

# RECLAMATION

*Managing Water in the West*

Technical Memorandum No. 86-68330-2012-16

## **2011 Annual Report Paradox Valley Seismic Network Paradox Valley Project, Colorado**



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

May 2012

## **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.

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*Prepared by*

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Bureau of Reclamation  
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Denver, Colorado**

**May 2012**

**Bureau of Reclamation  
Technical Service Center  
Seismotectonics and Geophysics Group**

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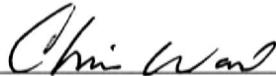
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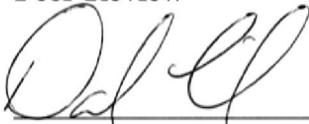


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## **1.0 INTRODUCTION**

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 2011. 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 project operations during 2011 are presented, including discussion of maintenance and upgrades of seismic stations and data acquisition systems, network performance, and data management activities. The earthquake data recorded during 2011 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**).

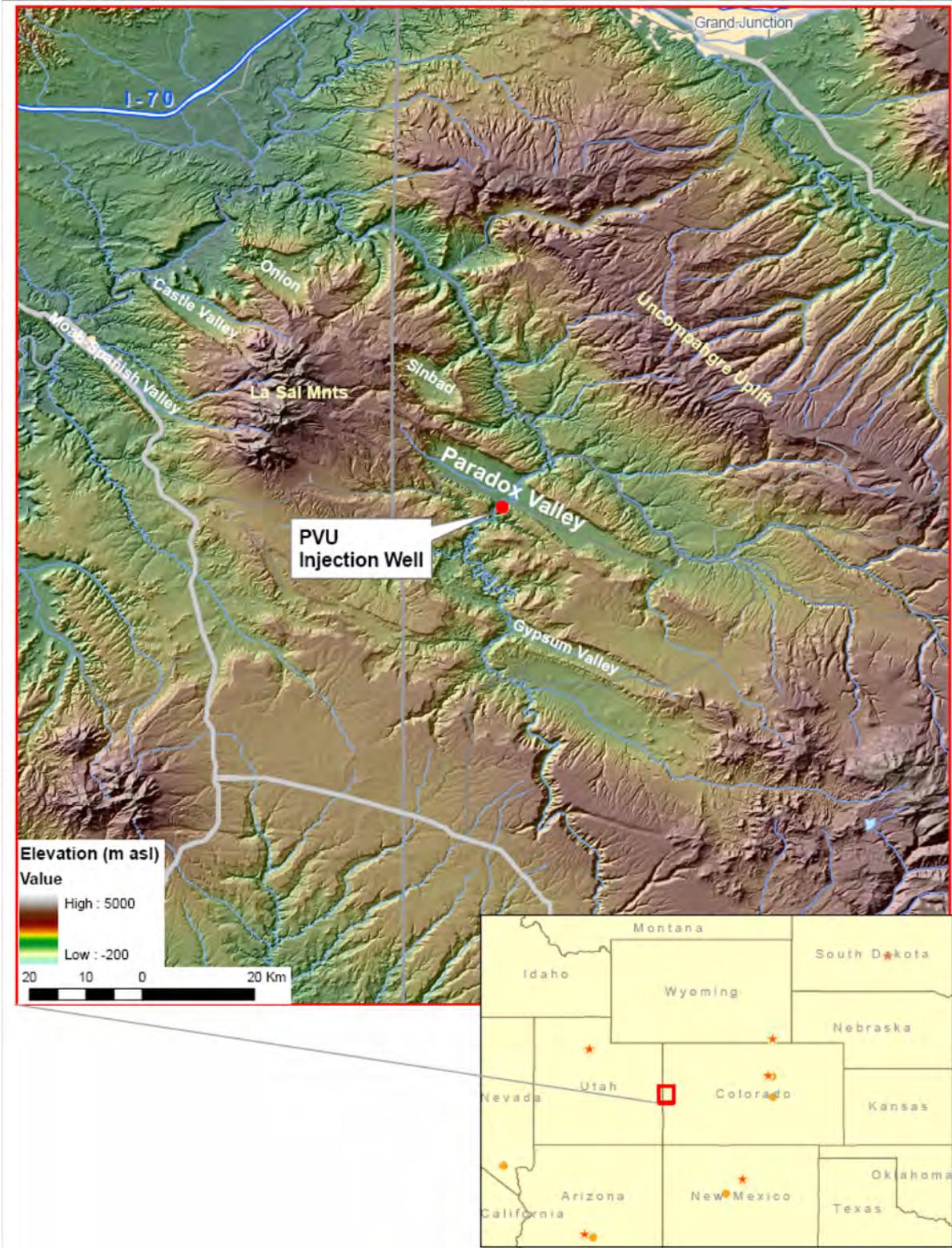
PVU Salinity Control Well No. 1 was completed in 1987 at a total depth of 4.88 km (approximately 16,000 ft). The well was built to Environmental Protection Agency (EPA) Underground Injection Code (UIC) Class I standards ("Isolate hazardous, industrial and municipal wastes through deep injection"), but 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.*

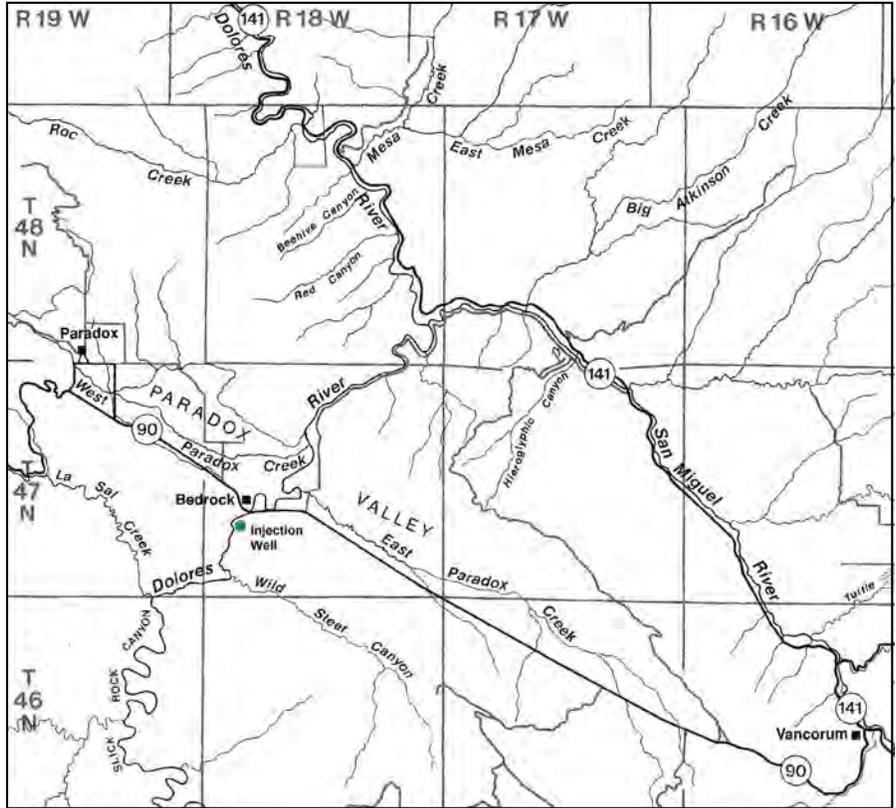


Figure 2-2 Location of the Paradox Valley Unit injection well (green dot) and local geography. Figure is adapted from Parker (1992). Each square is approximately 10 km by 10 km.

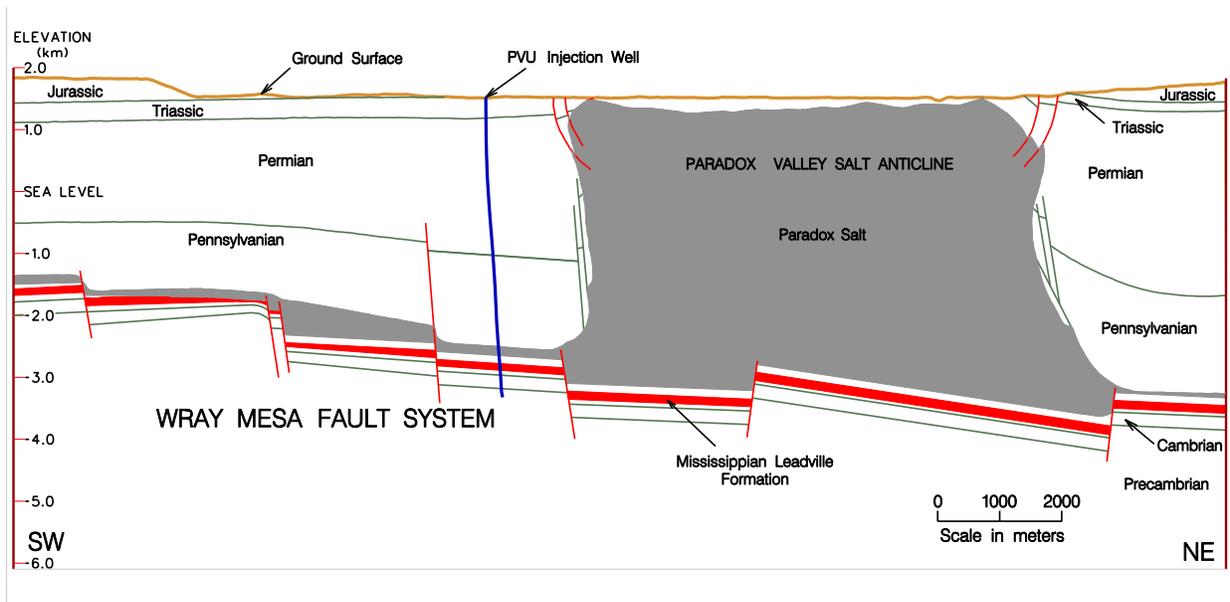


Figure 2-3 Vertical cross section roughly perpendicular to Paradox Valley, looking to the northwest. Based on figure from Harr and Bramkamp (1988).

