.2	near-well
2/6/14	5:57:06	38.3958	-109.0173	-4.1	5.6	0.7	N. valley
2/15/14	23:08:20	38.3080	-108.8947	-2.7	4.2	1.4	near-well
2/15/14	23:12:16	38.3080	-108.8942	-2.7	4.2	0.1	near-well
2/15/14	23:13:02	38.3080	-108.8946	-2.7	4.2	1.0	near-well
2/20/14	10:28:53	38.3239	-108.9691	-2.2	3.7	-0.2	NW cluster
2/21/14	11:24:50	38.3080	-108.8940	-2.7	4.2	1.7	near-well
3/7/14	2:23:19	38.2857	-108.9032	-2.0	3.6	0.9	near-well
3/8/14	10:16:58	38.2857	-108.9030	-2.0	3.6	-0.2	near-well
3/18/14	22:31:34	38.4062	-108.9317	-4.4	5.9	1.5	N. valley
3/24/14	12:35:53	38.4433	-108.9737	-4.7	6.2	1.1	N. valley
4/12/14	16:37:03	38.2853	-108.8956	-2.0	3.6	0.9	near-well
5/10/14	9:41:35	38.2861	-108.8998	-1.7	3.2	0.2	near-well
5/13/14	9:05:53	38.2835	-108.8825	-2.0	3.5	-1.2	near-well
5/13/14	9:05:58	38.2865	-108.8815	-1.9	3.5	-0.5	near-well
5/13/14	9:10:09	38.2843	-108.8843	-2.2	3.8	-0.1	near-well
5/23/14	13:24:40	38.2816	-108.8633	-2.5	4.0	-0.1	near-well
5/24/14	16:24:03	38.4011	-108.9272	-4.0	5.5	1.2	N. valley
5/26/14	5:03:15	38.3913	-108.9792	-3.8	5.4	1.1	N. valley
7/3/14	5:06:04	38.2857	-108.9027	-2.1	3.6	1.1	near-well
7/5/14	13:41:55	38.3213	-108.9860	-2.2	3.7	2.3	NW cluster
7/21/14	21:53:17	38.2817	-108.8270	-2.2	3.7	-0.5	SE cluster
7/26/14	4:38:20	38.2732	-108.8788	-0.9	2.5	-0.9	near-well
7/26/14	4:38:21	38.2744	-108.8799	-0.9	2.5	-0.1	near-well
9/15/14	0:11:33	38.2856	-108.9039	-2.0	3.5	0.0	near-well
9/17/14	14:37:54	38.3533	-108.6895	-9.3	10.8	1.8	other
9/28/14	15:51:14	38.3162	-108.7987	-4.4	5.9	0.1	other
10/4/14	4:45:52	38.2113	-108.7332	-4.6	6.2	1.0	other
10/4/14	8:20:38	38.2857	-108.9032	-2.1	3.6	0.6	near-well
10/6/14	5:01:31	38.3448	-108.8963	-5.3	6.8	0.1	central valley
10/7/14	16:09:43	38.2857	-108.9034	-2.1	3.6	0.1	near-well
10/12/14	8:54:31	38.2840	-108.9043	-2.1	3.7	-1.1	near-well
10/27/14	9:55:46	38.2929	-108.9216	-2.2	3.8	0.0	near-well
10/30/14	7:55:55	38.3689	-108.9409	-3.9	5.4	0.1	central valley
10/30/14	10:31:04	38.3688	-108.9409	-3.9	5.4	0.3	central valley
11/2/14	16:03:35	38.3689	-108.9411	-3.9	5.4	0.8	central valley
11/4/14	1:49:01	38.2769	-108.8324	-2.3	3.8	0.5	SE cluster
11/10/14	4:34:28	38.2148	-108.7510	-3.1	4.6	1.1	other
12/8/14	16:22:03	38.2866	-108.8837	-1.9	3.4	0.4	near-well
12/11/14	2:55:00	38.2760	-108.9010	0.6	0.9	-0.2	near-well
12/11/14	2:55:04	38.2757	-108.8997	0.6	0.9	0.1	near-well
12/11/14	2:57:38	38.2760	-108.9010	0.6	0.9	0.4	near-well
12/15/14	19:26:53	38.2748	-108.9513	0.9	0.6	-0.3	near-well
12/22/14	8:59:07	38.3087	-108.8889	-2.8	4.3	0.4	near-well

[1] Time listed is 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
[5] Earthquake location categories:

- near-well: located within approximately 5 km of the injection well
- northwest cluster (abbrev. “NW cluster”): located within the zone of induced seismicity that is centered approximately 7.5 km northwest of the injection well
- southeast cluster (abbrev. “SE cluster”): located approximately 6 km southeast of the injection well
- central valley: located within (north-central) Paradox Valley
- northern valley (abbrev. “N. valley”): located in or very near areas of recurring seismicity along the northern edges of Paradox Valley
- other: local earthquake not associated with any other location category, or locating deeper than 8 km