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Technical Memorandum No. 86-68330-2013-23

2012 Annual Report
Paradox Valley Seismic Network
Paradox Valley Unit, Colorado

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center

May 2013

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
Seismotectonics and Geophysics Group

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Paradox Valley Unit, Colorado

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2012 Annual Report
Paradox Valley Seismic Network
Paradox Valley Unit, Colorado

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1.0 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 2012. Project background information is included in section 2.0, including the history of PVU injection operations and details of the seismic network. In section 3.0, PVSN operations during 2012 are presented, including maintenance of seismic stations and data acquisition systems, and network performance. The earthquake data recorded during 2012 are presented in section 4.0 and compared to historical seismicity trends.

2.0 PROJECT BACKGROUND

2.1 Paradox Valley Unit

Reclamation's Paradox Valley Unit (PVU), a component of the Colorado River Basin Salinity Control Project, diverts 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 about 20 perforations/m 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 7 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 three 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.

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

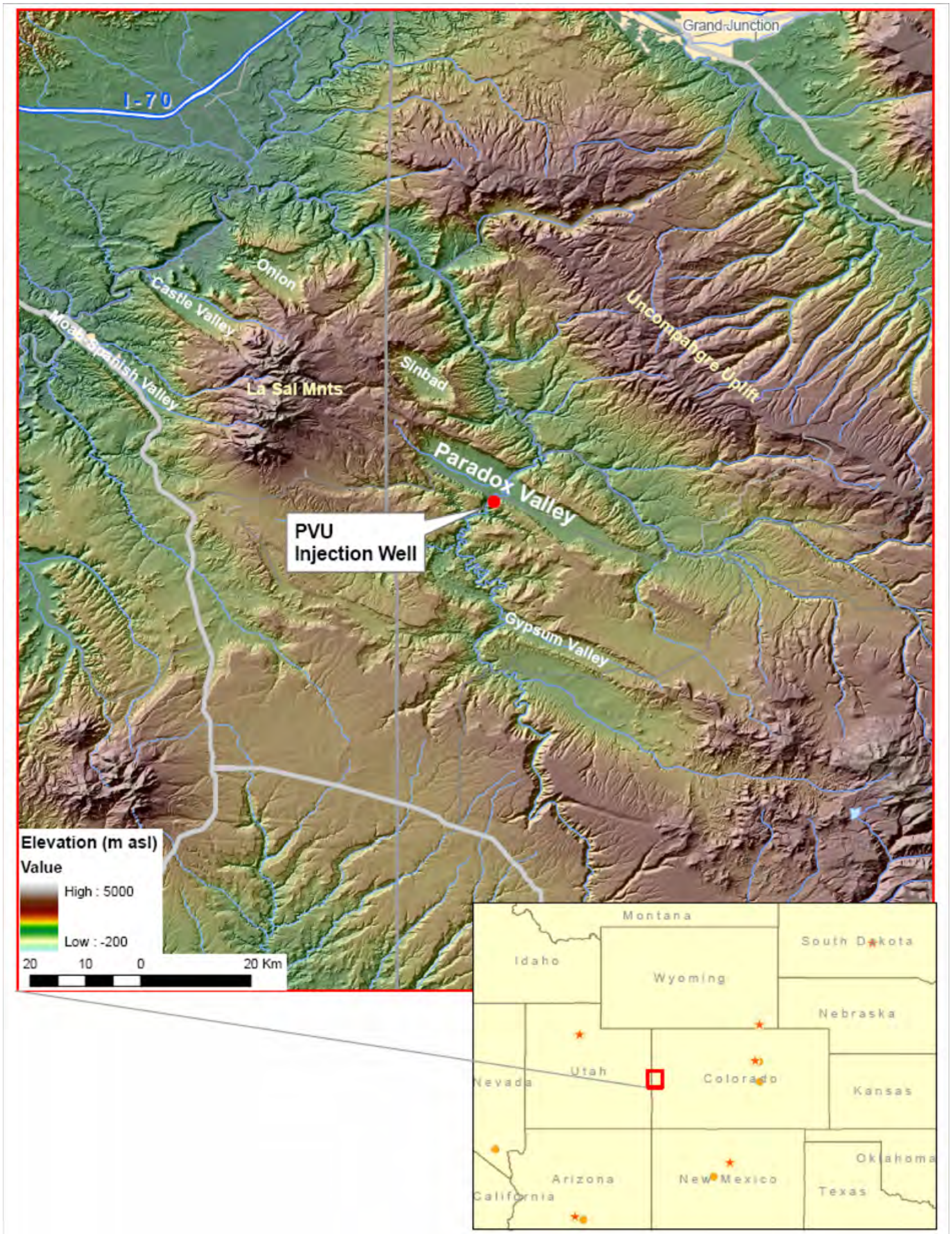

Figure 2-1 Location of the deep injection well at Reclamation's Paradox Valley Unit in western Colorado.

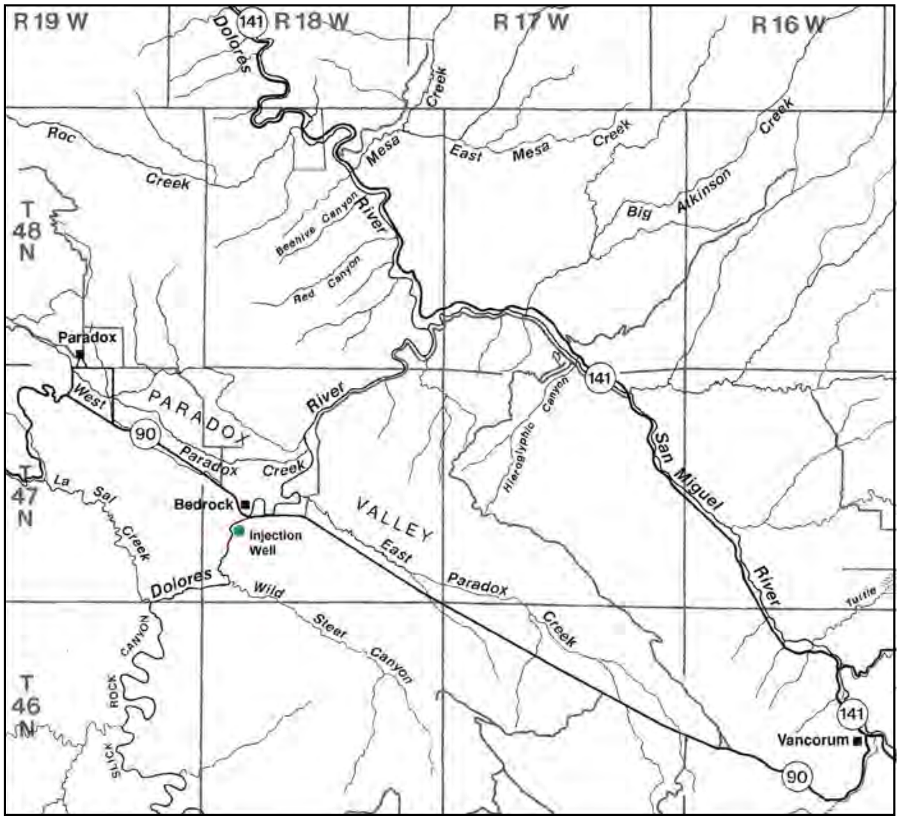

Figure 2-2 Location of the Paradox Valley Unit injection well (green dot) and local geography. Figure is adapted from Parker (1992). Each square is approximately 10 km by 10 km.

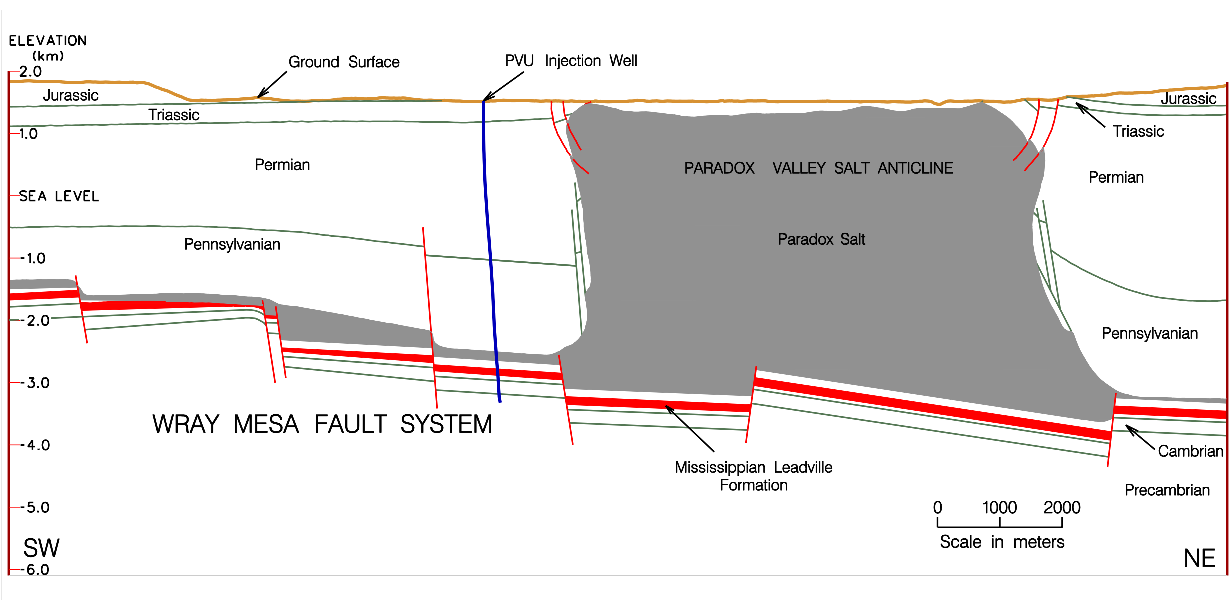

Figure 2-3 Vertical cross section roughly perpendicular to Paradox Valley, looking to the northwest. Based on figure from Harr and Bramkamp (1988).

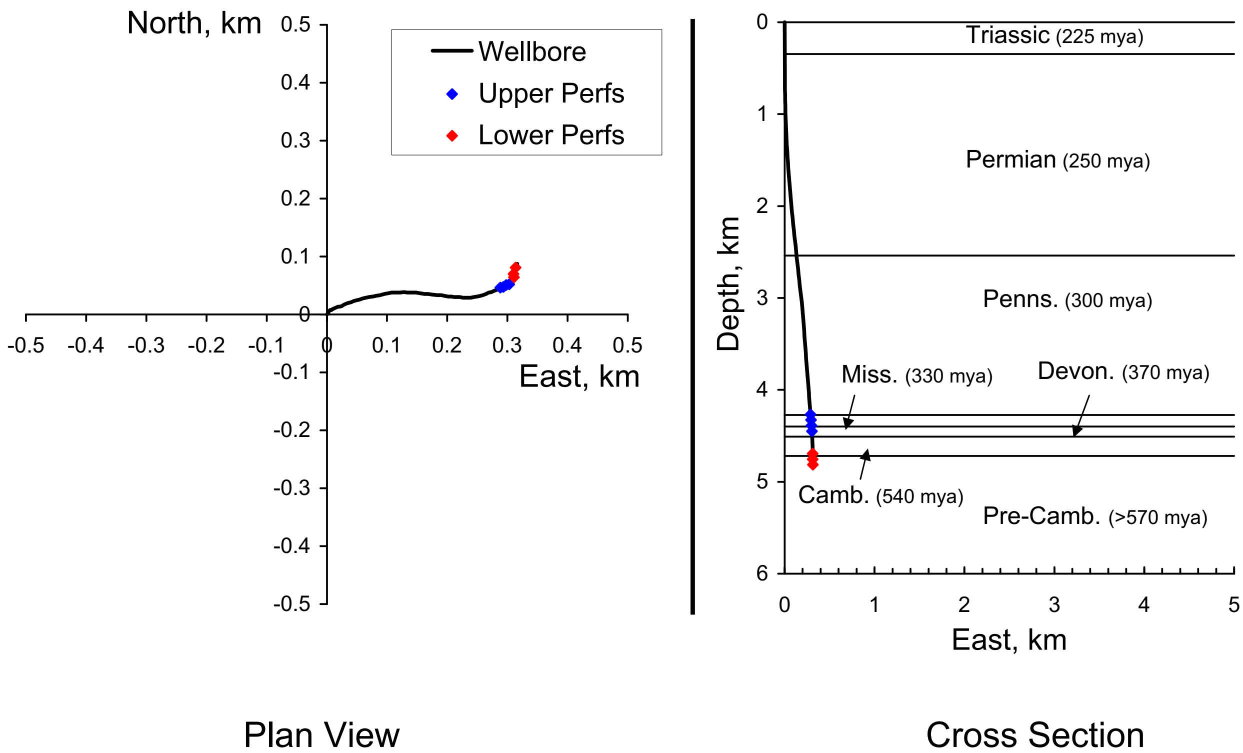

Figure 2-4 PVU injection well in plan view (left) and north-viewing vertical cross section (right). Figures include the near-wellbore stratigraphy and locations of the upper and lower casing perforations.

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 injection rate, and letting pressure drop a few hundred psi before returning to a 3-pump injection. 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 70% Paradox Valley Brine (PVB) and 30% fresh water.