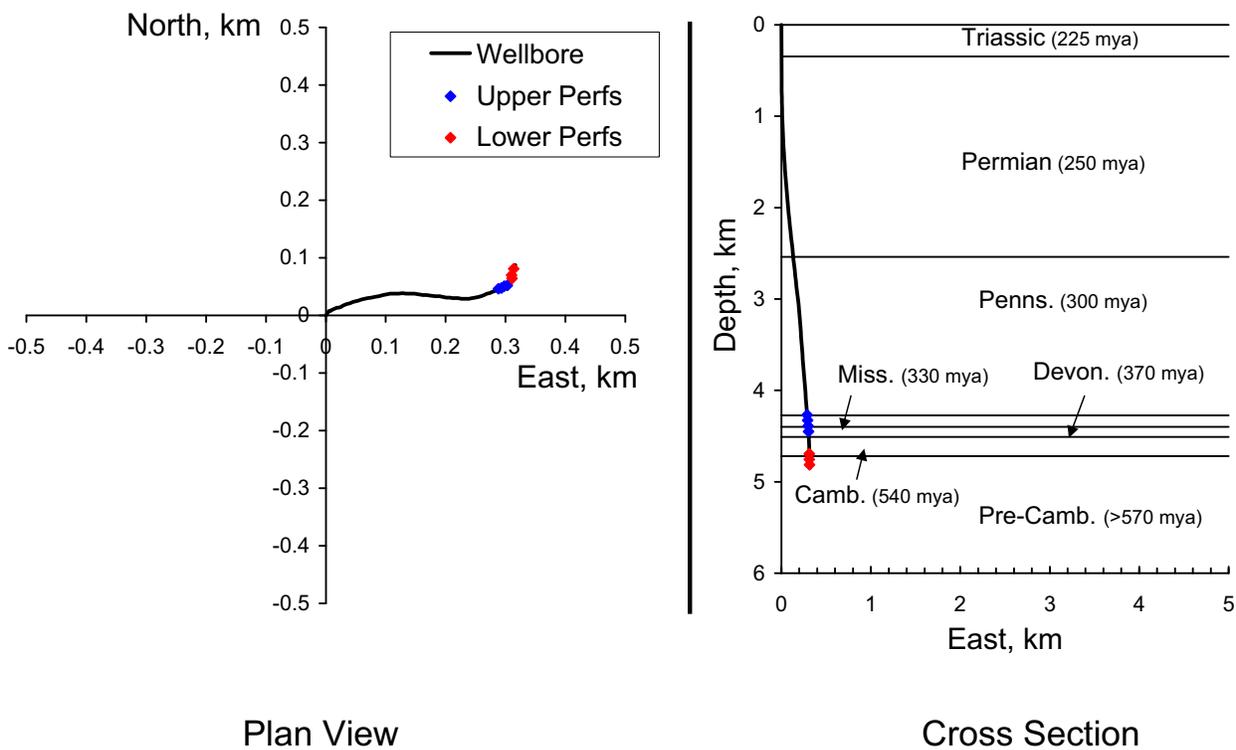


Figure 2-4 PVU injection well in plan view (left) and north-viewing vertical cross section (right). Figures include the near-wellbore stratigraphy and locations of the upper and lower casing perforations.

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 ~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 hoped that the biannual shutdowns would 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

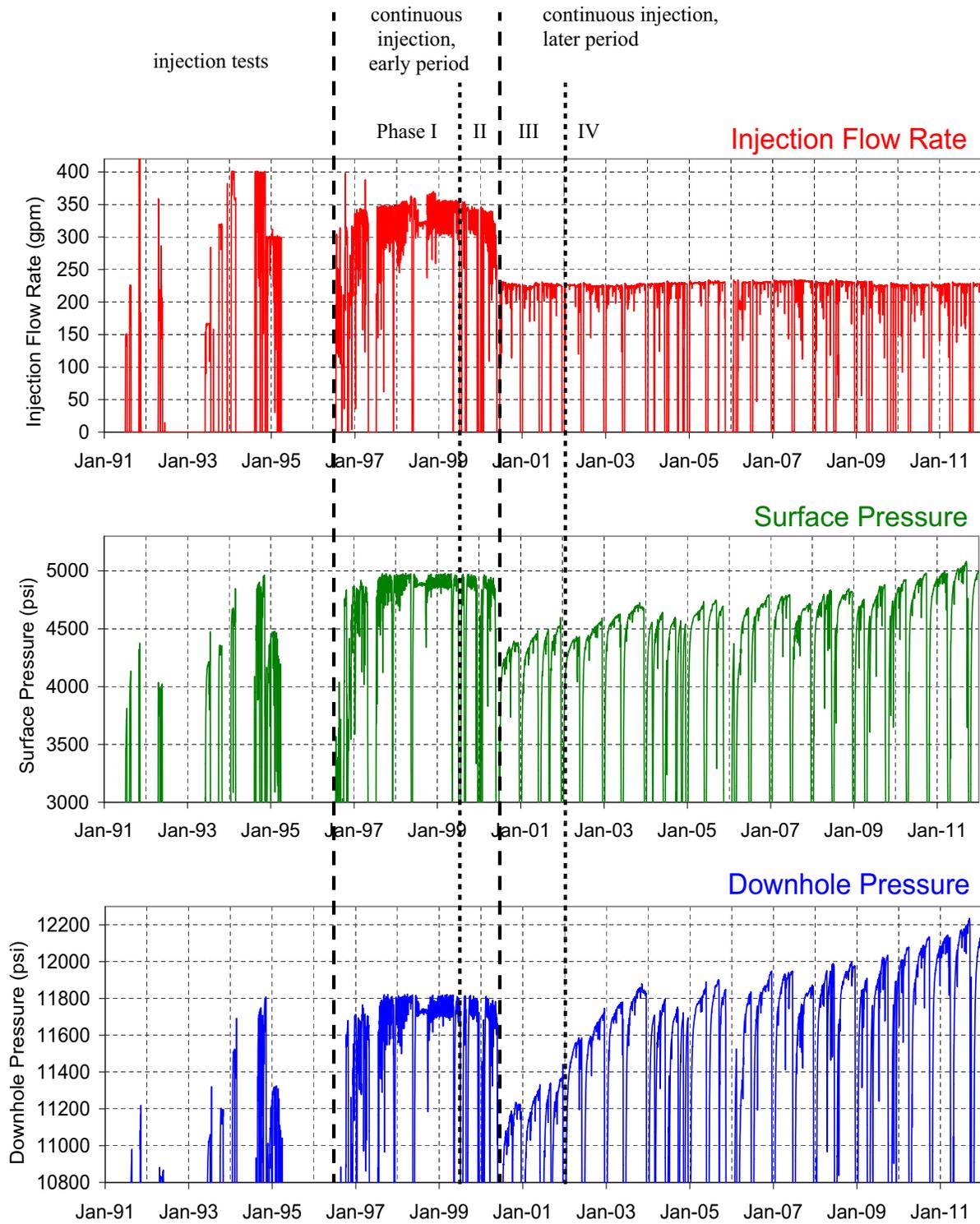


Figure 2-5 Daily average injection flow rate (top), daily average surface injection pressure (middle), and daily average downhole pressure at 4.3 km depth (bottom) during PVU injection operations.

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 three. This change decreased the injection flow rate by 33% compared to earlier phases, to 230 gpm (~871 l/min). The 70:30 ratio of brine to fresh water and the biannual 20-day shutdowns were maintained.

### **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 8.33 lbs/gal, results in a daily injection of ~1380 tons. The maximum expected precipitate is ~0.6% 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 affect 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 affect 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).

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.

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.