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

Following two magnitude M 3.5 events in June and July, 1999, PVU augmented injection to include a 20-day shutdown (i.e., a “shut-in”) every six months. Prior to these events, it was noted that the rate of seismicity in the near-wellbore region (i.e., within about a 2-km radius from the wellbore) decreased during and following unscheduled maintenance shutdowns and during the shutdowns following the injection tests of 1991 through 1995. It was hypothesized that the biannual shutdowns might reduce the potential for inducing large-magnitude earthquakes by allowing extra time for the injectate to diffuse from the pressurized fractures and faults into the

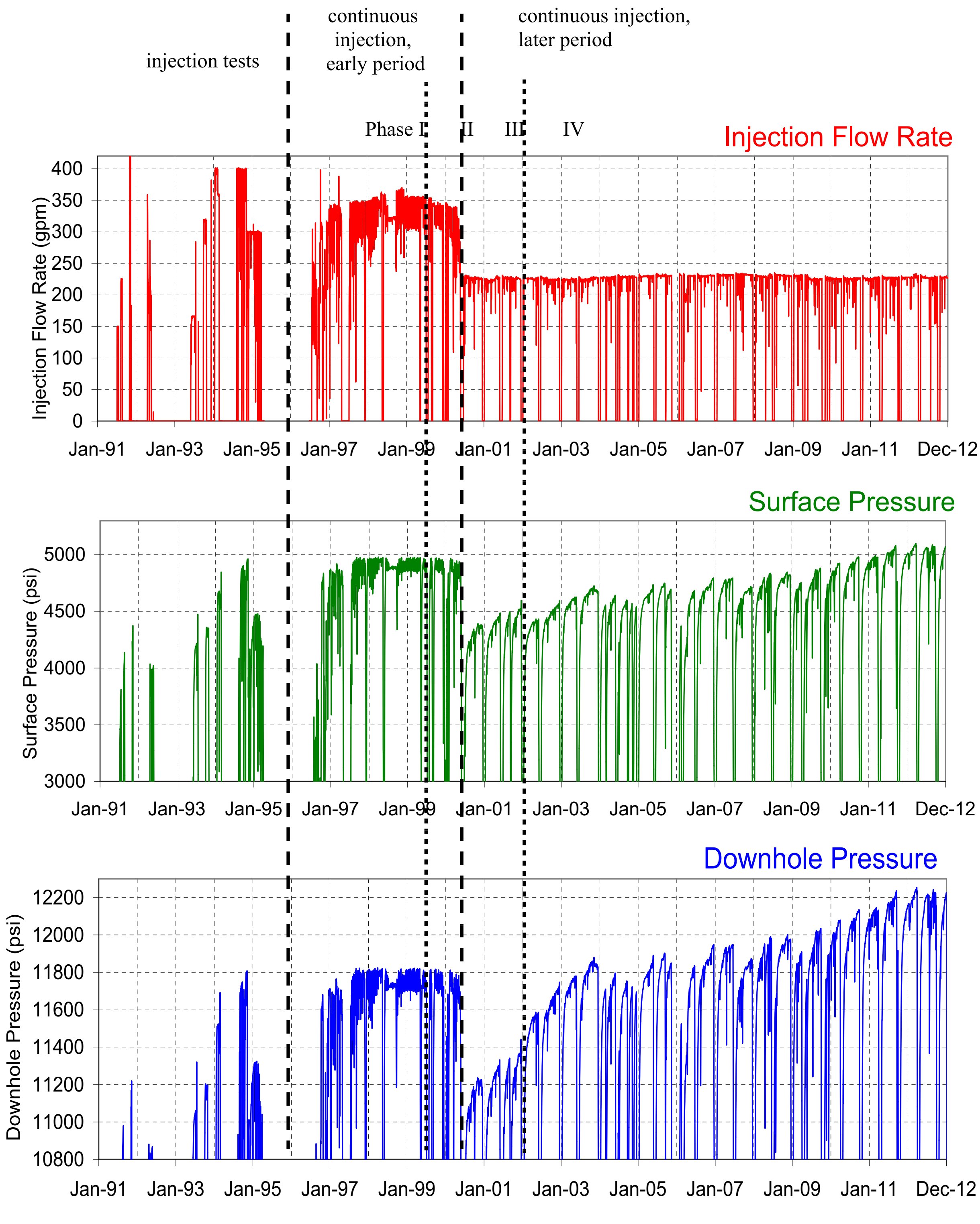

Figure 2-5 Daily average injection flow rate (top), daily average surface injection pressure (middle), and daily average downhole pressure at 4.3 km depth (bottom) during PVU injection operations.

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 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 - present)

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, assuming a density of 9.86 lbs/gal (17% more dense than fresh water), results in a daily injection 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 have been maintained. The only noticeable effect of the change to 100% PVB injectate has been increasing bottom hole pressure because of the increased density of 100% PVB (by about 5%) over the 70% PVB : 30% fresh water mix. No effect on the induced seismicity has been detected.

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 USGS at their facilities in Golden, Colorado. In 1990, responsibility for data acquisition and analysis was assumed by Reclamation. USGS has 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.

Recent upgrades to the high-gain seismic network have focused on replacing the original analog short-period seismic equipment, which has 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. Four of these stations went permanently offline during 2011 (PV02, PV07, PV08, and PV15). The remaining analog stations are currently still functioning but are anticipated to go offline in mid-2013, when the data aquisition center at Hopkins Field is 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 well-head 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.

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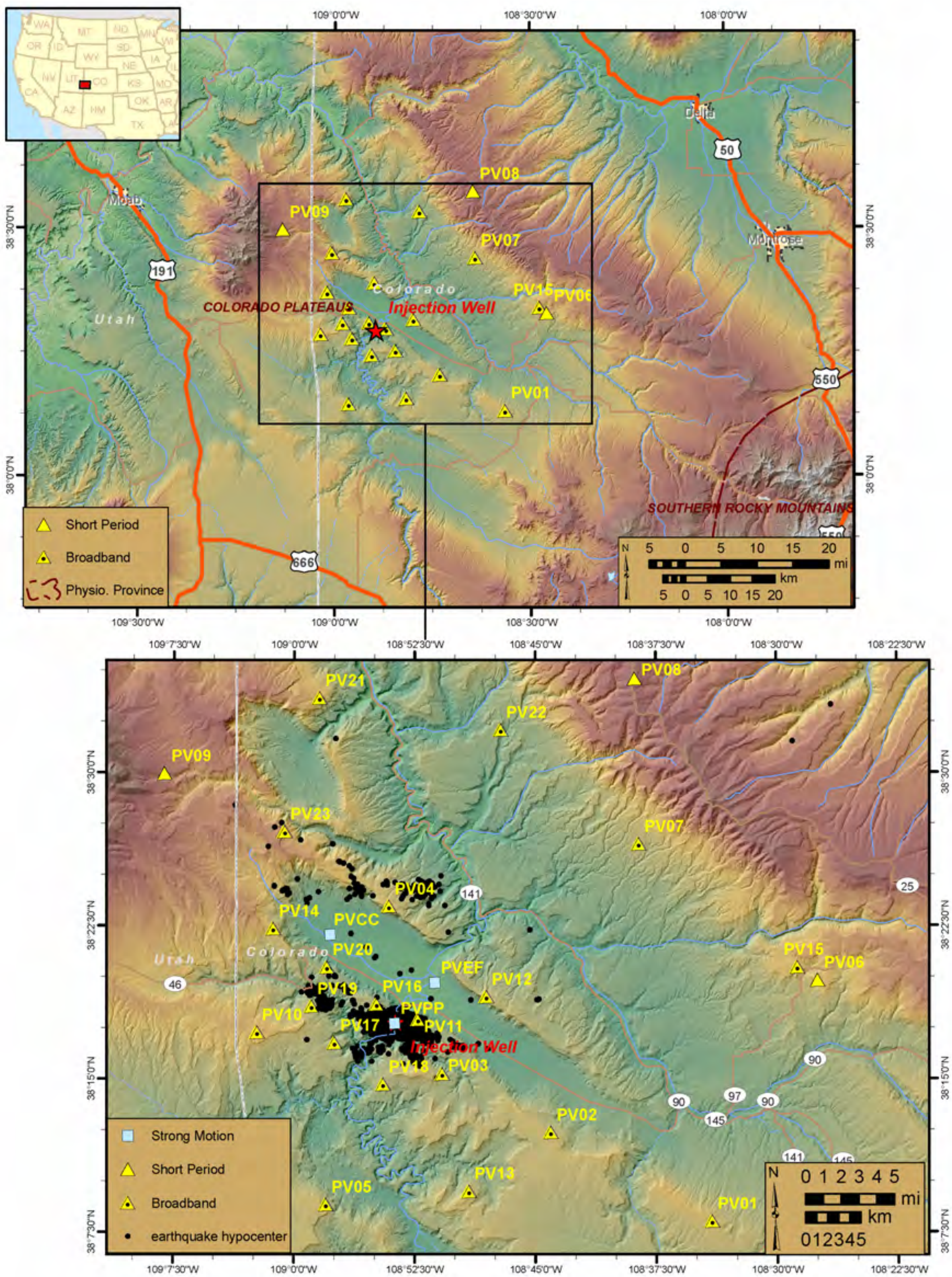


Figure 2-6 Locations of the Paradox Valley Seismic Network stations, Paradox Valley Unit injection well, and hypocenters of earthquakes less than 8 km deep. PVCC, PVEF & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Physiographic provinces from Fenneman and Johnson (1946).

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.

2.3.2 Induced Seismicity

Nearly 5,900 shallow 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 locate at depths 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) and anomalously shallow for naturally-occurring tectonic earthquakes. 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 continued to occur close to the well but also began occurring at greater and greater distances from the well. By 2002, earthquakes were occurring up to 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 temporal-spatial evolution of the seismicity since the start of injection operations demonstrated in Figure 2-7 strongly suggest that these earthquakes have been induced by PVU fluid injection.

Several distinct groups, or clusters, of induced seismicity have developed over the history of PVU injection operations. By the end of the injection tests in 1995, earthquakes were occurring 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).

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-present 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-present 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-present 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-present	short-period	vertical
PV10	38.29	109.04	2266	6/83-present 10/08-present	short-period broad-band	vertical triaxial
PV11	38.30	108.87	1882	12/89-present 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-present 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-present 5/10-present	short-period broad-band	triaxial 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

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
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

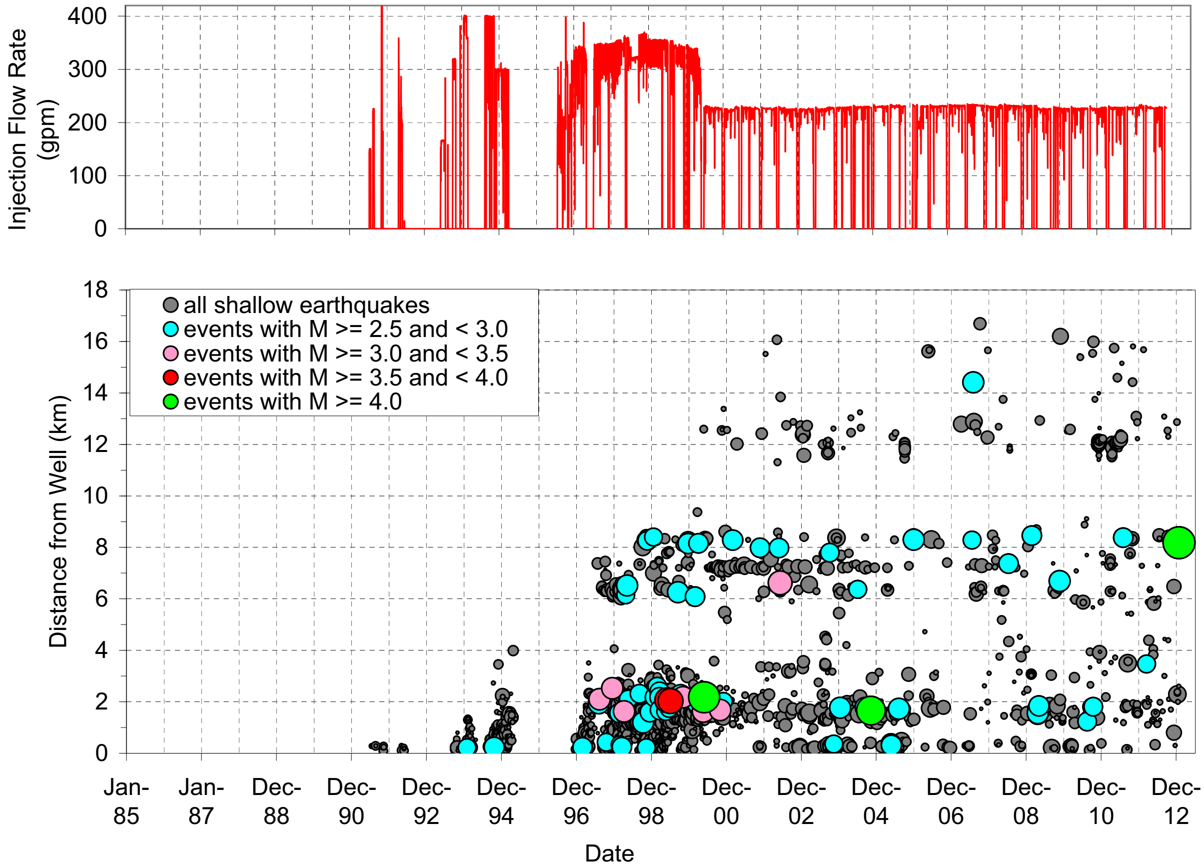
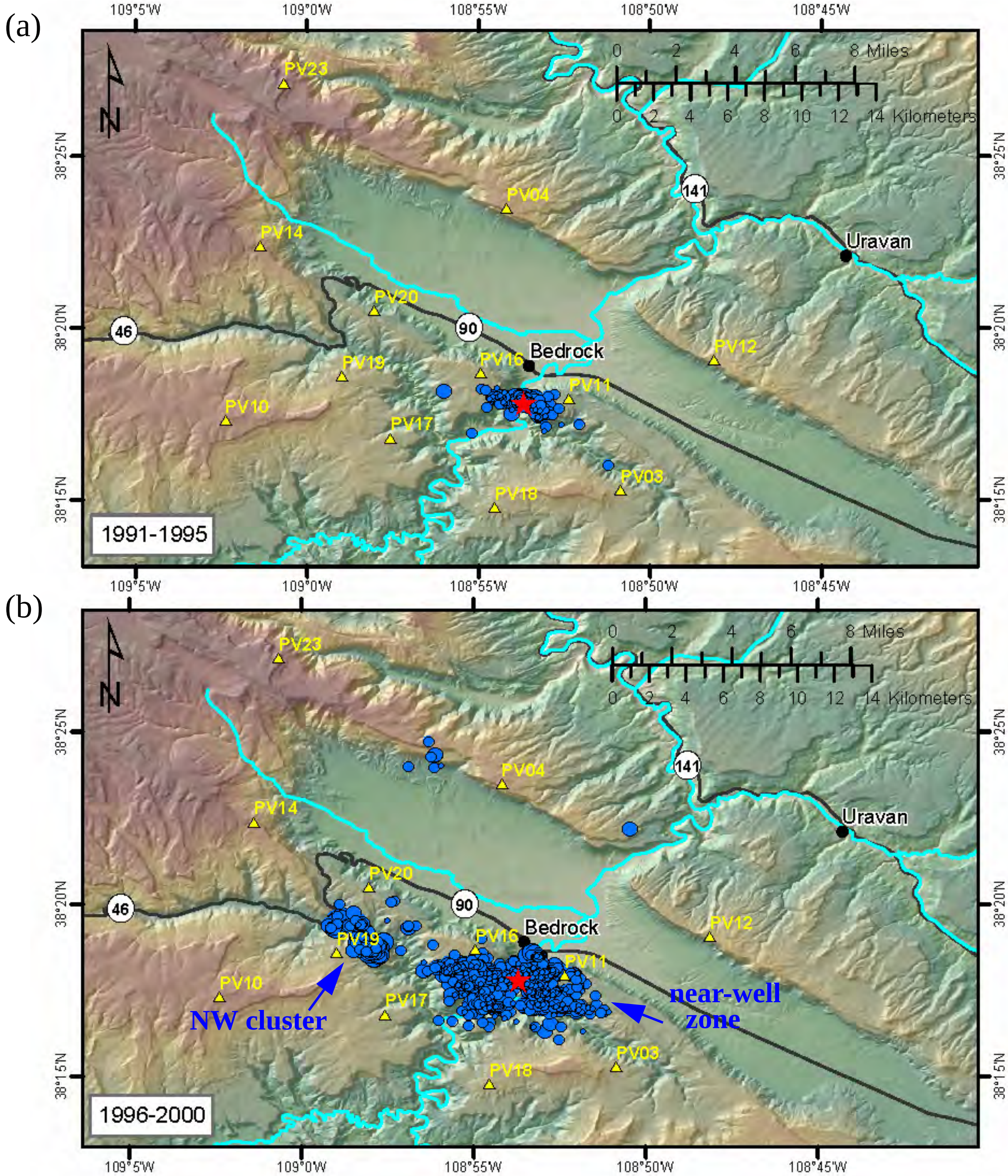