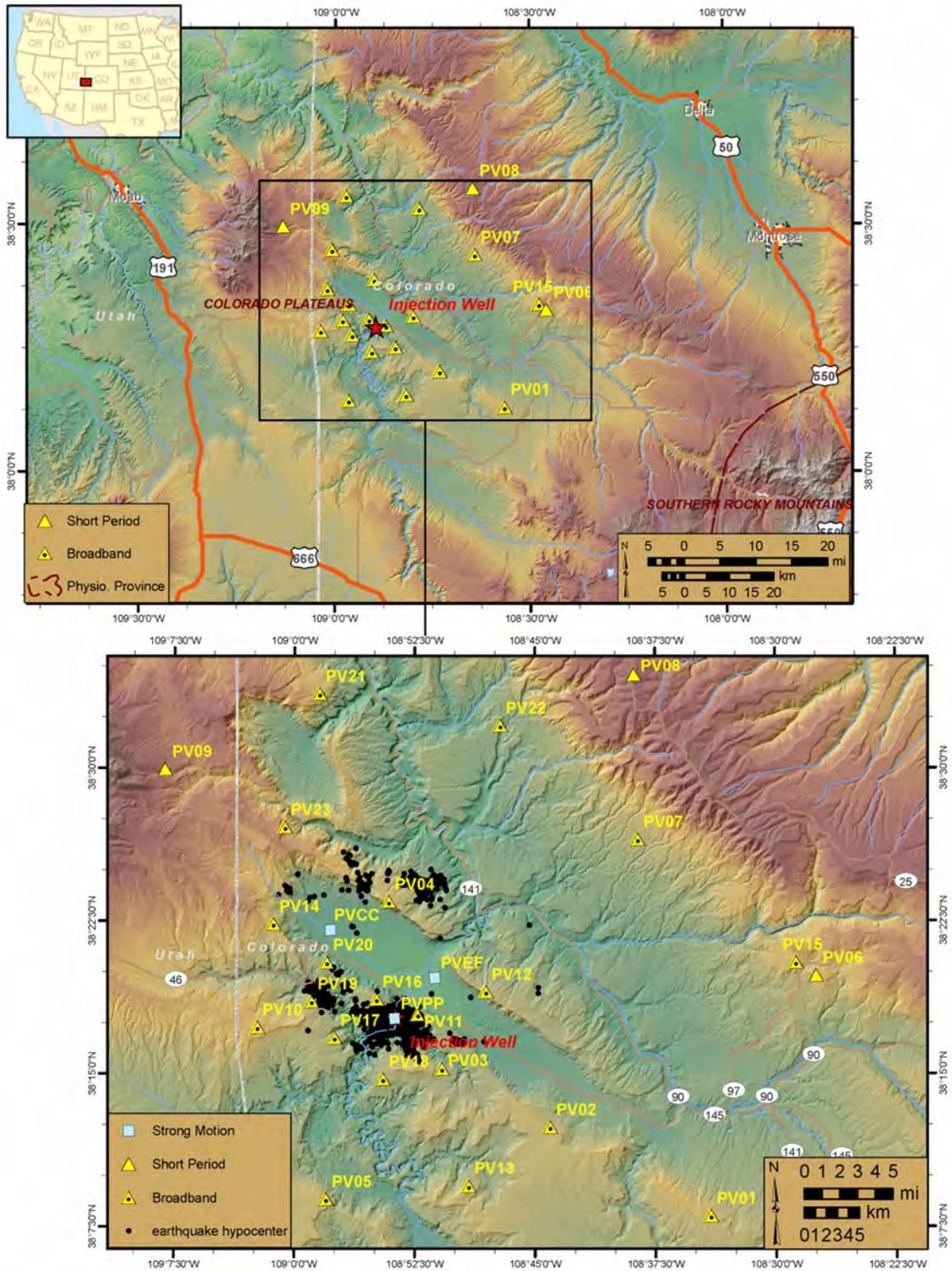


Figure 2-6 Locations of the Paradox Valley Seismic Network stations, Paradox Valley Unit injection well, and hypocenters of earthquakes less than 8 km deep. PVCC, PVEF & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Physiographic provinces from Fenneman and Johnson (1946).

**Table 2-1 PVSN Station Locations and Characteristics**

<b>Station Name</b>	<b>Latitude deg., N</b>	<b>Longitude deg., W</b>	<b>Elev. m</b>	<b>Dates of Operation</b>	<b>Station Type</b>	<b>Sensor Direction</b>
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-present 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-present 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-present	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-present 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**

<b>Station Name</b>	<b>Latitude deg., N</b>	<b>Longitude deg., W</b>	<b>Elev. m</b>	<b>Dates of Operation</b>	<b>Station Type</b>	<b>Sensor Direction</b>
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
<p><i>Notes: Table lists network configuration as of 12/31/2011. 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).</i></p>						

**Table 2-2 PVSN Telemetered Sites - Station Location Names**

<b>Station</b>	<b>Station Location Name</b>
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 Monitoring Operations**

Current PVSN monitoring operations include: (1) acquiring continuous ground motion data originating in and around Paradox Valley and the surrounding region; (2) sending this data in real time to processing facilities located at Reclamation's Technical Service Center in Lakewood, CO; (3) identifying local seismic events within these data; (4) determining the location, origin time, and magnitude of each seismic event; (5) determining the individual and cumulative characteristics of the events; (6) identifying and evaluating relationships between seismicity,

geology, subsurface brine and connate water/pressure movements and locations, and injection parameters; (7) maintaining a database of both events and injection parameters; and (8) documenting findings.

Natural seismicity rates in the Paradox Valley area are low. The pre-injection local earthquake catalog contains only a single earthquake, located 18 km north of the injection well. Upon initiation of injection, numerous induced earthquakes were detected in the immediate vicinity of the injection well. By the end of 1998, the region of induced seismicity had expanded to a maximum distance of 8.5 km from the well. The induced seismicity at that time occurred in two distinct zones: a primary zone immediately surrounding the well and extending to a radial distance of about 3.5 km, and a secondary zone centered approximated 7.5 km northwest of the well. In January, 1999, the frequency of recorded induced seismicity reached its peak value of over 150 events per month.

While the vast majority of seismicity induced by injection operations has been below the threshold of human detection, 74 events large enough to potentially be felt ( $M \geq 2.5$ ) occurred between 1991 and 2011. As discussed in section 2.2, injection operations have been adjusted twice in an attempt to minimize the potential for generating felt earthquakes. In response to two  $M$  3.5 events that occurred in mid-1999, the operation of the injection well was altered to require a minimum of two shut down periods per year, of at least 20 days each. In response to a  $M$  4.3 earthquake that occurred on May 27, 2000, operations were modified to reduce the nominal injection flow rate from 345 gpm to 230 gpm. Partially as a result of these changes in injection operations, the frequency of seismic activity generally declined from its peak value in January 1999 until late 2000.

Since late 2000, the frequency of seismic activity has fluctuated slightly in response to injection operations, but has remained low compared to pre-2000 levels. Although the rate of induced seismic activity continues to be low, induced seismic events have been detected in several new locations since 2009. Earthquakes believed to be induced by fluid injection are now being detected at distances up to 9 km from the injection well in several directions. In addition to these clearly-induced earthquakes, more than 700 shallow ( $< 8.5$  km depth) local earthquakes have been detected in the Paradox Valley area at distances greater than 9 km from the well since 2000, mostly near the northern end of the valley (**Figure 2-6**). The shallow depths of these events and the onset of seismic activity after a few years of deep-well injection suggests that they may be related to injection operations.

Nearly 5000 seismic events located within 9 km of the injection well have been recorded by PVSN since injection operations began in 1991 (through 2011). Computed event focal depths indicate that the vast majority of the induced earthquakes follow the targeted injection horizons, suggesting that the injected brine is remaining below the confining layers as anticipated.

## 3.0 PVSN OPERATIONS IN 2011

### 3.1 Network Maintenance and Upgrades

During 2011, digital broadband seismic stations were installed at one existing site, PV15, and at six new sites: PV18, PV19, PV20, PV21, PV22, and PV23. The locations of these seismic stations are shown in **Figure 3-1**. For all stations except PV23, site preparations (seismometer vaults, tower bases, buried conduit, ground rods) were completed in April, and all remaining equipment (solar panels, enclosures, antennas, cabling, seismometers, radios) was installed and the stations brought online in July. Site preparations and installation of all equipment were performed at station PV23 in October, after the required permit was issued by the U.S. Forest Service. The station was brought online in November.

Maintenance, repairs, and minor upgrades were performed at existing seismic stations during several site visits in 2011. Digital stations PV02 and PV11 were damaged by lightning strikes in August and September, 2011, respectively. The damage at station PV02 was substantial and required repairs to the seismometer vault and replacement of nearly all electronic components and cabling. The lightning damage at station PV11 was less severe but required replacement of the radio and seismometer. Additional grounding was installed at both stations to help protect against future lightning strikes. Other tasks performed during site visits include replacing the solar panel surge protector at PV03 and replacing or reprogramming digital radios at a few stations. Further details of the work performed at the seismic stations during 2011 are included in the attached site visit reports (Appendix B).

### 3.2 Network Performance

PVSN performed well during 2011. 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).

The individual digital seismic stations performed very well during most of 2011, while the performance of the analog stations declined due to aging equipment and a decision to devote resources to the maintenance and installation of the digital stations. **Figure 3-2** indicates the performance of the digital seismic stations during 2011, while **Figure 3-3** shows the analog station performance. Each horizontal line across the plots represents one seismic data channel, as indicated in the figures. Thick blue lines indicate that the data channel was installed and 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. The plots in **Figure 3-2** and **Figure 3-3** only indicate whether the individual seismic data channels were functioning properly and not whether they were being recorded by the acquisition system. Further details of individual station performance are given in **Table 3-1** for the digital stations and in **Table 3-2** for the analog stations. None of the station performance issues significantly degraded the performance of the seismic network.

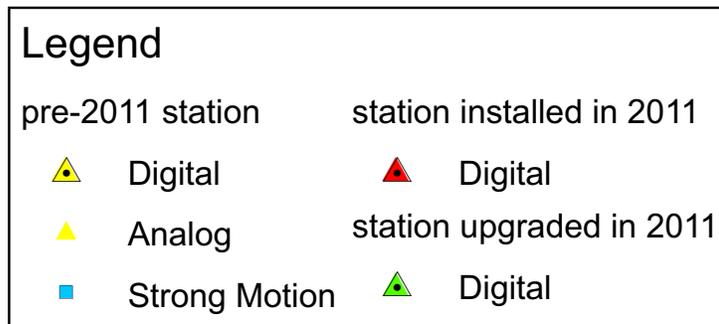
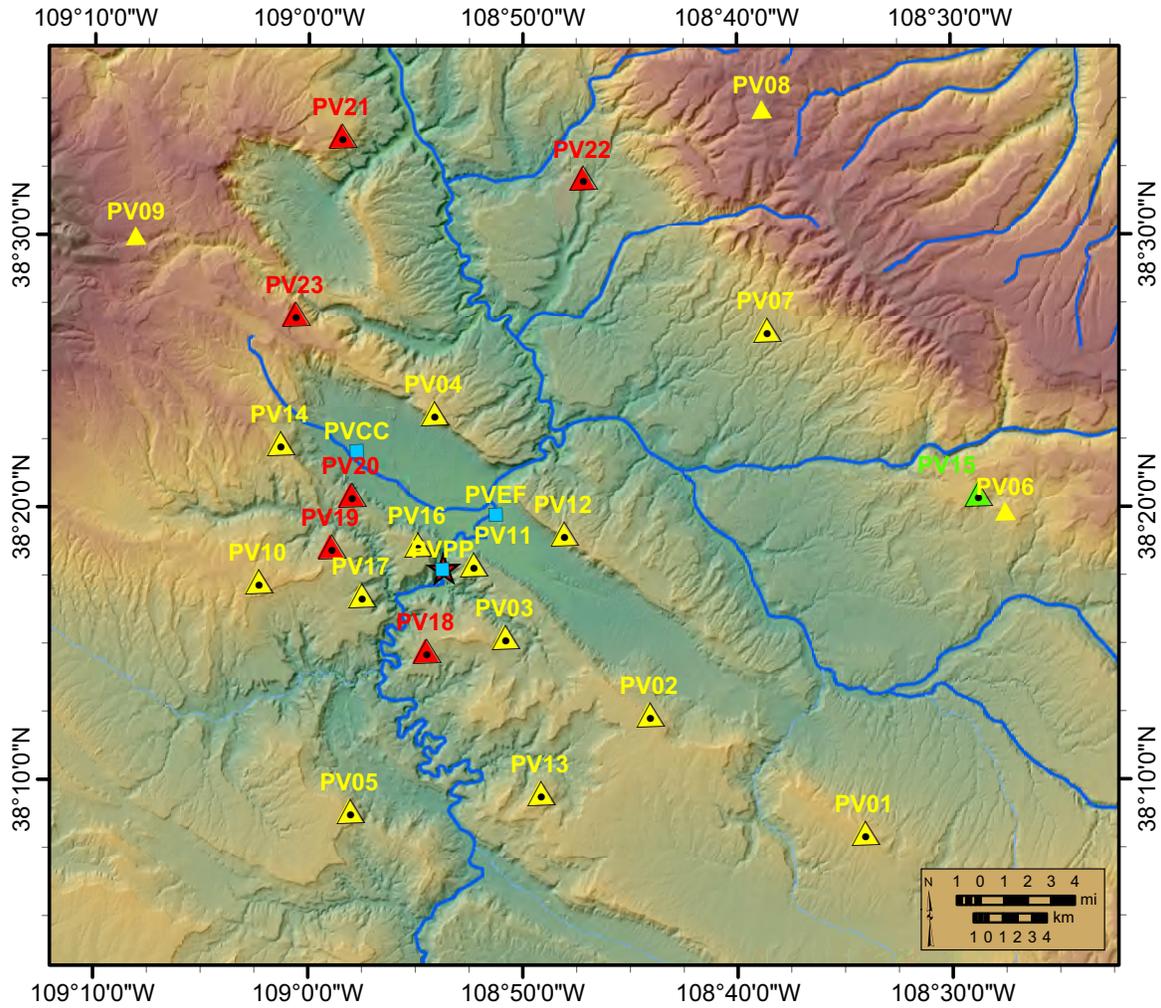
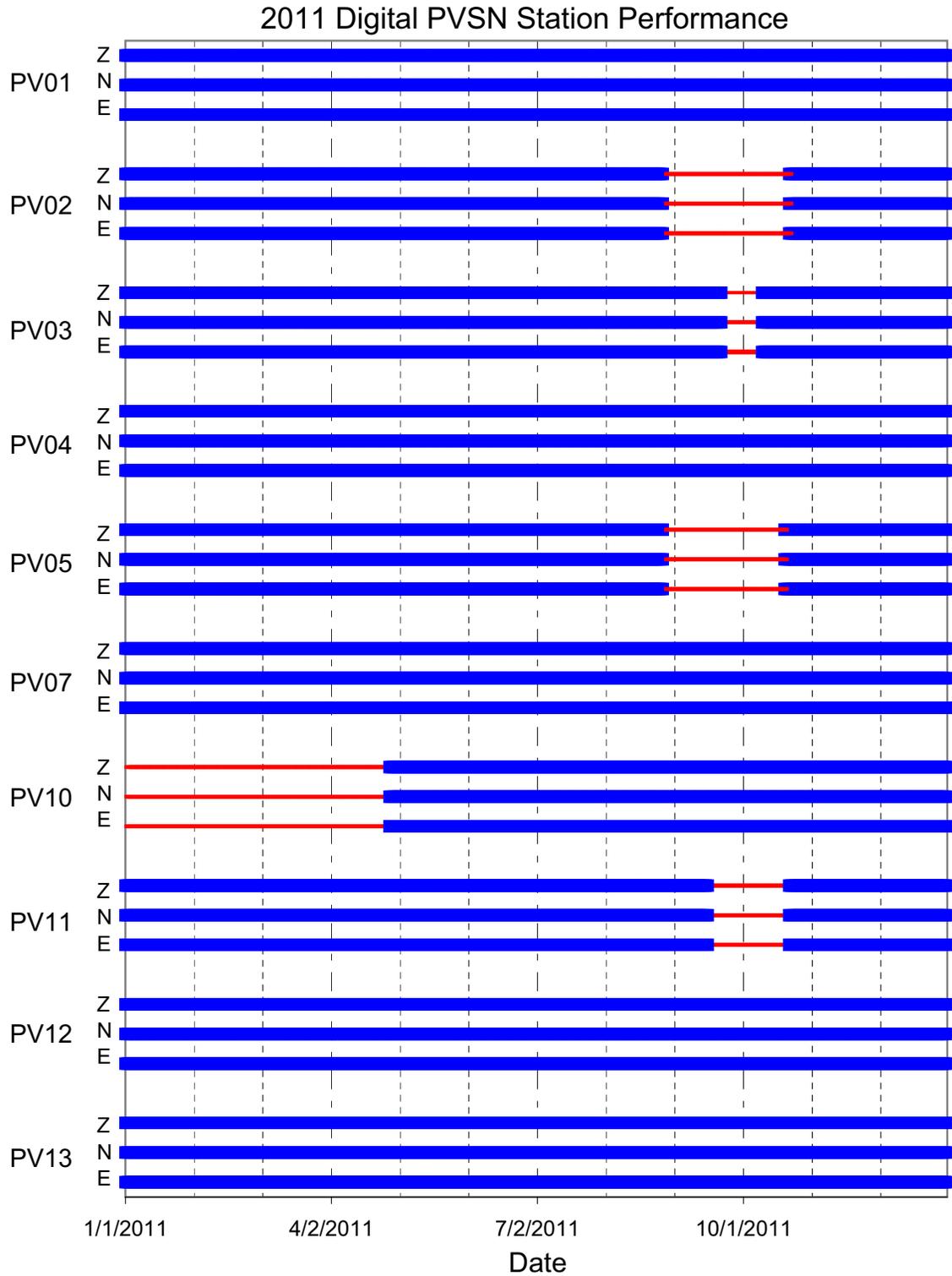


Figure 3-1 Locations of the digital broadband seismic stations installed in 2011 at new sites (red triangles) and at an existing site (green triangle), and locations of seismic stations installed prior to 2011.