Figure 2-7 Lower plot - scatter plot of earthquakes having $magnitude \geq 0.5$ *and locating less than 8.5 km deep (relative to the ground surface elevation at the injection wellhead), plotted as a function of date and distance from the PVU injection well. Each circle represents a single earthquake, with the width of the circle scaled by the event magnitude. The upper plot shows the daily average injection flow rate.*



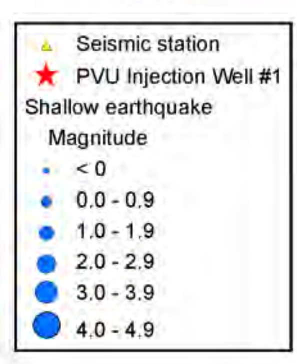
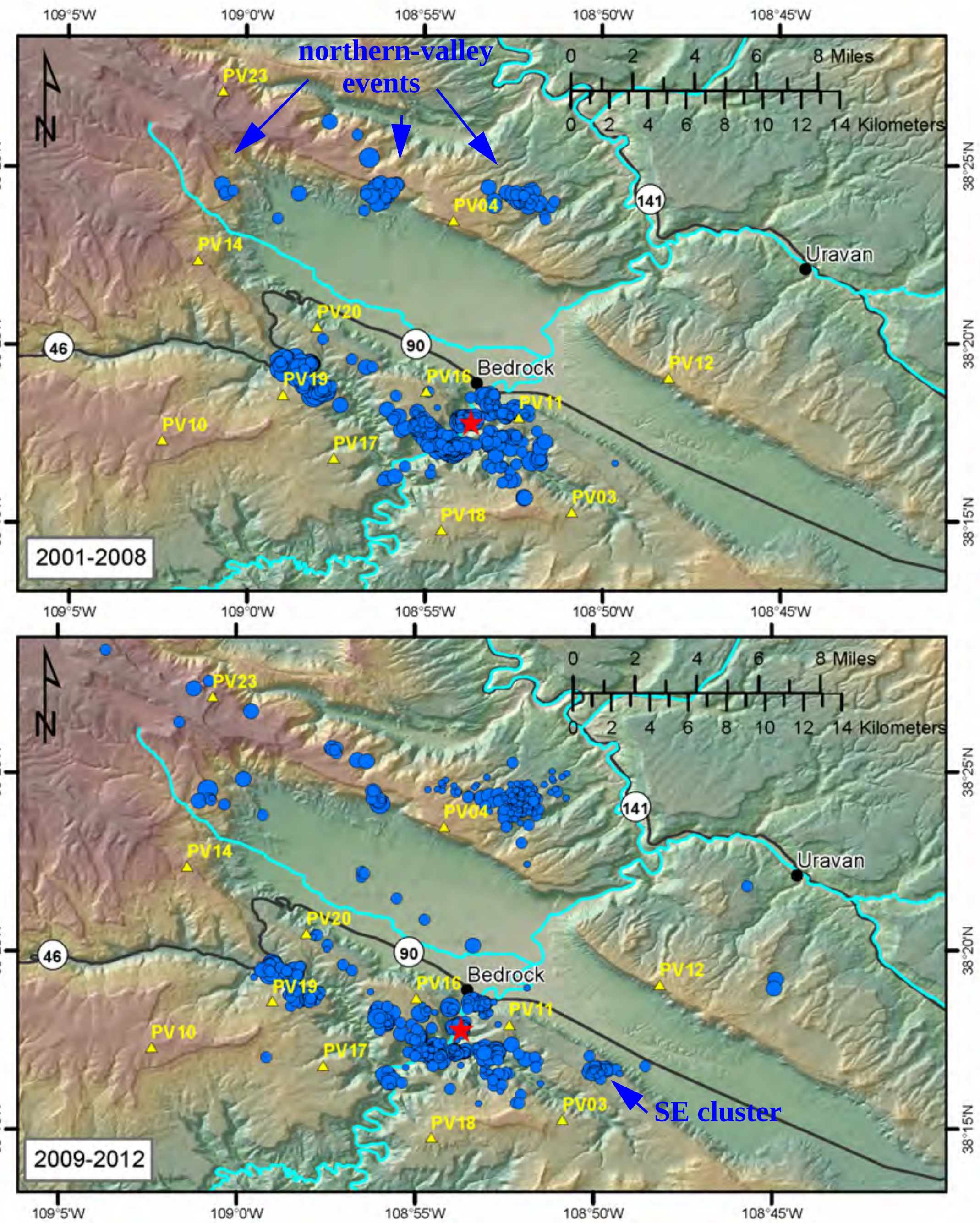


Figure 2-8 Maps showing the spatial distribution of shallow seismicity recorded in the Paradox Valley area over time: (a) injection tests, 1991-1995 (b) continuous injection,1996-2000 (c) continuous injection, 2001-2008 (d) continuous injection, 2009-2012. All detected earthquakes locating less than 8.5 km deep (relative to the ground surface elevation at the injection wellhead) are included.

(c)

(d)



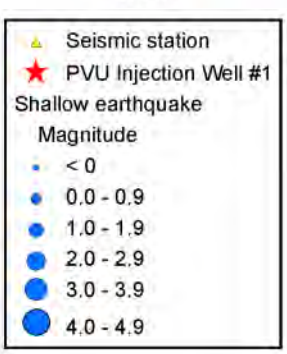


Figure 2-8, continued.

3.0 PVSN OPERATIONS IN 2012

3.1 Network Maintenance and Upgrades

Upgrade efforts during 2012 were focused on improving lightning protection at remote seismic stations. Insulating glass plates were installed in seismometer vaults at several stations. The benefits of the glass plates are electrical insulation and an improved base for leveling and orienting seismometers. Additional lightning protection upgrades included installation of air terminals, grounding conductors on antenna masts, and more grounding rods Also, grounding resistance was measured at each station to identify stations that still need additional grounding.

Routine remedial and preventive maintenance was performed for the 20-station digital broadband seismic network and for the three PVSN strong motion instruments. Because the upgrade to digital broadband instrumentation is complete at all stations, Reclamation is no longer maintaining the obsolete analog seismic stations. Further details of the work performed at the seismic stations during 2012 are included in the attached site visit reports (Appendix B).

3.2 Network Performance

PVSN performed very well during 2012. The annual network performance can be characterized by two aspects: performance of individual seismic stations (how well individual stations functioned throughout the year) and performance of network data acquisition (the continuity of data acquisition and recording).

Nearly all of the individual digital seismic stations functioned with no problems throughout 2012, as indicated in Figure 3-1.Each horizontal line in this plot represents one seismic data channel, as indicated in the figure. The plot only indicates whether the individual seismic data channels were functioning properly and not whether they were being recorded by the acquisition system. Thick blue lines indicate that the data channel was functioning normally. Thin red lines indicate that the data channel was offline and therefore no data from that channel were being recorded. Intermediate-thickness green lines indicate either that the data channel was offline intermittently or that there was some problem with data quality. Further details of individual station performance are given in Table 3-1

As mentioned above, the old analog seismic stations are no longer considered active components of PVSN and are not being maintained. Analog stations PV02, PV07, PV08, and PV15 have been permanently offline since 2011. The remaining analog stations are currently still functioning but are anticipated to go permanently offline in mid-2013 when the data acquisition center at Hopkins Field is moved into a new building. The annual operating status of the analog stations during 2012 is reported in Figure 3-2 and Table 3-2.

The performance of PVSN data acquisition during 2012 is represented by the graph shown in Figure 3-3. This graph plots the performance of data acquisition and recording as a function of time. A performance rating of 100% indicates that the data acquisition system was operating sufficiently to record all seismic events above the normal detection threshold. A performance rating of 0% indicates that some component of the data acquisition system was offline and that no seismic data were being saved during that time period. Intermediate ratings indicate that data

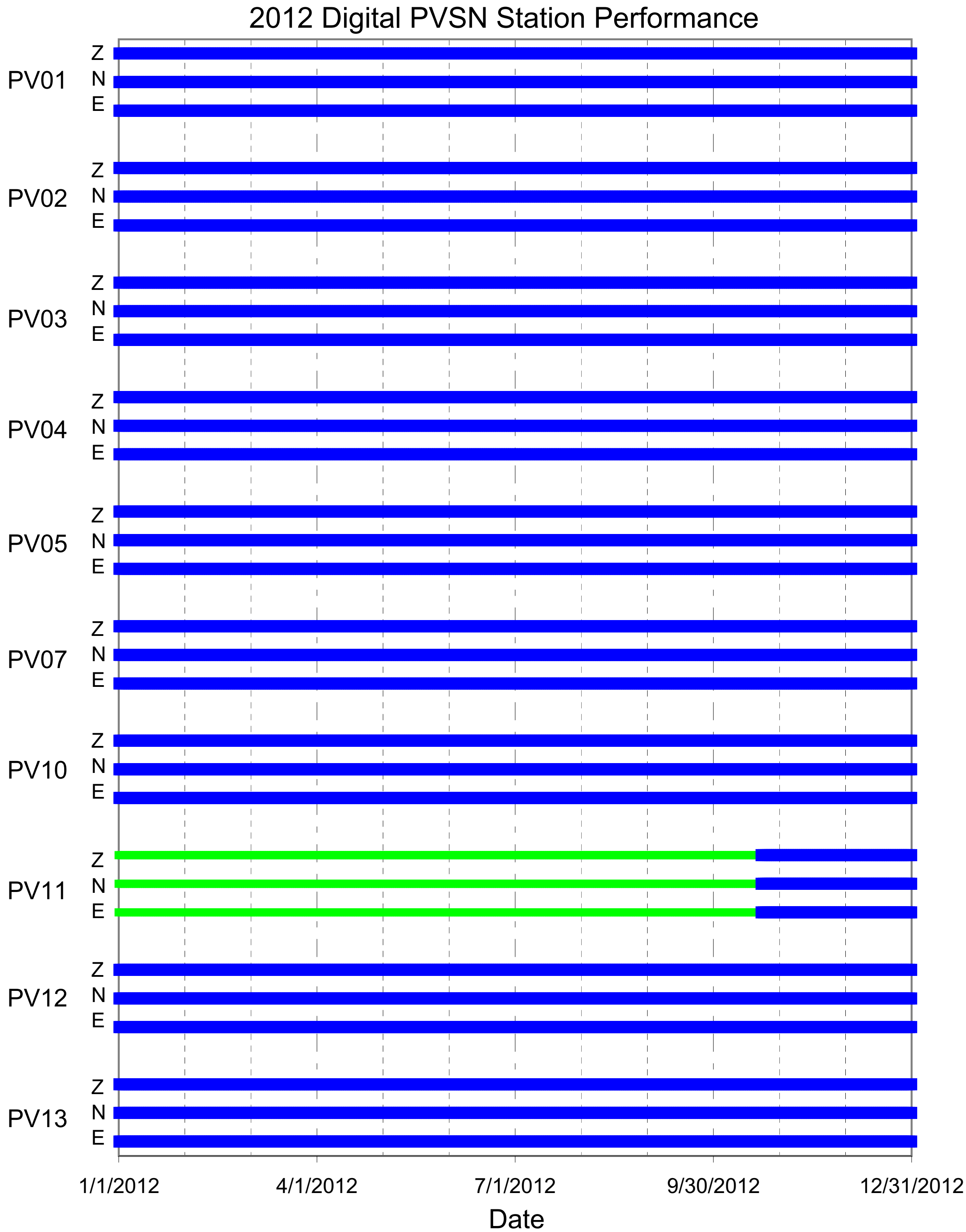


Figure 3-1 Annual performance of PVSN digital seismic data channels. Trace components are labeled as: Z = vertical component, N = north-south horizontal component, E = east-west horizontal component. Thick blue lines indicate that the channel was functioning well. Thin red lines indicate that the channel was offline. Intermediate-thickness green lines indicate that the channel was either operating intermittently or had some other data quality issue.

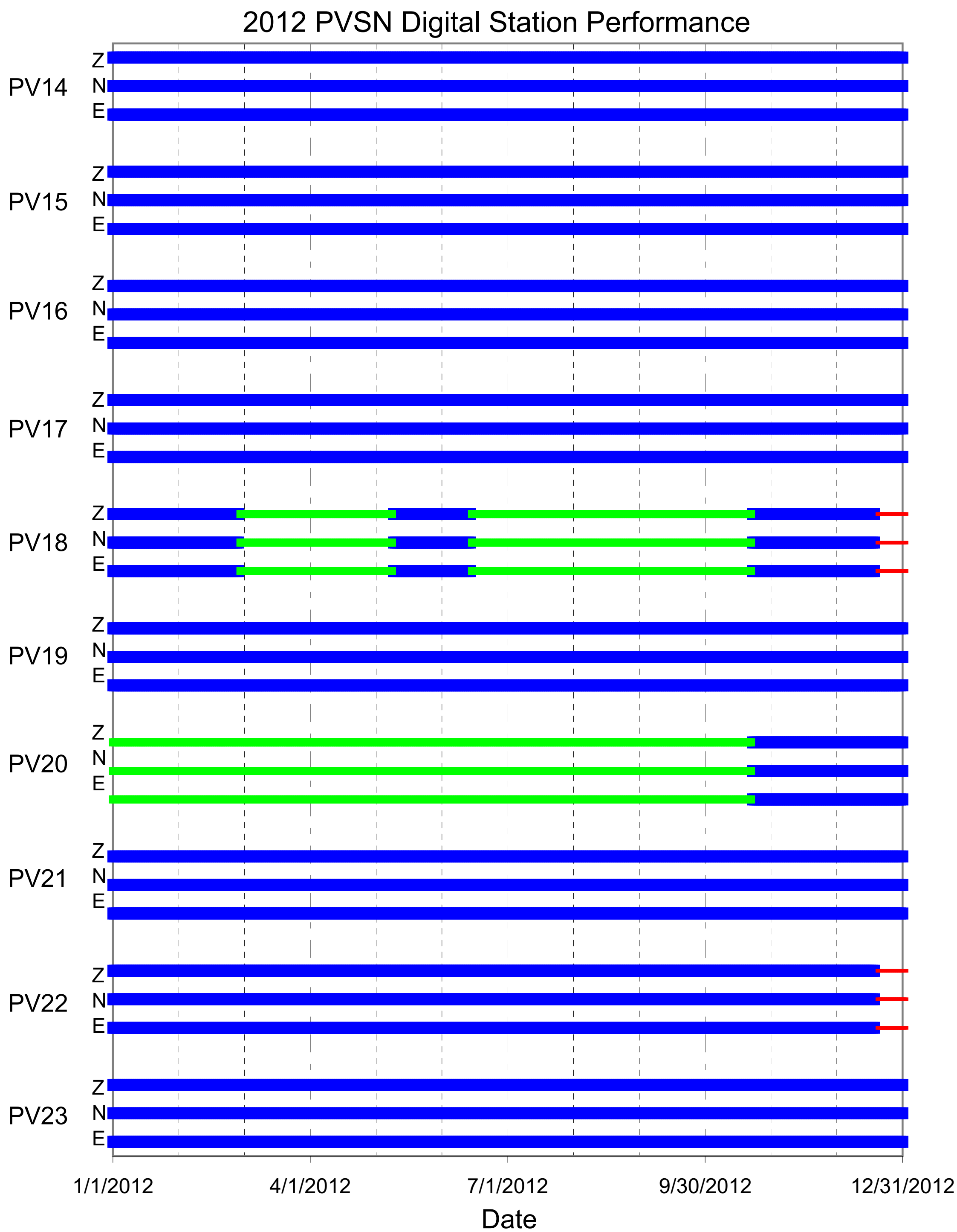


Figure 3-1, continued.