*Figure 3-2 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 installed and functioning well. Thin red lines indicate that the channel was offline.*

### 2011 PVSN Digital Station Performance

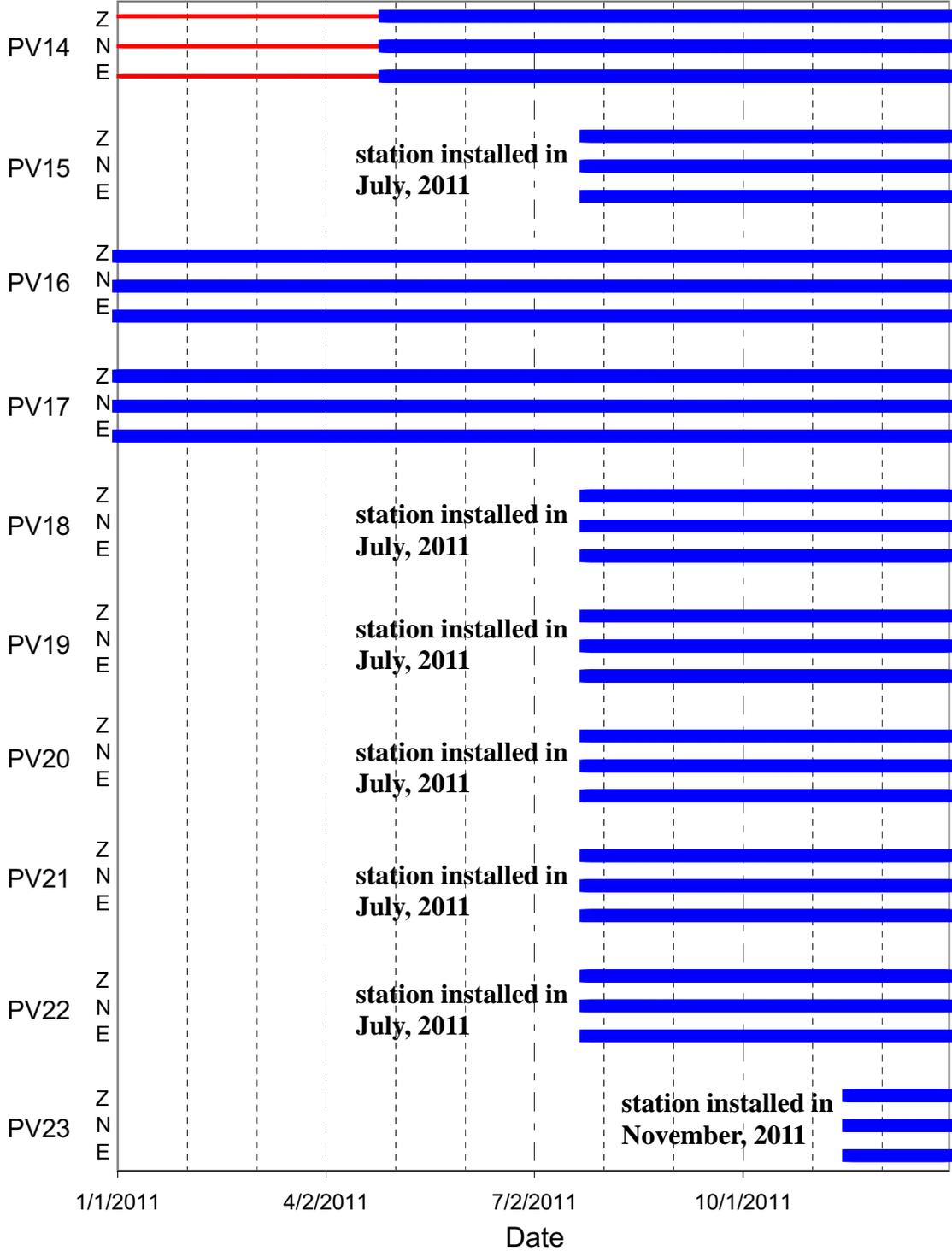
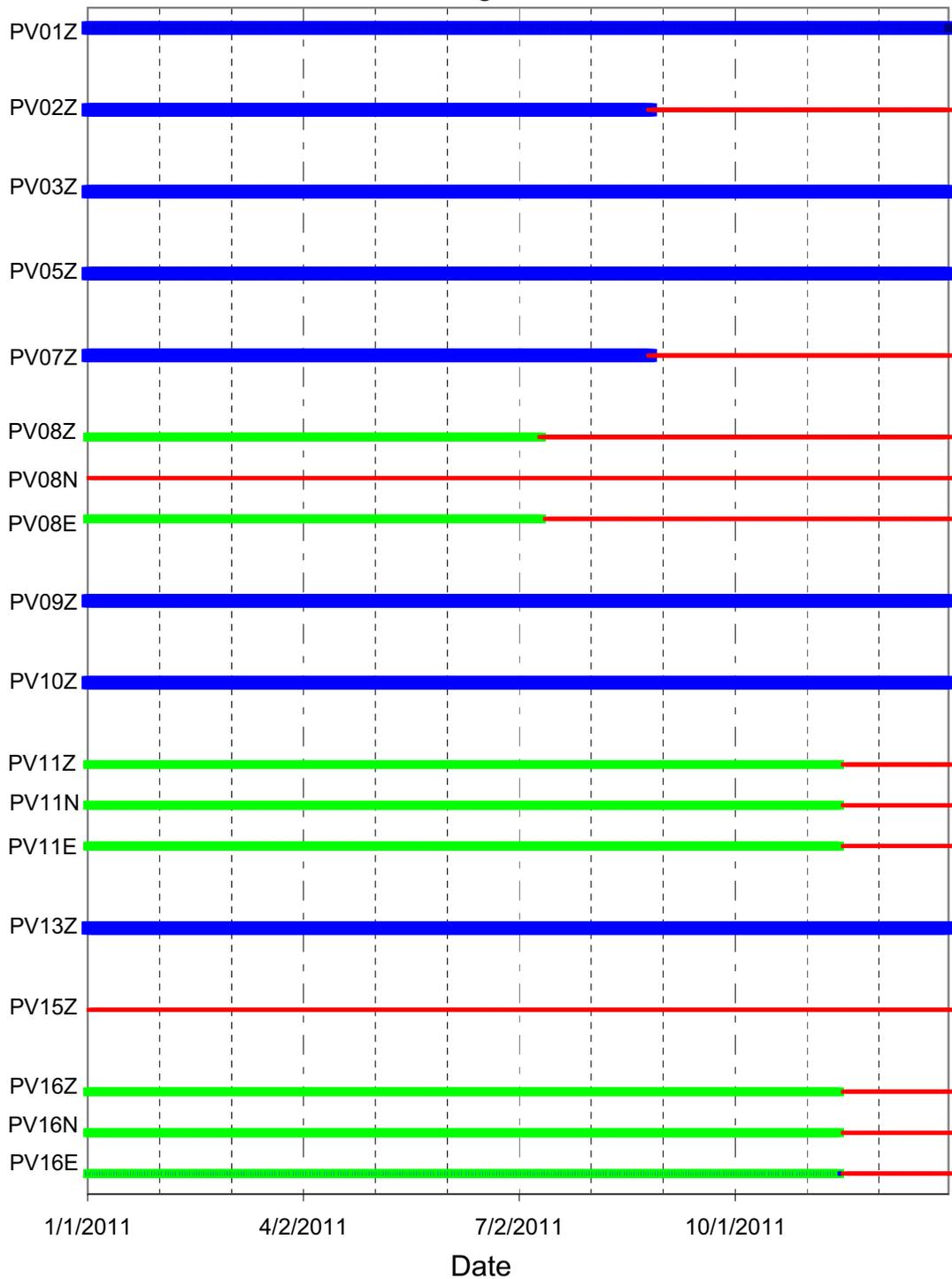


Figure 3-2, continued.

### 2011 PVSN Analog Station Performance



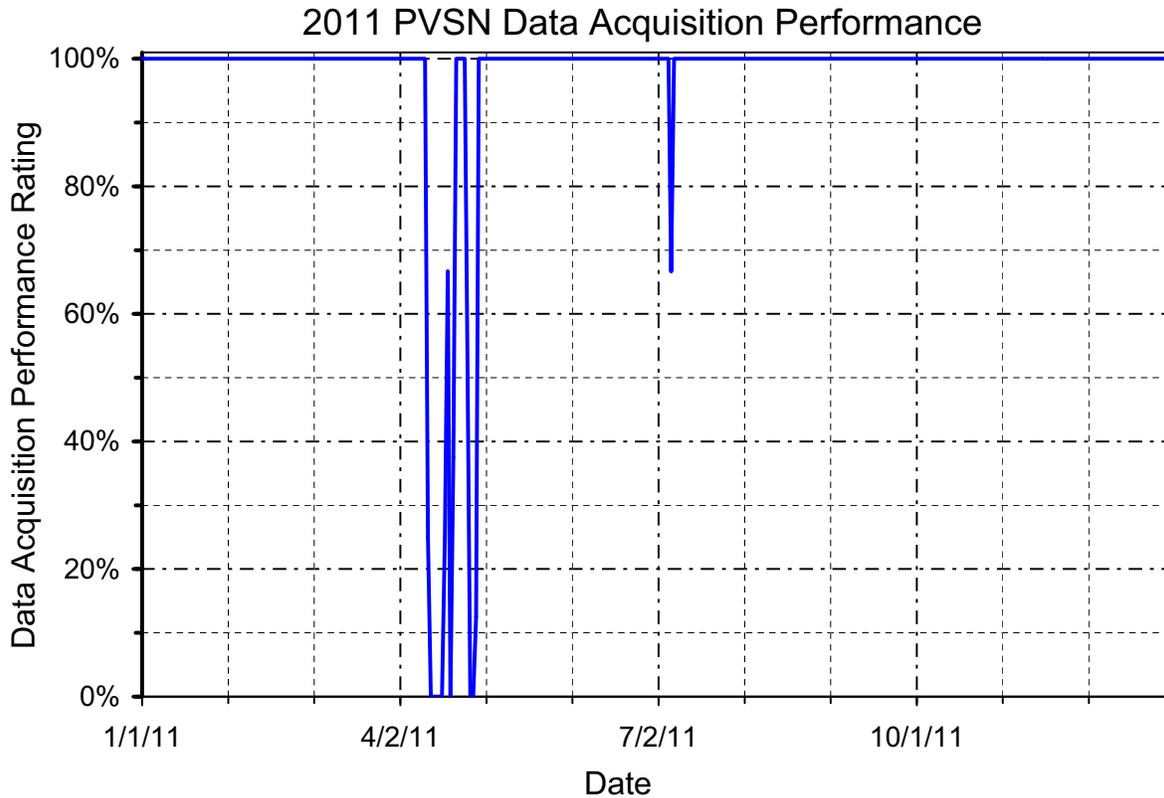
*Figure 3-3 Annual performance of PVSN analog seismic data channels. Trace components are labeled as: Z = vertical component, N = north-south horizontal component, E = east-west horizontal component. Thick blue lines indicate that the channel was installed and functioning well. Thin red lines indicate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

**Table 3-1 Performance of digital seismic stations during 2011**

Station	Performance
PV01	Online and functioning normally throughout the year
PV02	Sustained severe damage from lightning strike on August 28; offline until Oct. 22
PV03	Offline from Sept. 23 to Oct. 9, due to a failed solar panel surge protector
PV04	Online and functioning normally throughout the year
PV05	Offline from Aug. 28 to Oct. 19, due to loss of radio relay station PV02
PV07	Online and functioning normally throughout the year
PV10	Offline from Dec. 24, 2010 to April 27, 2011, due to a tripped fusible link in the seismometer power supply
PV11	Sustained moderate damage from lightning on Sept. 16; offline until October 22
PV12	Online and functioning normally throughout the year
PV13	Online and functioning normally throughout the year
PV14	Offline from Dec. 24, 2010 to April 27, 2011, due to a tripped fusible link in the seismometer power supply
PV15	New station brought online on July 25; functioned normally throughout rest of year
PV16	Online and functioning normally throughout the year
PV17	Online and functioning normally throughout the year
PV18	New station brought online on July 25; functioned normally throughout rest of year
PV19	New station brought online on July 25; functioned normally throughout rest of year
PV20	New station brought online on July 25; functioned normally throughout rest of year
PV21	New station brought online on July 25; functioned normally throughout rest of year
PV22	New station brought online on July 25; functioned normally throughout rest of year
PV23	New station brought online on November 17; functioned normally throughout rest of year

**Table 3-2 Performance of analog seismic stations during 2011**

Station	Performance
PV01	Online and functioning normally through the year
PV02	Offline since August 28, due to damage from lightning strike
PV03	Online and functioning normally through the year
PV05	Online and functioning normally through the year
PV07	Offline since August 28, due to loss of radio relay station PV02
PV08	North component was dead throughout the year; data from vertical and east components were recorded intermittently until July 12, then these channels also went offline
PV09	Online and functioning normally through the year
PV10	Online and functioning normally through the year
PV11	Data recorded intermittently through November 15, then station went offline due to equipment failure at Hopkins Field
PV13	Online and functioning normally through the year
PV15	Station offline throughout the year, due to problems with data relay at station PV02
PV16	Data recorded intermittently through November 15, then station went offline due to equipment failure at Hopkins Field



*Figure 3-4 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.*

The performance of PVSN data acquisition during 2011 is represented by the graph shown in **Figure 3-4**. 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 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 2011 is 96.7% and is compared to that for previous years in **Table 3-3**.

Several significant interruptions in data acquisition occurred during April, 2011, and one shorter interruption occurred in July. 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. A series of unplanned power outages occurred during April. In

addition, repeated power cycling caused computer disk and wide-area network (WAN) failures. These issues resulted in approximately 12 days of total network downtime during April (outage times, in Coordinated Universal Time (UTC), are: 4/12 06:00 – 4/18 18:00; 4/19 16:00 – 4/21 15:00; and, 4/26 12:00 – 4/29 21:00). Another power failure at Hopkins Field caused 8 hours of downtime on July 7. 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. A long-term solution likely will require use of a generator-based backup, and possibly an instrumentation building with a dedicated power supply.

**Table 3-3 Annual PVSN Uptime**

<b>Year</b>	<b>Annual Number of Down Days</b>	<b>Percent Uptime</b>
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%
**not tabulated in 2001		

## 4.0 SEISMIC DATA RECORDED IN 2011

### 4.1 Annual Summary

234 earthquakes were recorded within or near the perimeter of the Paradox Valley Seismic Network during 2011. 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 2011, 74 earthquakes were detected in the near-well region of induced seismicity (within 5 km of the injection well, magenta circles in **Figure 4-1**), 24 earthquakes were detected in the northwest (NW) cluster (6 to 9 km northwest of well, blue circles), 17 earthquakes were detected in the southeast (SE) cluster (6 to 7 km southeast of well, green circles), and 113 earthquakes were detected in areas of recurring seismicity located around the northern edge of Paradox Valley (yellow circles). In addition, 6 earthquakes occurred in locations not associated with any of the historically active areas defined above. Two of these isolated earthquakes locate deep (10 to 15 km depth, purple circles in **Figure 4-1**), and four of them locate at shallow depths (2 to 7 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 PVSAN during 2011 are plotted as a function of date, earthquake magnitude, and location category in **Figure 4-2**. This graph shows that the seismic activity in all regions was sporadic during 2011. Seismicity rates were low in all areas during most of the first three months of the year. The seismicity rates in the northern valley and SE cluster were highest from late March to mid-July. The seismicity rate in the near-well region was highest in August, September, and December, while that in the NW cluster was highest in late March and October.

### 4.2 Shallow Earthquakes Locating within 10 km of the Injection Well

#### 4.2.1 2011 Seismicity

The vast majority of the earthquakes induced within 10 km of the injection well during 2011 locate in areas of previous seismic activity. The hypocenters of the earthquakes that occurred in 2011 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 2011 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.

Two earthquakes that were likely induced occurred within Paradox Valley in 2011, in areas with no previously-recorded seismic activity. The locations of these anomalous earthquakes are labeled on the map in **Figure 4-3**. One earthquake locates almost 8 km southeast of the injection

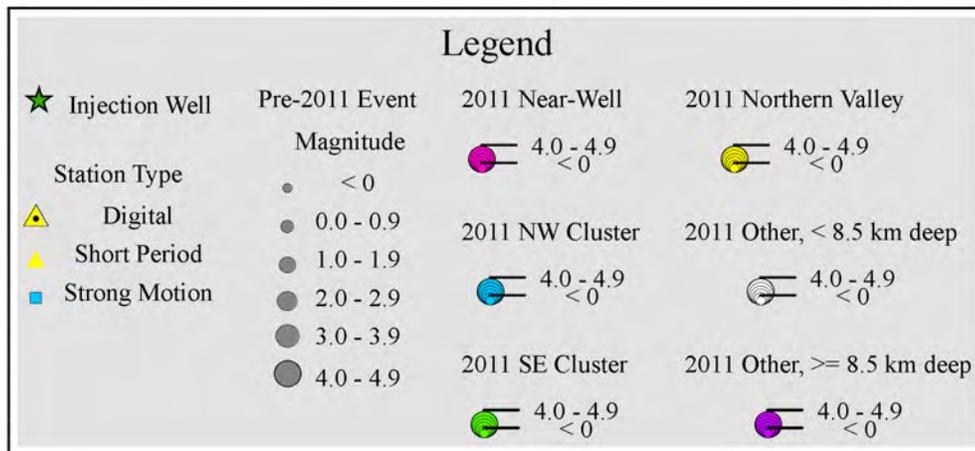
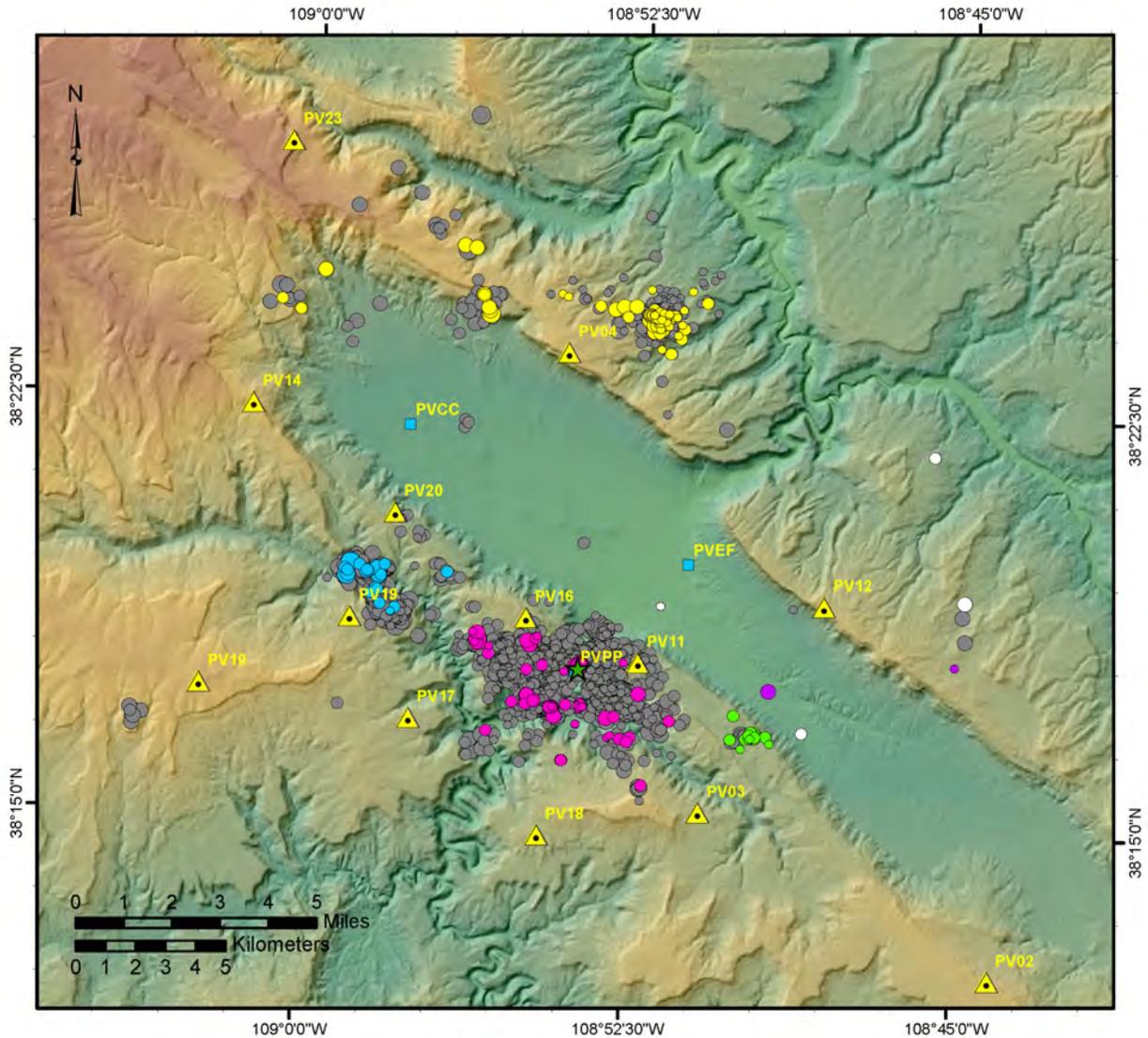