Table 3-1 Performance of digital seismic stations during 2012

Station	Performance
PV01	Online and functioning normally throughout the year
PV02	Online and functioning normally throughout the year
PV03	Online and functioning normally throughout the year
PV04	Online and functioning normally throughout the year
PV05	Online and functioning normally throughout the year
PV07	Online and functioning normally throughout the year
PV10	Online and functioning normally throughout the year
PV11	Had intermittent data drop-outs of 6 hours duration or less because of defective battery-protection circuits from January - Oct. 22
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	Online and functioning normally throughout the year
PV17	Online and functioning normally throughout the year
PV18	No synchronization of internal clock with GPS time from early March - May 10 (absolute times unreliable); clock not outputting time stamp from mid-June to Oct. 22 (absolute times unreliable); offline from Dec. 19 to end of year, likely due to fusible link tripping on power supply
PV19	Online and functioning normally throughout the year
PV20	Had intermittent data drop-outs of 6 hours duration or less because of defective battery-protection circuits from January - Oct. 22
PV21	Online and functioning normally throughout the year
PV22	Offline from Dec. 19 to end of year, likely due to fusible link tripping on power supply
PV23	Online and functioning normally throughout the year

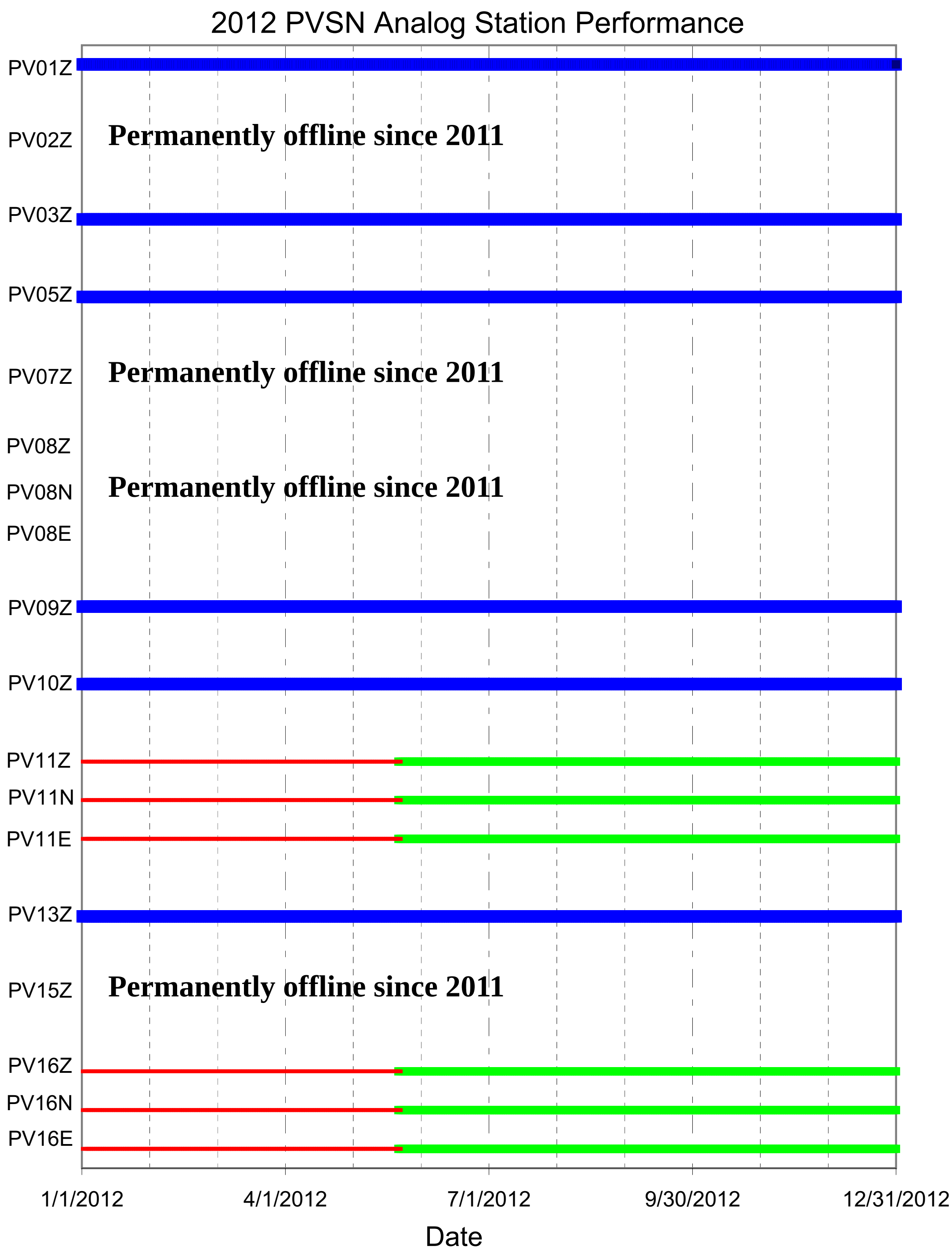


Figure 3-2 Annual performance of PVSN analog seismic data channels. Trace components are labeled as: Z = vertical component, N = north-south horizontal component, E = east-west horizontal component. Thick blue lines indicate that the channel was installed and functioning well. Thin red lines indicate that the channel was offline. Intermediate-thickness green lines indicate that the channel was operating intermittently.

Table 3-2 Performance of analog seismic stations during 2012

Station	Performance
PV01	Online and functioning normally through the year
PV02	Permanently offline since 2011
PV03	Online and functioning normally through the year
PV05	Online and functioning normally through the year
PV07	Permanently offline since 2011
PV08	Permanently offline since 2011
PV09	Online and functioning normally through the year
PV10	Online and functioning normally through the year
PV11	Station offline due to equipment failure at Hopkins Field from January to May 21; data recorded intermittently through rest of year
PV13	Online and functioning normally through the year
PV15	Permanently offline since 2011
PV16	Station offline due to equipment failure at Hopkins Field from January to May 21; data recorded intermittently through rest of year

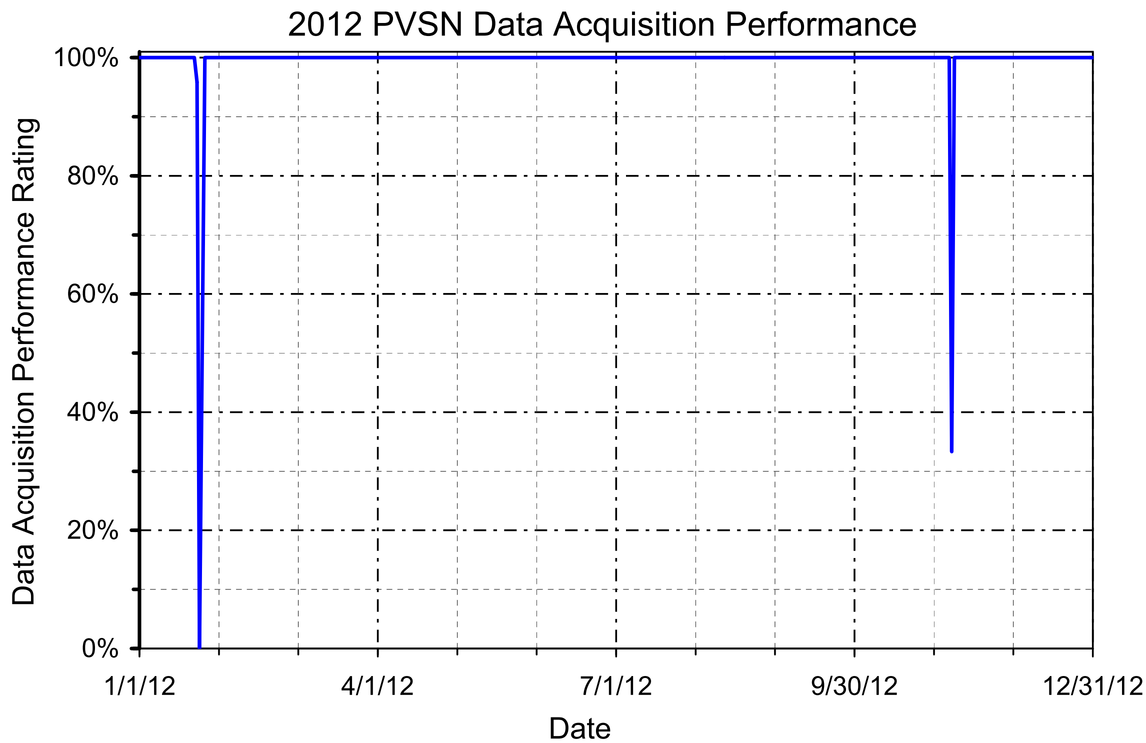


Figure 3-3 Annual performance of PVSN data acquisition. A performance of 100% indicates that PVSN was continuously triggering on seismic events above the detection threshold and properly recording the seismic datafiles. A rating of 0% indicates that some part of the data acquisition, transmission, or recording system was down and no data were recorded. See text for further explanations.

acquisition occurred for part of the day, with the given percentage corresponding to the percent daily uptime. (Periodic shut-downs for routine equipment maintenance lasting less than two hours are ignored in this performance rating.) PVSN uptime for 2012 was 99.4% and is compared to that for previous years in **Table 3-3.**

Only two minor interruptions in data acquisition occurred during 2012. These disruptions were caused by power outages at Hopkins Field Airport in Nucla, Colorado. Data from the seismic stations are transmitted via radio signal to Hopkins Field, before being transmitted by phone line to Reclamation's Denver Office. The data acquisition servers at Hopkins Field have backup power supplies that sustain data recording during brief power failures. If a power outage lasts more than about one hour, however, the data acquisition system shuts down. Unplanned power outages occurred on January 23 - 25 (37 hours) and on Nov. 8 (2 hours). After the November power outage, a critical networking switch was inoperable and had to be replaced. The combined power outage and subsequent equipment failure resulted in a 16-hour period with no data acquisition.

Since 2010, Hopkins Field has been staffed for only 4 hours each weekday, so the availability of on-site personnel to quickly respond to power or utility problems has become limited. Installation of a new instrumentation building at Hopkins Field to house the PVSN data acquisition equipment, with a dedicated power supply, is planned for 2013 and should alleviate the power outage problems.

Table 3-3 Annual PVSN 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%
**not tabulated in 2001		

4.0 SEISMIC DATA RECORDED IN 2012

4.1 Annual Summary

193 earthquakes were recorded within or near the perimeter of the Paradox Valley Seismic Network during 2012. 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 2012, 93 earthquakes were detected in the near-well region of induced seismicity (within 5 km of the injection well, magenta circles in Figure 4-1), 55 earthquakes were detected in the northwest (NW) cluster (6 to 9 km northwest of well, blue circles), 25 earthquakes were detected in the southeast (SE) cluster (6 to 7 km southeast of well, green circles), and 10 earthquakes were detected in areas of recurring seismicity located around the northern edge of Paradox Valley (yellow circles). In addition, 10 earthquakes occurred in locations not associated with any of the historically active areas defined above. Five of these earthquakes locate beneath the floor of Paradox valley, at fairly shallow depths (~ 5 to 8 km, white circles in Figure 4-1). Of the remaining five earthquakes, two events locate deep (~10 to 30 km depth, purple circles), and three locate at shallow depths (5 to 8 km depth, white circles). 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 A.

The local earthquakes recorded by PVSN during 2012 are plotted as a function of date, earthquake magnitude, and location category in Figure 4-2. This graph shows that the seismic activity in the near-well region was distributed somewhat uniformly throughout the year, whereas the seismic activity in other areas was more sporadic. The NW cluster was most active in July and mid-September to mid-October. Most of the SE-cluster 2012 seismicity occurred from late March to early July, with very little activity occurring during the second half of the year. Half of the 2012 northern valley seismicity occurred during March and April.

4.2 Shallow Earthquakes Locating within 10 km of the Injection Well

4.2.1 2012 Seismicity

The vast majority of the earthquakes induced within 10 km of the injection well during 2012 locate in areas of previous seismic activity. The hypocenters of the earthquakes that occurred in 2012 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 2012 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 a traditional earthquake location algorithm employing manually-determined absolute arrival times, because the waveform data were not of sufficient quantity or quality to include in the relative location.

Five shallow, likely-induced earthquakes occurred beneath the floor of Paradox Valley in 2012, at distances of 4.4 to 7.3 km from the injection well (Figure 4-3). Four of these events locate at

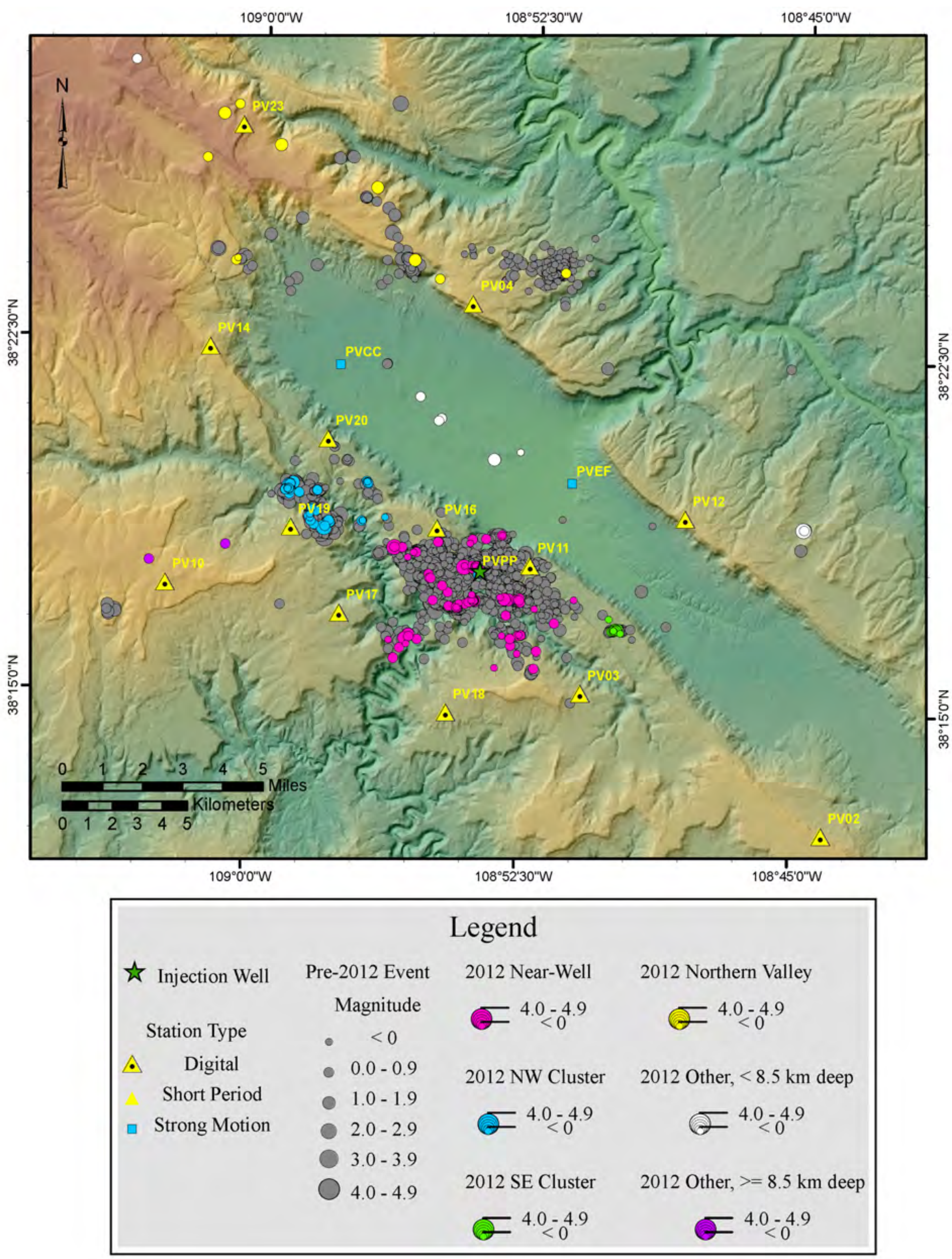


Figure 4-1 Locations of local earthquakes recorded by PVSN during 2012 (colored circles) and previous years (gray circles).

Table 4-1 Summary of events recorded during 2012 by location category

Location Category	Number of Earthquakes	Magnitude Range	Median Magnitude
near-well	93	-0.6 - 2.5	0.20
NW cluster	55	-1.5 - 2.0	0.30
SE cluster	25	-0.6 - 1.9	0.20
northern valley	10	-0.5 - 1.7	0.75
central valley	5	-0.3 - 1.4	0.40
other	5	0.5 - 2.1	0.70
TOTAL	193	-1.5 - 2.5	0.30

Table 4-2 Average daily seismicity rates of local earthquakes recorded by PVSN during 2012. These rates were computed using the number of days the network was operational, 363.8, as discussed in section 3.

Earthquake Group	All Magnitudes		Magnitude >= **M** 0.5	
	Number of Events Recorded	Average Daily Rate	Number of Events Recorded	Average Daily Rate
near-well	93	0.256	25	0.069
NW-cluster	55	0.151	14	0.038
SE cluster	25	0.069	6	0.016
northern valley	10	0.027	7	0.019
central valley	5	0.014	2	0.005
other	5	0.014	5	0.014
TOTAL	193	0.531	59	0.162

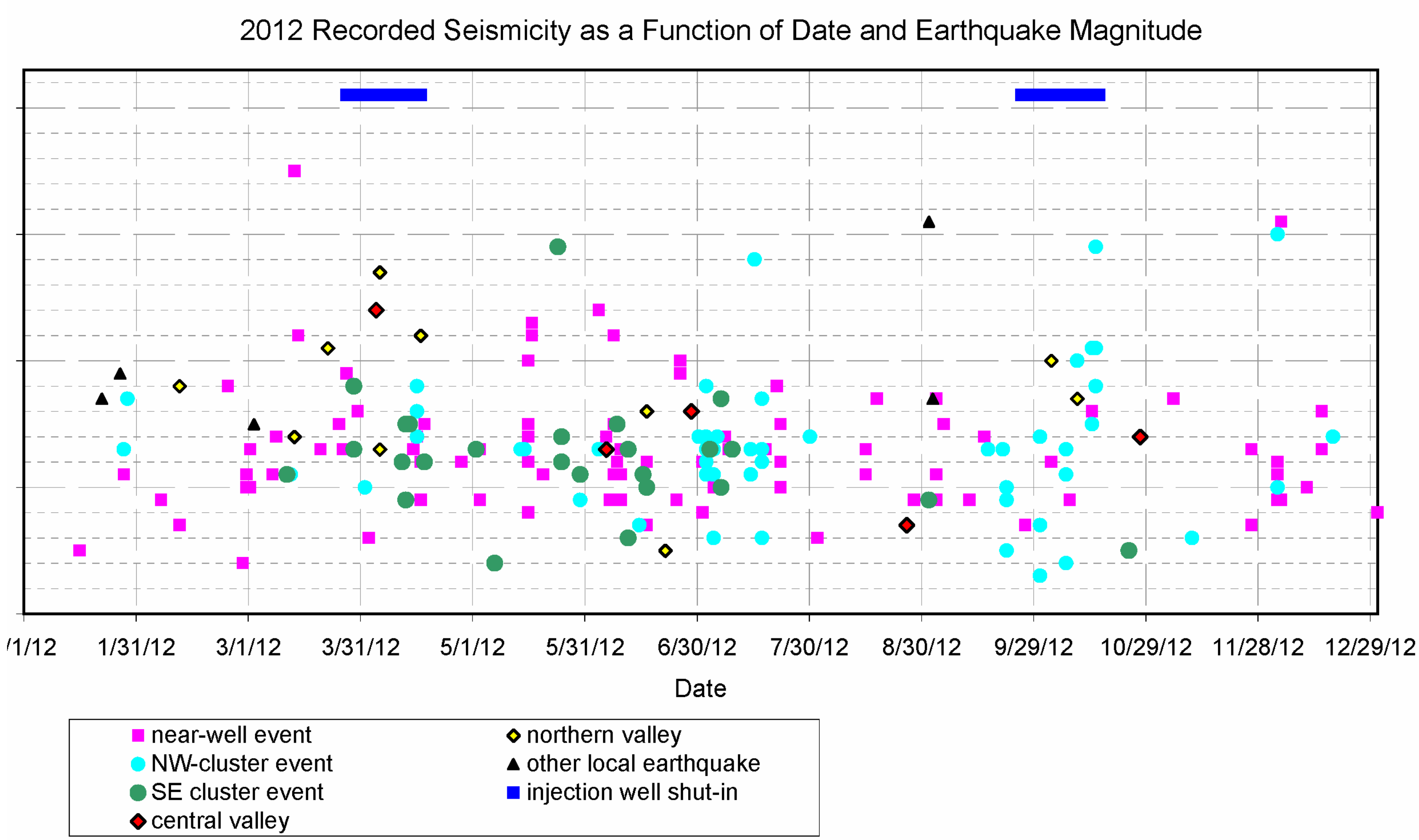


Figure 4-2 Earthquakes recorded by PVSN during 2012, plotted as a function of date, magnitude, and event location category. The dates of injection well shut-ins are included as indicated by the legend.

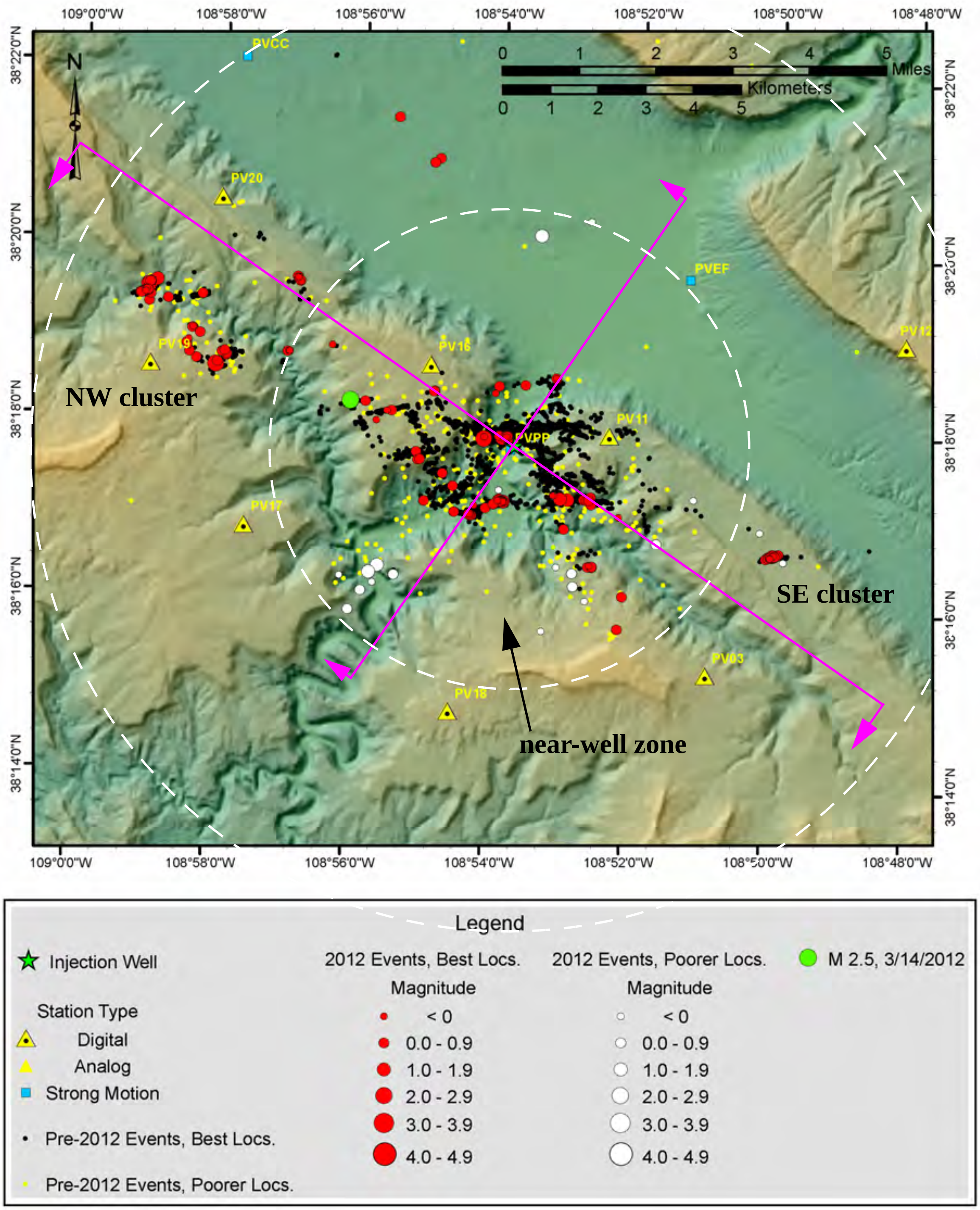
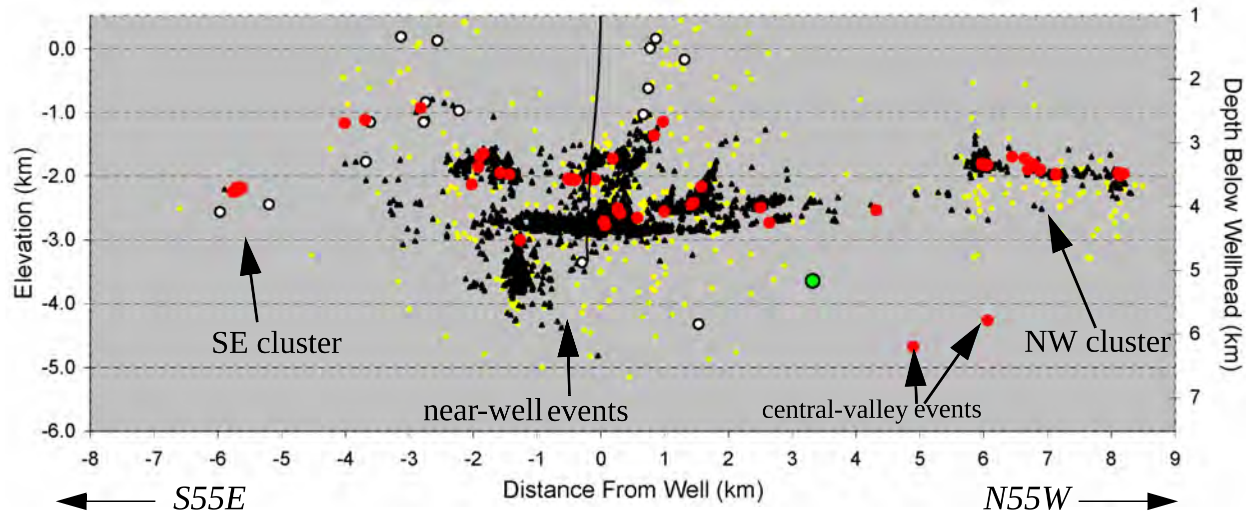


Figure 4-3 Map showing the epicenters of shallow earthquakes (< 8.5 km depth) locating in the vicinity of the injection well in 2012, compared to the locations of previously-induced events. The white dashed circles indicate radial distances of 5 and 10 km from the injection well. The magenta lines indicate 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

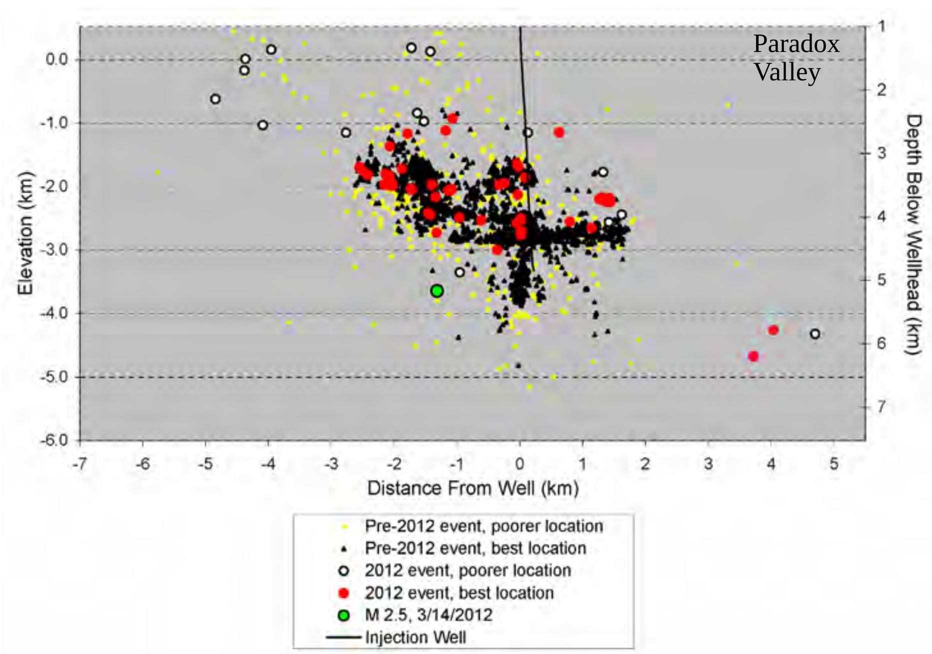


Figure 4-4 Vertical cross sections showing the locations of earthquakes induced in the vicinity of the injection well in 2012, compared to the locations of previously-induced events: (a) section parallel to Paradox Valley (b) section perpendicular to Paradox Valley. The orientations of the cross sections are indicated by the magenta lines in Figure 4-3.

depths between about 5.8 and 6.2 km (relative to the ground surface elevation at the injection wellhead) and range in magnitude from -0.3 to 0.6. The remaining event locates at a depth of 7.8 km and has an estimated duration magnitude of 1.4. Earthquakes were first detected beneath the floor of Paradox Valley in 2010. Three such events were recorded in 2010 and two in 2011. The number of earthquakes detected beneath Paradox Valley during 2012 (five) represents the highest rate of central-valley seismicity recorded to date.