Figure 4-1 Locations of local earthquakes recorded by PVSN during 2011 (colored circles) and previous years (gray circles).

**Table 4-1 Summary of events recorded during 2011 by location category**

Location Category	Number of Earthquakes	Magnitude Range	Median Magnitude
near-well	74	-0.9 - 2.4	0.30
NW cluster	24	-0.6 - 2.7	0.55
SE cluster	17	-0.4 - 1.5	0.10
northern valley	113	-0.8 - 2.0	0.60
other	6	-0.1 - 1.4	0.40
<b>TOTAL</b>	<b>234</b>	<b>-0.9 - 2.7</b>	<b>0.40</b>

**Table 4-2 Average daily seismicity rates of local earthquakes recorded by PVSN during 2011. These rates were computed using the number of days the network was operational, 352.8, as discussed in section 3.**

Earthquake Group	All Magnitudes		Magnitude $\geq$ M 0.5	
	Number of Events Recorded	Average Daily Rate	Number of Events Recorded	Average Daily Rate
near-well	74	0.2098	27	0.0765
NW-cluster	24	0.0680	14	0.0397
SE cluster	17	0.0482	6	0.0170
northern valley events	113	0.3203	61	0.1729
other	6	0.0170	3	0.0085
<b>TOTAL</b>	<b>234</b>	<b>0.6633</b>	<b>111</b>	<b>0.3146</b>

### 2011 Recorded Seismicity as a Function of Date and Earthquake Magnitude

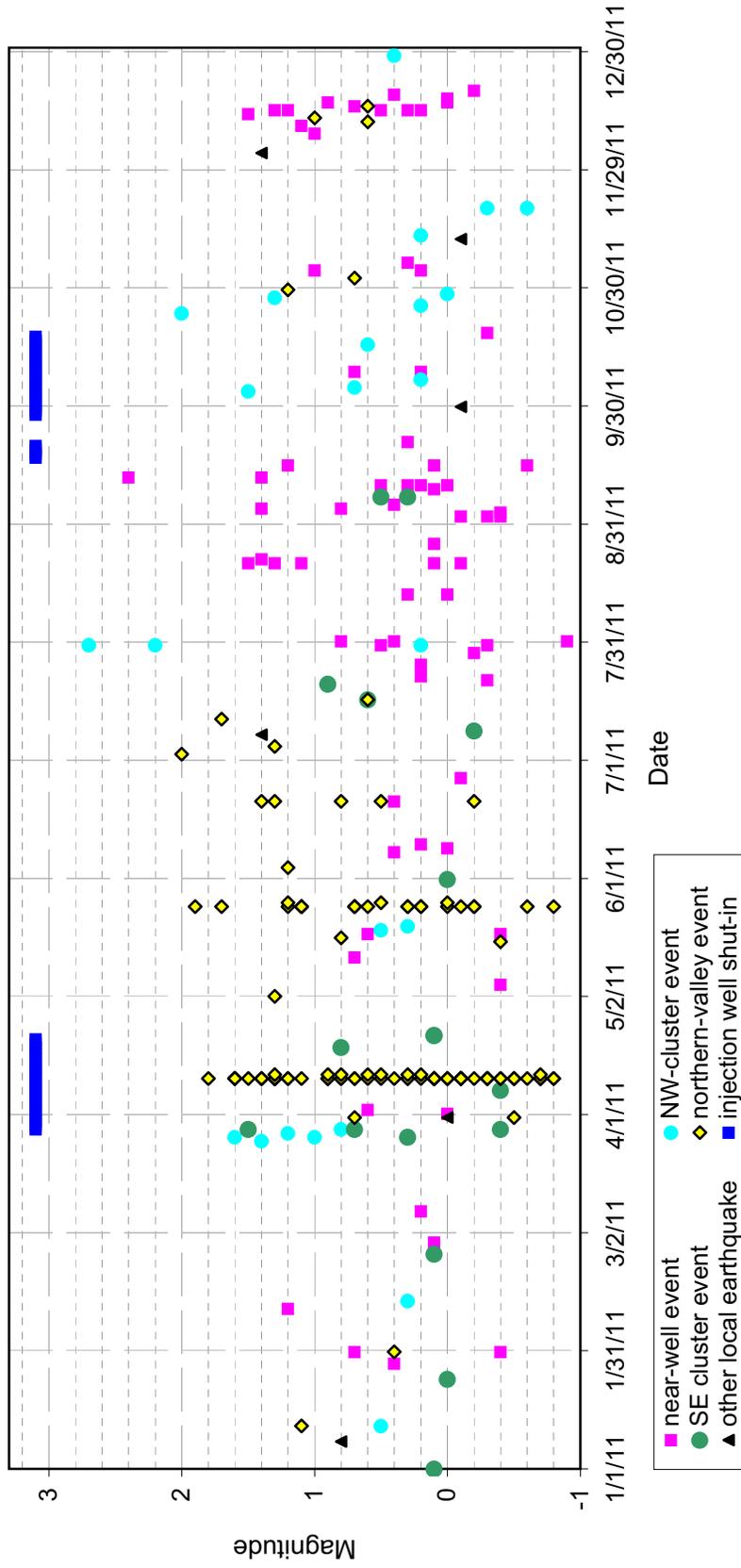


Figure 4-2 Earthquakes recorded by PVSN during 2011, plotted as a function of date, magnitude, and event location category. The dates of injection well shut-ins are included as indicated by the legend.