One induced earthquake with magnitude greater than or equal to M 2.5 (M 2.5+) was recorded during 2012. This magnitude threshold is significant because it represents the approximate threshold for human detection in the nearby communities of Paradox and Bedrock. The M 2.5+ earthquake recorded during 2012 locates at the far northwestern edge of the near-well region. Its location is indicated by the green circle in Figures 4-3 and 4-4. The event occurred at an estimated depth of about 5.2 km (relative to the ground surface elevation at the injection wellhead), about one kilometer deeper than most of the seismicity occurring in the same area. This earthquake occurred on March 14, 2012 and has an estimated duration magnitude of M 2.5. (No strong motion instruments were triggered.)

4.2.2 Comparison to 2011 Seismicity

Overall, the rate of earthquakes induced within 10 km of the injection well increased by 52% in 2012 (178 events) compared to 2011 (117 events), while the magnitude distribution remained similar. The PVSN event detection threshold and network uptime were comparable for the two years. The percent increase in seismic activity was larger for regions located 5 to 10 km from the well than for the area within 5 km of the well. These trends are shown in Figure 4-5 and Figure 4-6 and are discussed below.

The numbers of earthquakes recorded during 2012 and 2011 are plotted as a function of magnitude in Figure 4-5. Individual histograms are shown for earthquakes induced within 5 km of the injection well (the near-well region and one event within Paradox Valley), for those induced at distances of 5 to 10 km from the well (the NW and SE clusters and four events in Paradox Valley), and for all induced 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 occurrence rate for earthquakes locating within 5 km of the injection well increased by 25% in 2012 (94 events) compared to the previous year (75 events). This increased rate occurred primarily for earthquakes with magnitudes between -0.5 and 0.5. (Figure 4-5, top). The largest near-well earthquake recorded during 2011 had a magnitude of M 2.4. The largest near-well earthquake recorded during 2012 had a similar magnitude, M 2.5.

The occurrence rate for earthquakes locating at distances of 5 to 10 km from the injection well increased by 100% in 2012 (84 events) compared to the previous year (42 events). This increased rate occurred primarily for earthquakes with magnitudes less than 0.5. (Figure 4-5, middle). The maximum earthquake magnitude in this region decreased in 2012 compared to 2011. The largest event recorded during 2011 had a magnitude of M 2.7, whereas the largest event recorded during 2012 had a magnitude of M 2.0 (both events occurred in the NW cluster).

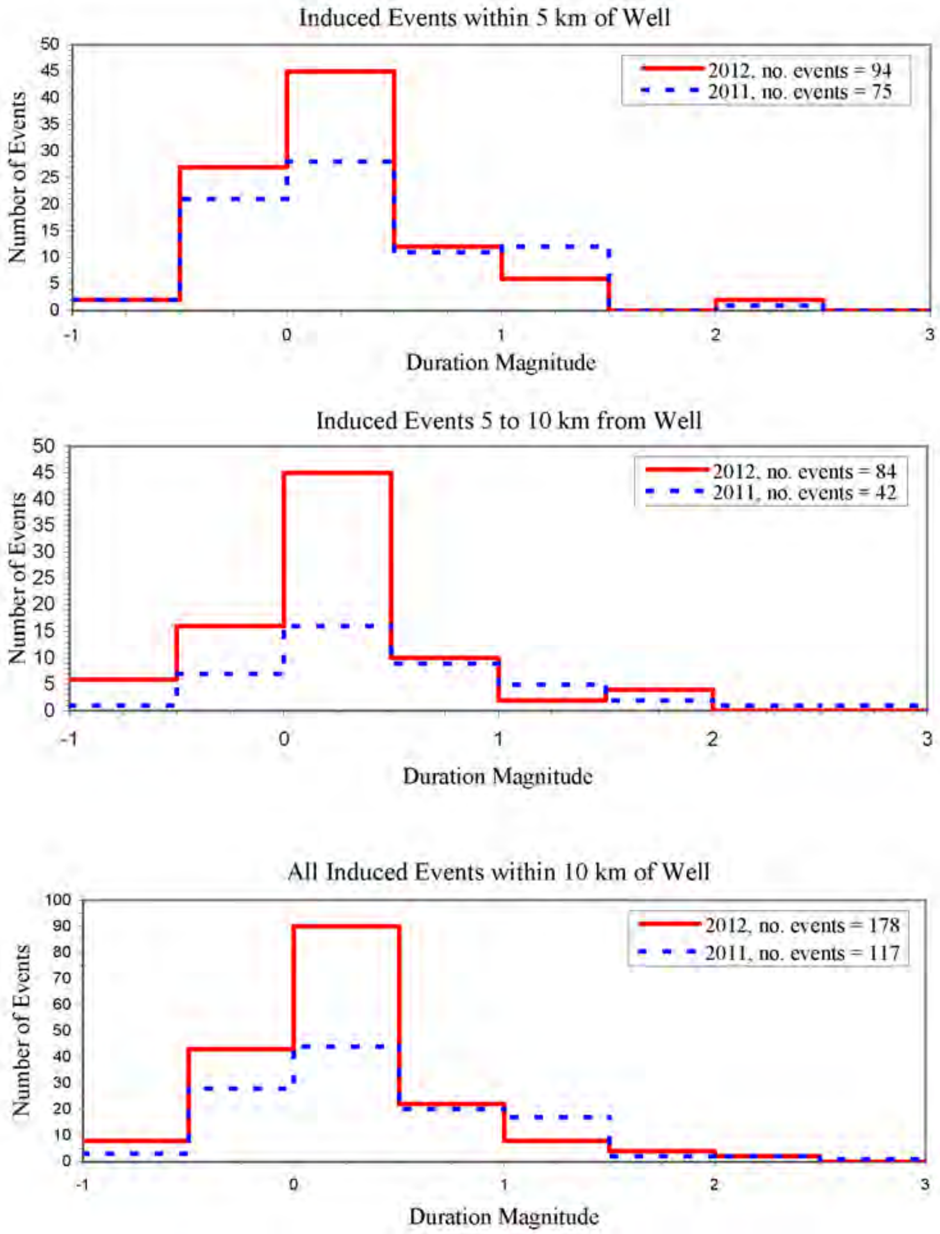


Figure 4-5 Magnitude histograms of induced events recorded within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and in both regions (bottom) during 2012 (solid red lines) and 2011 (dashed blue lines).

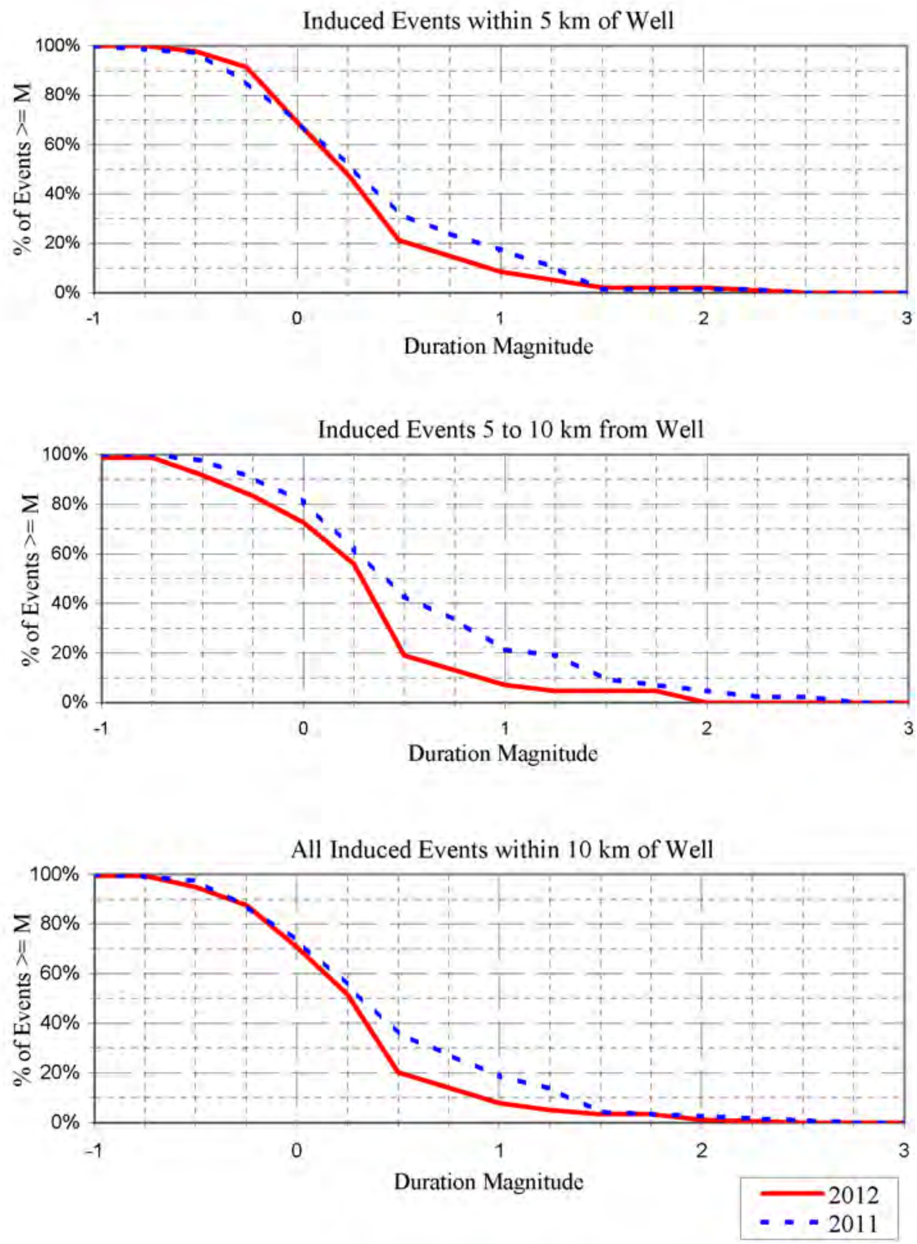


Figure 4-6 Cumulative magnitude-frequency plots of induced events recorded within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and in both areas (bottom) during 2012 (solid red lines) and 2011 (dashed blue lines).

4.3 Northern Valley Earthquakes

The magnitudes and estimated depths of the ten northern valley earthquakes recorded during 2012 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 2011 range from M -0.8 to M 2.9, with all but one event having magnitude <= M 2.3. Magnitudes of the earthquakes that occurred during 2012 range from M -0.5 to M 1.7. Estimated depths of the northern valley earthquakes recorded in 2012 range from 3.2 to 8.6 km (relative to the ground surface elevation at the injection wellhead), with a median value of 5.4 km. This is comparable to estimated depths of previous northern valley earthquakes having reasonably well-constrained hypocenters.

Four of the earthquakes recorded during 2012 that are classified as northern valley events locate in a previously aseismic area (near seismic station PV23), rather than within previously-active northern valley seismicity clusters (Figure 4-1). These earthquakes locate at horizontal distances of 18.5 to 20.8 km from the injection well, somewhat greater than previous northern valley seismicity epicentral distances (~11 to 17 km).

4.4 Historical Seismicity Trends

The bubble plots in Figure 4-7 show the occurrence of shallow seismicity (< 8.5 km depth, relative to the ground surface elevation at the injection wellhead) as a function of date and earthquake magnitude. The area of each circle in these plots is scaled by the number of earthquakes occurring in a given quarter-year and magnitude range. Only events with magnitude >= M 0.5 are included, since the detection capability for earthquakes with magnitude less than this threshold has varied considerably over the history of PVSN. 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 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.

Compared to seismicity patterns observed in the previous three years, the 2012 induced seismicity located within 5 km of the well shows fairly typical rates for events with magnitudes between 0.5 and 1.0 and between 2.0 and 3.0, but reduced rates for the intermediate-magnitude bins (1.0 to 2.0) (Figure 4-7, uppermost bubble plot). The rate of M 0.5+ earthquakes occurring at distances of 5 to 10 km from the injection well during 2012 is similar to the rates observed since mid-2007 (Figure 4-7, middle bubble plot).

The lower bubble plot in Figure 4-7, which presents the northern valley seismicity, shows that the northern valley seismicity is returning to more historical rates after the significantly increased rates of 2010 and 2011.

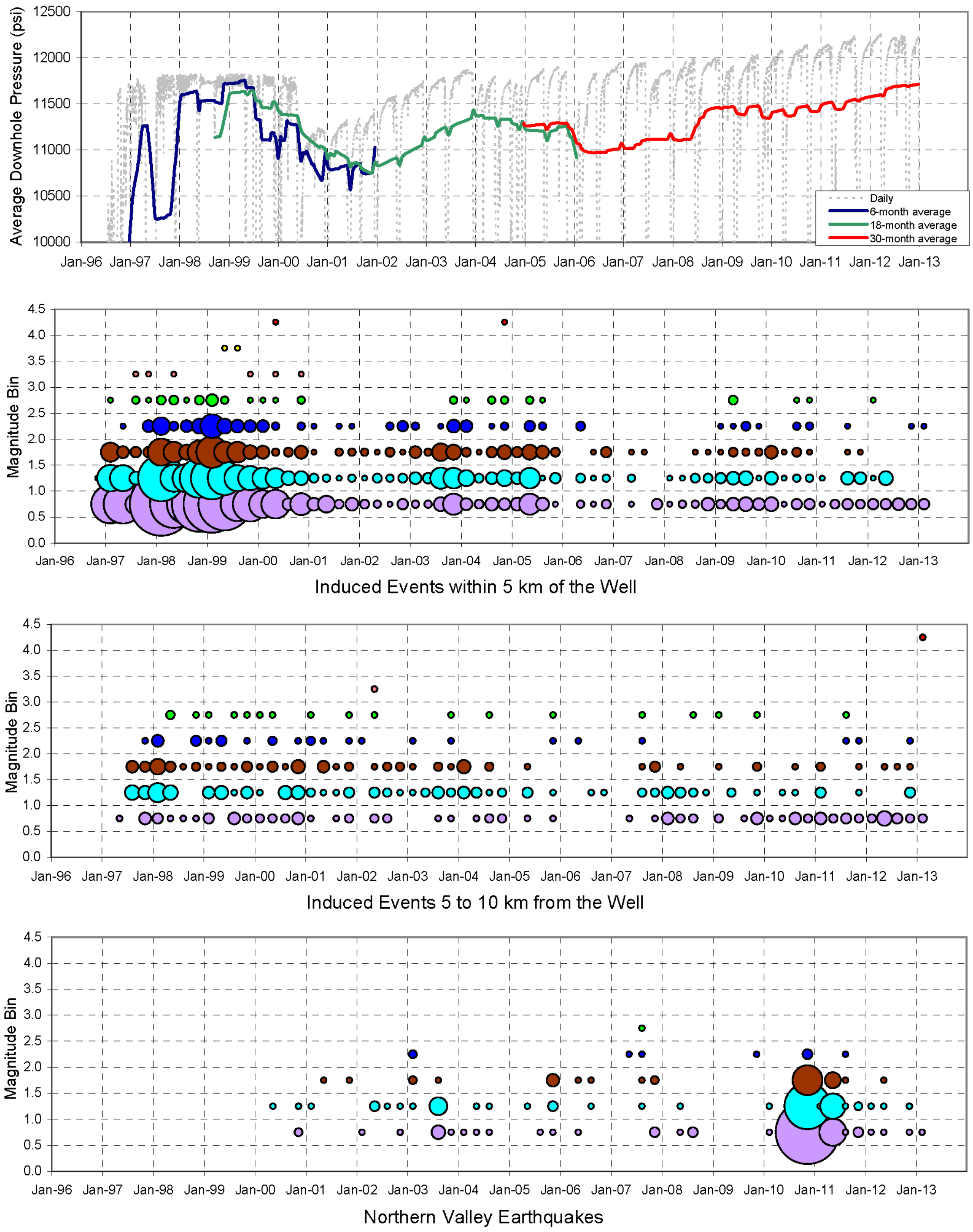


Figure 4-7 Injection well downhole pressure data averaged over daily, 6-month, 18-month, and 30-month time periods (top) and occurrence of shallow seismicity as a function of date and magnitude within 5 km of the injection well, at distances of 5 to 10 km from the well, and in the northern valley region. 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. Data recorded during continuous PVU injection operations from 1996 through 2012 are included.

5.0 REFERENCES

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APPENDIX A
PVSN 2012 LOCAL EARTHQUAKE CATALOG

Table A-1: Local earthquakes recorded by PVSN during 2012

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
1/16/12	18:24:32	38.2625	-108.8870	-1.2	2.7	-0.5	near-well
1/22/12	18:13:14	38.4737	-109.0612	-3.9	5.4	0.7	other
1/27/12	10:27:09	38.2963	-109.0470	-8.4	9.9	0.9	other
1/28/12	9:07:56	38.3167	-108.9732	-1.9	3.4	0.3	NW cluster
1/28/12	23:06:59	38.2688	-108.8682	-1.1	2.6	0.1	near-well
1/29/12	17:47:29	38.3138	-108.9745	-1.8	3.3	0.7	NW cluster
2/7/12	20:32:24	38.2874	-108.8855	-3.0	4.5	-0.1	near-well
2/12/12	18:13:37	38.3004	-108.9284	-2.7	4.3	-0.3	near-well
2/12/12	23:56:00	38.4037	-109.0122	-2.7	4.3	0.8	N. valley
2/25/12	15:27:30	38.2868	-108.8781	-1.6	3.2	0.8	near-well
2/29/12	22:32:31	38.2971	-108.8955	-2.8	4.3	-0.6	near-well
3/1/12	4:39:46	38.2948	-108.9186	-2.2	3.7	0.1	near-well
3/1/12	11:35:21	38.2933	-108.9181	-2.4	3.9	0.0	near-well
3/1/12	18:49:12	38.2969	-108.8953	-2.7	4.2	0.1	near-well
3/2/12	2:07:46	38.2934	-108.9176	-2.4	4.0	0.0	near-well
3/2/12	6:22:38	38.2971	-108.8952	-2.7	4.2	0.3	near-well
3/3/12	5:03:41	38.3028	-109.0123	-29.4	30.9	0.5	other
3/8/12	12:47:52	38.2728	-108.8803	0.1	1.4	0.1	near-well
3/9/12	1:37:55	38.2703	-108.8800	-0.8	2.4	0.4	near-well
3/12/12	3:12:33	38.2771	-108.8325	-2.2	3.8	0.1	SE cluster
3/13/12	2:39:19	38.3126	-108.9653	-1.8	3.3	0.1	NW cluster
3/14/12	8:24:44	38.4033	-108.8607	-3.7	5.2	0.4	N. valley
3/14/12	18:39:51	38.3040	-108.9347	-3.6	5.2	2.5	near-well
3/15/12	17:07:50	38.2867	-108.8819	-1.9	3.5	1.2	near-well
3/21/12	2:15:42	38.3040	-108.9347	-3.7	5.2	0.3	near-well
3/23/12	15:12:03	38.4557	-109.0200	-3.9	5.4	1.1	N. valley
3/26/12	7:06:18	38.2873	-108.8765	-1.9	3.4	0.5	near-well
3/27/12	3:35:04	38.2788	-108.8603	-1.2	2.7	0.3	near-well
3/28/12	11:41:24	38.3080	-108.8929	-2.7	4.2	0.9	near-well
3/30/12	2:37:41	38.2771	-108.8333	-2.2	3.7	0.3	SE cluster
3/30/12	6:25:53	38.2771	-108.8336	-2.2	3.7	0.8	SE cluster
3/31/12	9:52:54	38.2831	-108.9048	-2.0	3.6	0.6	near-well
4/2/12	4:33:46	38.3158	-108.9713	-1.9	3.4	0.0	NW cluster
4/3/12	11:06:46	38.2880	-108.8985	-3.4	4.9	-0.4	near-well
4/5/12	22:40:19	38.3362	-108.8903	-6.3	7.8	1.4	central valley
4/6/12	7:11:57	38.4452	-108.9933	-3.0	4.5	1.7	N. valley
4/6/12	10:39:25	38.4592	-109.0130	-1.7	3.2	0.3	N. valley
4/12/12	16:14:09	38.2774	-108.8322	-2.2	3.7	0.2	SE cluster
4/13/12	16:36:33	38.2774	-108.8322	-2.2	3.7	-0.1	SE cluster
4/13/12	19:02:11	38.2774	-108.8323	-2.2	3.7	0.5	SE cluster
4/14/12	5:00:25	38.2773	-108.8323	-2.2	3.7	0.5	SE cluster

Table A-1: Local earthquakes recorded by PVSN during 2012

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
4/15/12	0:29:46	38.3024	-108.9247	-2.5	4.0	0.3	near-well
4/15/12	6:55:54	38.2859	-108.8763	-2.1	3.7	0.3	near-well
4/16/12	9:48:07	38.3117	-108.9650	-1.8	3.3	0.8	NW cluster
4/16/12	9:49:18	38.3117	-108.9649	-1.8	3.3	0.6	NW cluster
4/16/12	10:06:13	38.3120	-108.9647	-1.8	3.3	0.4	NW cluster
4/16/12	23:21:03	38.2741	-108.8756	-0.9	2.5	0.4	near-well
4/17/12	17:18:54	38.2837	-108.9091	-1.7	3.2	0.2	near-well
4/17/12	19:24:13	38.2698	-108.9280	-1.0	2.6	-0.1	near-well
4/17/12	21:52:42	38.4313	-108.9485	-7.1	8.6	1.2	N. valley
4/18/12	2:11:53	38.2768	-108.8340	-2.2	3.7	0.2	SE cluster
4/18/12	8:51:14	38.2867	-108.8775	-1.7	3.2	0.5	near-well
4/28/12	4:33:09	38.2715	-108.9230	1.0	0.5	0.2	near-well
5/2/12	8:39:09	38.2772	-108.8330	-2.2	3.7	0.3	SE cluster
5/3/12	15:54:38	38.3062	-108.9000	-1.1	2.7	-0.1	near-well
5/3/12	16:10:38	38.3076	-108.8991	-2.6	4.1	0.3	near-well
5/7/12	6:29:28	38.2762	-108.8298	-2.6	4.1	-0.6	SE cluster
5/14/12	16:57:13	38.3111	-108.9721	-1.7	3.2	0.3	NW cluster
5/15/12	23:22:56	38.3231	-108.9710	-2.0	3.5	0.3	NW cluster
5/16/12	5:43:40	38.2859	-108.8973	-2.0	3.6	-0.2	near-well
5/16/12	5:44:39	38.2859	-108.8973	-2.0	3.6	0.2	near-well
5/16/12	6:12:49	38.2860	-108.8973	-2.0	3.6	0.4	near-well
5/16/12	6:20:16	38.2859	-108.8973	-2.0	3.6	1.0	near-well
5/16/12	6:45:22	38.2860	-108.8974	-2.0	3.6	0.5	near-well
5/17/12	0:32:33	38.2718	-108.9290	0.2	1.4	1.2	near-well
5/17/12	11:25:34	38.2732	-108.9270	1.1	0.4	1.3	near-well
5/20/12	0:56:31	38.2856	-108.9163	-1.4	2.9	0.1	near-well
5/24/12	17:43:12	38.2774	-108.8324	-2.2	3.7	1.9	SE cluster
5/25/12	1:35:00	38.2773	-108.8318	-2.2	3.8	0.4	SE cluster
5/25/12	7:24:41	38.2774	-108.8315	-2.2	3.8	0.2	SE cluster
5/30/12	11:17:17	38.2775	-108.8322	-2.2	3.7	0.1	SE cluster
5/30/12	18:53:39	38.3167	-108.9731	-1.9	3.4	-0.1	NW cluster
6/4/12	1:58:29	38.2978	-108.8982	-2.6	4.1	1.4	near-well
6/4/12	23:53:04	38.3122	-108.9738	-1.7	3.2	0.3	NW cluster
6/6/12	7:45:24	38.2981	-108.8973	-2.5	4.1	0.4	near-well
6/6/12	9:01:52	38.3493	-108.9164	-4.7	6.2	0.3	central valley
6/7/12	10:00:22	38.2677	-108.8770	0.2	1.3	-0.1	near-well
6/8/12	7:22:19	38.2867	-108.8837	-2.0	3.5	1.2	near-well
6/8/12	19:34:17	38.2627	-108.8691	-1.2	2.7	0.1	near-well
6/8/12	21:42:16	38.2832	-108.9052	-2.0	3.6	0.5	near-well
6/9/12	3:00:25	38.2772	-108.8325	-2.2	3.7	0.5	SE cluster
6/9/12	13:58:37	38.2981	-108.8973	-2.5	4.0	0.2	near-well
6/10/12	2:49:16	38.2860	-108.8975	-2.0	3.6	0.3	near-well

Table A-1: Local earthquakes recorded by PVSN during 2012

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
6/10/12	2:49:29	38.2861	-108.8977	-2.0	3.6	-0.1	near-well
6/10/12	3:09:43	38.2860	-108.8977	-2.1	3.6	0.3	near-well
6/10/12	3:40:14	38.2860	-108.8978	-2.0	3.6	0.1	near-well
6/10/12	3:46:10	38.2860	-108.8979	-2.1	3.6	0.1	near-well
6/10/12	9:41:54	38.2860	-108.8978	-2.1	3.6	-0.1	near-well
6/12/12	17:15:20	38.2771	-108.8331	-2.2	3.7	0.3	SE cluster
6/12/12	17:15:40	38.2770	-108.8331	-2.2	3.7	-0.4	SE cluster
6/15/12	2:25:28	38.3132	-108.9740	-1.8	3.3	-0.3	NW cluster
6/16/12	7:09:57	38.2770	-108.8335	-2.2	3.7	0.1	SE cluster
6/17/12	0:27:06	38.2771	-108.8330	-2.2	3.7	0.0	SE cluster
6/17/12	5:56:20	38.4398	-109.0268	-3.1	4.6	0.6	N. valley
6/17/12	14:27:30	38.2834	-108.9054	-2.0	3.6	-0.3	near-well
6/17/12	23:01:09	38.2834	-108.9055	-2.1	3.6	0.2	near-well
6/22/12	19:02:59	38.4045	-109.0113	-4.0	5.5	-0.5	N. valley
6/25/12	22:38:31	38.3143	-108.9395	-2.5	4.1	-0.1	near-well
6/26/12	2:05:26	38.2861	-108.8983	-2.1	3.6	1.0	near-well
6/26/12	9:52:58	38.2861	-108.8982	-2.0	3.6	0.9	near-well
6/29/12	3:45:46	38.3577	-108.9253	-4.3	5.8	0.6	central valley
7/1/12	14:29:26	38.3231	-108.9710	-2.0	3.5	0.4	NW cluster
7/2/12	0:21:12	38.2861	-108.8987	-2.1	3.6	-0.2	near-well
7/2/12	0:43:50	38.2861	-108.8987	-2.1	3.6	0.2	near-well
7/3/12	14:13:43	38.3231	-108.9854	-2.0	3.5	0.1	NW cluster
7/3/12	14:13:55	38.3232	-108.9852	-2.0	3.5	0.2	NW cluster
7/3/12	15:05:19	38.3230	-108.9854	-2.0	3.5	0.3	NW cluster
7/3/12	16:39:54	38.3230	-108.9857	-2.0	3.5	0.4	NW cluster
7/3/12	17:05:21	38.3230	-108.9854	-2.0	3.5	0.8	NW cluster
7/3/12	17:52:45	38.3230	-108.9859	-2.0	3.5	0.3	NW cluster
7/3/12	19:56:59	38.3229	-108.9857	-2.0	3.5	0.1	NW cluster
7/4/12	19:04:29	38.2773	-108.8318	-2.2	3.8	0.3	SE cluster
7/5/12	6:53:17	38.3233	-108.9848	-2.0	3.5	0.3	NW cluster
7/5/12	7:11:31	38.3235	-108.9843	-1.9	3.5	0.1	NW cluster
7/5/12	7:12:34	38.3236	-108.9845	-2.0	3.5	-0.4	NW cluster
7/5/12	16:11:03	38.2647	-108.9337	-0.6	2.1	0.0	near-well
7/6/12	8:59:43	38.3233	-108.9843	-1.9	3.5	0.4	NW cluster
7/7/12	6:23:10	38.2772	-108.8320	-2.2	3.8	0.7	SE cluster
7/7/12	6:23:45	38.2773	-108.8320	-2.2	3.8	0.0	SE cluster
7/8/12	10:17:10	38.2983	-108.8988	-2.6	4.2	0.4	near-well
7/9/12	10:30:22	38.3063	-108.9147	-2.8	4.4	0.3	near-well
7/10/12	16:42:33	38.2777	-108.8310	-2.2	3.8	0.3	SE cluster
7/15/12	7:01:23	38.3228	-108.9835	-1.9	3.4	0.3	NW cluster
7/15/12	7:05:51	38.3235	-108.9842	-2.0	3.5	0.1	NW cluster
7/16/12	3:13:12	38.3245	-108.9836	-2.1	3.6	1.8	NW cluster

Table A-1: Local earthquakes recorded by PVSN during 2012

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
7/18/12	1:59:31	38.3237	-108.9836	-1.9	3.5	0.7	NW cluster
7/18/12	3:10:05	38.3233	-108.9841	-1.9	3.5	0.3	NW cluster
7/18/12	16:33:30	38.3231	-108.9850	-2.0	3.5	0.2	NW cluster
7/18/12	16:33:50	38.3231	-108.9847	-2.0	3.5	-0.4	NW cluster
7/19/12	13:14:12	38.2866	-108.8769	-1.8	3.3	0.3	near-well
7/22/12	18:50:16	38.2811	-108.8826	-3.3	4.8	0.8	near-well
7/23/12	1:13:28	38.2859	-108.8978	-2.0	3.6	0.0	near-well
7/23/12	2:17:51	38.2860	-108.8976	-2.0	3.6	0.5	near-well
7/23/12	9:57:50	38.2860	-108.8978	-2.0	3.6	0.2	near-well
7/31/12	17:55:54	38.3251	-108.9837	-2.1	3.6	0.4	NW cluster
8/2/12	23:25:33	38.2738	-108.8842	-1.0	2.5	-0.4	near-well
8/15/12	0:14:53	38.2854	-108.8997	-2.2	3.7	0.1	near-well
8/15/12	0:32:50	38.2854	-108.8996	-2.2	3.7	0.3	near-well
8/18/12	3:38:37	38.2846	-108.9016	-2.5	4.0	0.7	near-well
8/26/12	13:36:25	38.3392	-108.8785	-4.3	5.8	-0.3	central valley
8/28/12	16:40:46	38.2850	-108.9043	-2.5	4.0	-0.1	near-well
9/1/12	19:22:04	38.2810	-108.8355	-2.4	3.9	-0.1	SE cluster
9/1/12	23:03:49	38.3150	-108.7476	-6.0	7.5	2.1	other
9/2/12	11:34:00	38.3150	-108.7473	-6.0	7.6	0.7	other
9/3/12	0:31:29	38.3023	-108.9259	-2.4	3.9	-0.1	near-well
9/3/12	15:25:07	38.2742	-108.8757	-0.9	2.4	0.7	near-well
9/3/12	15:38:15	38.2742	-108.8756	-0.9	2.4	0.1	near-well
9/5/12	15:50:07	38.2683	-108.9308	0.0	1.5	0.5	near-well
9/12/12	18:33:07	38.2836	-108.8696	-2.1	3.6	-0.1	near-well
9/16/12	15:10:25	38.3040	-108.9311	-2.6	4.1	0.4	near-well
9/17/12	6:22:49	38.3221	-108.9792	-1.9	3.4	0.3	NW cluster
9/21/12	13:48:25	38.3124	-108.9659	-1.8	3.3	0.3	NW cluster
9/22/12	5:34:04	38.3129	-108.9498	-2.4	4.0	-0.5	NW cluster
9/22/12	5:34:53	38.3129	-108.9497	-2.4	4.0	-0.5	NW cluster
9/22/12	5:35:24	38.3128	-108.9501	-2.4	4.0	0.0	NW cluster
9/22/12	5:36:55	38.3129	-108.9497	-2.4	4.0	-0.1	NW cluster
9/27/12	21:40:52	38.3094	-108.8855	-2.7	4.3	-0.3	near-well
10/1/12	10:38:36	38.3271	-108.9484	-2.4	3.9	-1.5	NW cluster
10/1/12	10:38:38	38.3269	-108.9483	-2.4	4.0	-0.3	NW cluster
10/1/12	10:38:49	38.3270	-108.9484	-2.4	3.9	0.4	NW cluster
10/1/12	10:39:19	38.3268	-108.9481	-2.4	4.0	-0.7	NW cluster
10/4/12	10:02:00	38.2886	-108.9095	-2.7	4.3	0.2	near-well
10/4/12	23:46:01	38.4060	-108.9300	-4.6	6.1	1.0	N. valley
10/8/12	10:00:46	38.3266	-108.9481	-2.4	3.9	0.3	NW cluster
10/8/12	10:00:59	38.3261	-108.9476	-2.4	3.9	0.1	NW cluster
10/8/12	10:01:50	38.3260	-108.9475	-2.4	4.0	-0.6	NW cluster
10/9/12	0:06:53	38.2873	-108.8518	-1.8	3.3	-0.1	near-well

Table A-1: Local earthquakes recorded by PVSN during 2012

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
10/11/12	1:05:36	38.3235	-108.9841	-2.0	3.5	1.0	NW cluster
10/11/12	15:20:01	38.3996	-108.9184	-5.0	6.5	0.7	N. valley
10/15/12	6:24:00	38.3064	-108.9146	-2.8	4.4	0.6	near-well
10/15/12	15:20:48	38.3256	-108.9820	-2.1	3.6	1.1	NW cluster
10/15/12	16:18:37	38.3252	-108.9835	-2.1	3.6	0.5	NW cluster
10/16/12	4:12:50	38.3250	-108.9842	-2.1	3.6	0.8	NW cluster
10/16/12	5:17:26	38.3250	-108.9832	-2.1	3.6	1.9	NW cluster
10/16/12	6:51:58	38.3247	-108.9842	-2.1	3.6	1.1	NW cluster
10/25/12	18:08:03	38.2769	-108.8330	-2.3	3.8	-0.5	SE cluster
10/28/12	18:11:00	38.3501	-108.9152	-4.5	6.0	0.4	central valley
11/6/12	6:49:28	38.3094	-108.8855	-2.7	4.2	0.7	near-well
11/11/12	17:19:05	38.3145	-108.9741	-1.8	3.3	-0.4	NW cluster
11/27/12	17:13:18	38.2741	-108.8766	-0.9	2.4	0.3	near-well
11/27/12	17:14:11	38.2743	-108.8762	-0.9	2.5	-0.3	near-well
12/4/12	0:23:41	38.2980	-108.8971	-2.7	4.2	-0.1	near-well
12/4/12	4:38:02	38.3100	-108.9673	-1.7	3.3	2.0	NW cluster
12/4/12	5:07:28	38.3104	-108.9670	-1.7	3.3	0.0	NW cluster
12/4/12	12:32:06	38.2982	-108.8969	-2.5	4.0	0.1	near-well
12/4/12	13:13:48	38.2983	-108.8967	-2.5	4.0	0.2	near-well
12/5/12	5:36:26	38.2977	-108.9025	-2.6	4.1	2.1	near-well
12/5/12	10:23:18	38.2980	-108.9024	-2.6	4.1	-0.1	near-well
12/12/12	2:41:36	38.2909	-108.9122	-2.5	4.0	0.0	near-well
12/16/12	12:31:37	38.2981	-108.8967	-2.5	4.0	0.6	near-well
12/16/12	18:56:49	38.2981	-108.8968	-2.5	4.1	0.3	near-well
12/19/12	0:07:04	38.3215	-108.9838	-1.8	3.4	0.4	NW cluster
12/31/12	9:34:02	38.2710	-108.9360	-0.2	1.7	-0.2	near-well

[1] Time listed is Coordinated Universal Time, UTC (Mountain Standard Time = UTC – 7 hours)
[2] Elevation is given with respect to mean sea level.
[3] Depth is referenced to the surveyed elevation of the injection wellhead, 1.524 km.
[4] Earthquake location categories:

near-well: located within 5 km of the injection well
NW cluster: located within the zone of induced seismicity that is centered approximately 7.5 km northwest of the injection well
SE cluster: located within the zone of induced seismicity that is centered approximately 6 km southeast of the injection well
northern valley: located in or near areas of recurring seismicity along the northern edge of Paradox Valley
central valley: located beneath the floor of Paradox Valley
other: local earthquake not associated with any of the other location categories.

APPENDIX B

2012 SITE VISIT REPORTS

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: PVSN-2012-1 **Departure Date:** 5/3/2012 **Return Date:** 5/11/2012

Purpose: Install additional lightning protection at vulnerable stations, and other maintenance.

Work Summary: Improved grounding systems were installed at the two sites struck by lightning last year, as well as at a new station where nearby trees showed evidence of lightning strikes. Seismometer vaults at five stations were retrofitted with heavy glass plates for improved electrical and thermal insulation. Ground-rod resistance measurements and diagrams were made at most sites visited, to aid planning for future grounding work. Standard maintenance activities (seismometer and/or battery replacement, etc) were performed at several stations. Seismometers were precision-oriented with a fiber-optic gyroscope system.

Action Items:

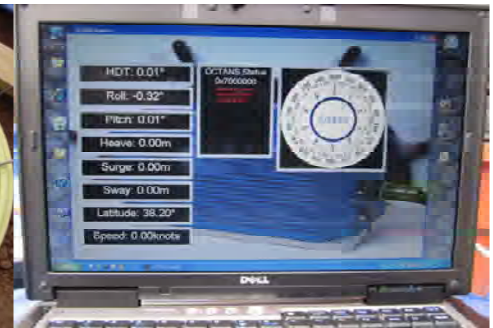
1	Planning and acquisitions for Hopkins Field building and tower replacement, including field trips in July and August.
2	Planning for field trips in September and October to complete cable and radio testing of digital stations installed last year.
3	Install additional surge protection and glass plates.
4	Troubleshoot power dropouts at several sites.
5	Upgrade server disk array at Hopkins Field during next maintenance trip.

Personnel:

	Name	Organization
1	Chris Wood	Reclamation, Seismotectonics & Geophysics, 86-68330
2	Mark Meremonte	US Geological Survey, Golden

Work by Site:

	Site	Work Accomplished
1	PV02	Installed new grounding system, including chem-rod, cabling, and two SBI air-terminals on mast. Measured resistance of individual grounds. Oriented seismometer with Octans gyroscope.
2	PV03	Installed glass plate in seismometer vault, and oriented seismometer with Octans gyroscope. Measured resistance of individual grounds. Replaced batteries. Replaced DM24BOB with upgraded unit.
3	PV10	Installed glass plate in seismometer vault, and oriented seismometer with Octans gyroscope. Installed precision-cut foam insulation to improve temperature stability. Measured resistance of individual grounds. Replaced DM24BOB with upgraded unit.
4	PV11	Installed new grounding system, including SBI air-terminal on mast. Measured resistance of individual grounds, and disconnected bad grounds. Replaced batteries. Installed glass plate in seismometer vault, and oriented seismometer with Octans gyroscope.
5	PV13	Installed glass plate in seismometer vault, and oriented seismometer with Octans gyroscope. Measured resistance of individual grounds. Installed LVD blocks for station batteries.
6	PV17	Installed glass plate in seismometer vault, and oriented seismometer with Octans gyroscope. Measured resistance of individual grounds.
7	PV18	Tested GPS receiver and brought back on line. Measured resistance of individual grounds.
8	PV19	Tested radio signal levels and removed obstructions blocking antenna. Measured resistance of individual grounds.
9	PV20	Measured resistance of individual grounds. Replaced antenna. Replaced antenna cable surge protection device. Tested power disconnection problem. Re-oriented seismometer with Octans gyroscope.
10	PV23	Installed new grounding system, including SBI air-terminal on mast. Measured resistance of individual grounds. Re-oriented seismometer with Octans gyroscope.



Clockwise from upper left: (1) Spline-ball ionizer (SBI) air terminals installed on top of towers for lightning protection. (2) 1/2-inch frosted glass plates were retrofitted into several seismometer vaults (yellow barrel) to provide electrical insulation and a uniform surface for leveling seismometers. (3) Precision True North orientation is done using an Octans fiber-optic gyroscope. (4) Glass plate in seismometer vault provides electrical insulation and a surface for easy leveling. (5) Local fauna. (6) Local flora. (7) Mountain lion tracks at PV02. (8) Horizontal chemical grounding rod installation consisting of a copper tube filled with electrolytes covered with a ground-augmentation fill (GAF) mixture. (9) Cabling for new grounding system.

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: PVSN-2012-2 **Departure Date:** 5/22/2012 **Return Date:** 5/23/2012

Purpose: Meet with Montrose County about proposed reconstruction of Hopkins Field facility.

Work Summary: Tested radio communications at the surface treatment facility (STIF) to determine if base site could be relocated there. Met with Montrose County representative at Hopkins Field.

Action Items:

1	Planning for new building and tower at Hopkins Field
2	Coordinate with acquisitions, property, and legal staff regarding options
3	Coordinate schedules and plans with Montrose County.

Personnel:

	Name	Organization
1	Chris Wood	Reclamation, Seismotectonics & Geophysics, 86-68330

Work by Site:

	Site	Work Accomplished
4	STIF	Measured signal levels from existing hub sites at PV02, PV04, and PV12. Tests indicated very poor potential for relocating Hopkins Field base site to the STIF since signals were received only from PV02, and these were well below normal operation levels. These tests confirmed results from computer terrain models indicating poor reception from hub sites at the STIF.
9	Hopkins Field	Met with Montrose County airport operations manager to discuss plans for replacement of airport building, and tower. Repaired signal splitter for analog stations PV11 and PV16. Tested analog equipment.

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: PVSN-2012-3 **Departure Date:** 10/16/2012 **Return Date:** 10/24/2012

Purpose: Improve station grounding and lightning protection, and general maintenance.

Work Summary: Additional grounding and lightning protection was installed at most stations to improve reliability. Normal preventive and remedial maintenance tasks were done.

Action Items:

1	Planning for new building and tower at Hopkins Field
2	Coordinate with acquisitions, property, and legal staff regarding options
3	Coordinate schedules and plans with Montrose County.

Personnel:

	Name	Organization
1	Chris Wood	Reclamation, Seismotectonics & Geophysics, 86-68330
2	Will Yeck	Reclamation, Seismotectonics & Geophysics, 86-68331
3	Mark Meremonte	USGS, Golden

Work by Site:

	Site	Work Accomplished
1	Hopkins Field	Replaced IP KVM and LCD monitor. Replaced bad disk drives in server.
2	PV01	Measured ground resistance. Installed additional grounding. Tested antennas and radio. Installed glass plate in seismometer vault.
3	PV04	Measured ground resistance. Tested antennas and radio. Checked foundation for seismometer vault.
4	PV05	Measured ground resistance. Installed additional grounding. Tested antennas and radio.
5	PV07	Measured ground resistance. Installed additional grounding. Tested antennas and radio. Installed LVD blocks for solar panel and batteries. Installed glass plate in seismometer vault.
6	PV11	Tested antennas and radio. Removed LVD blocks for batteries.
7	PV12	Measured ground resistance. Installed additional grounding. Tested antennas and radio. Installed glass plate in seismometer vault.
8	PV13	Measured ground resistance. Installed additional grounding. Tested antennas and radio. Installed LVD blocks for solar panel and batteries. Installed glass plate in seismometer vault.
9	PV15	Measured ground resistance. Installed additional grounding. Tested antennas and radio.
10	PV18	Replaced GPS antenna.
11	PV19	Tested antennas and radio. Removed LVD blocks for batteries.
12	PV20	Tested antennas and radio. Removed LVD blocks for batteries.
13	PV21	Measured ground resistance. Installed additional grounding. Tested antennas and radio.
14	PV22	Measured ground resistance. Installed additional grounding. Tested antennas and radio.
15	PV23	Tested antennas and radio.

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: PVSN-2012-4 **Departure Date:** 11/8/2012 **Return Date:** 11/9/2012

Purpose: Replace failed IP switch

Work Summary: An IP switch was replaced that had failed during a recent power outage.

Action Items:

1	Planning for new building and tower at Hopkins Field
2	Coordinate with acquisitions, property, and legal staff regarding options
3	Coordinate schedules and plans with Montrose County.

Personnel:

	Name	Organization
1	Will Yeck	Reclamation, Seismotectonics & Geophysics, 86-68330

Work by Site:

	Site	Work Accomplished
1	Hopkins Field	Replaced IP switch