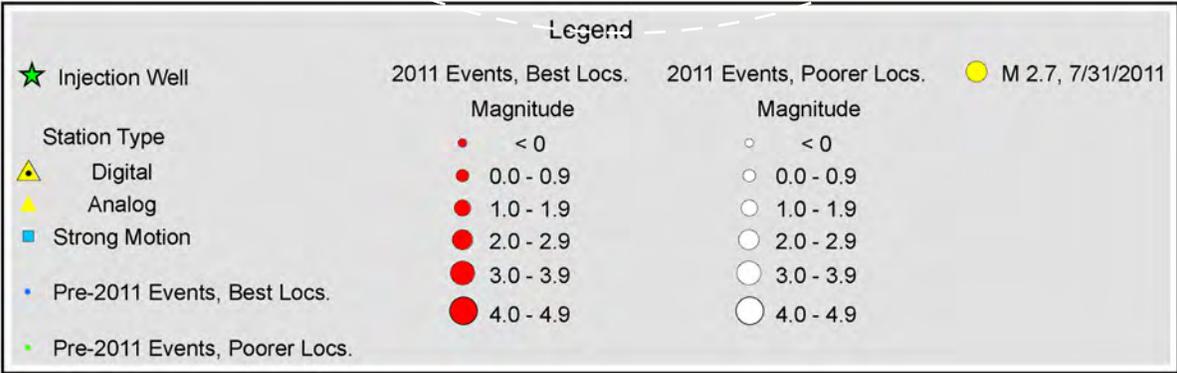
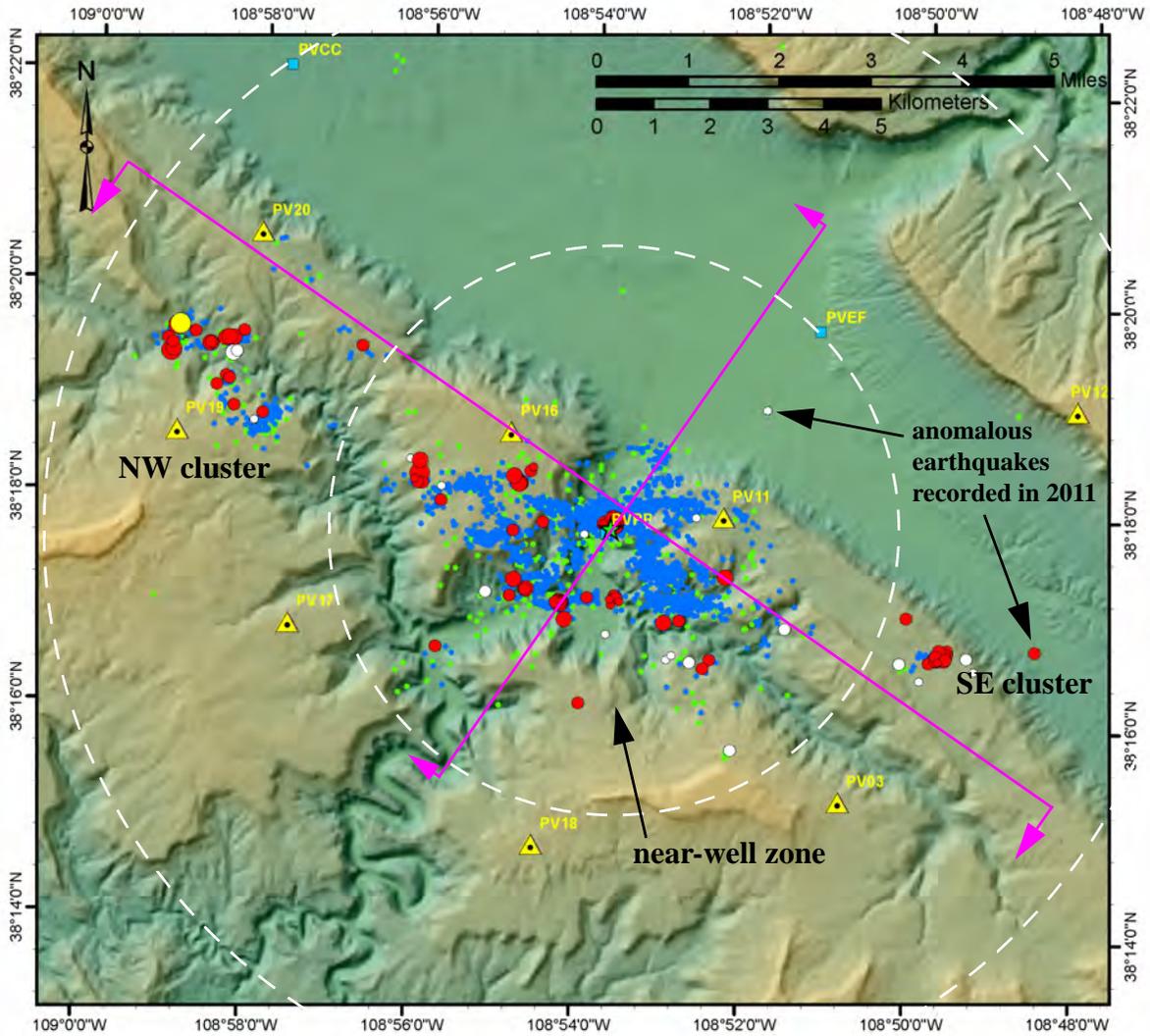
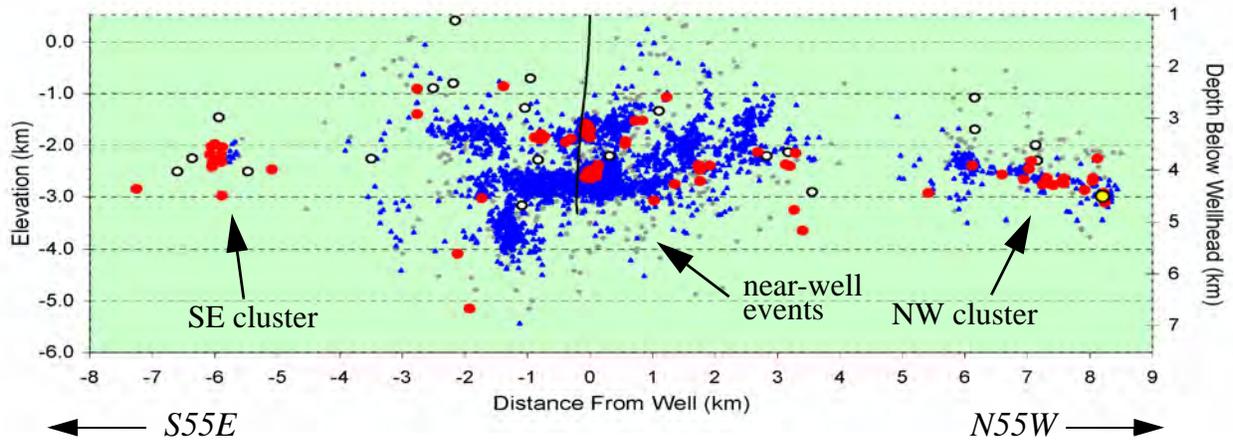


Figure 4-3 Map showing the epicenters of shallow earthquakes (< 8.5 km depth) locating in the vicinity of the injection well in 2011, compared to the locations of previously-induced events. The white dashed circles indicate radial distances of 5 and 10 km from the injection well. The magenta lines indicate 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

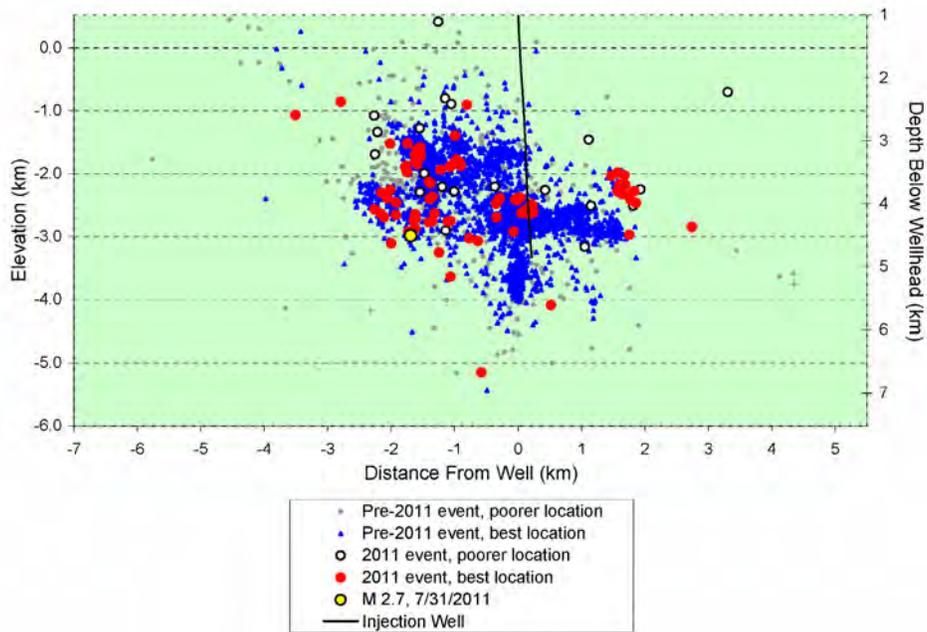


Figure 4-4 Vertical cross sections showing the locations of earthquakes induced in the vicinity of the injection well in 2011, compared to the locations of previously-induced events: (a) section parallel to Paradox Valley (b) section perpendicular to Paradox Valley. The orientations of the cross sections are indicated by the magenta lines in Figure 4-3.

well and about 1.5 km east of the SE cluster. The estimated duration magnitude of this earthquake is **M** 0.8. Its computed depth is 4.4 km (relative to the ground surface elevation at the injection wellhead), only slightly deeper than the 3.5 to 4.0 km depth range of the earthquakes in the SE cluster. The second anomalous earthquake locates approximately 3.5 km northeast of the injection well and more than 1.5 km from the edge of the historical near-well region of induced seismicity. It is a small earthquake, with an estimated magnitude of only **M** -0.1. Its computed depth is 2.2 km, but this estimate has a fairly high uncertainty because of poor data quality (due to the earthquake's small magnitude) and inaccuracies in the velocity model in the vicinity of the earthquake. However, the earthquake is definitely a shallow event (< 8 km depth) and therefore is considered to be likely induced.

One induced earthquake with magnitude greater than or equal to **M** 2.5 (**M** 2.5+) was recorded during 2011. 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 2011 locates at the far edge of the NW cluster, at an estimated depth of 4.5 km (relative to the ground surface elevation at the injection wellhead). Its location is indicated by the yellow circle in **Figures 4-3** and **4-4**. This earthquake occurred on July 31, 2011 and has an estimated duration magnitude of **M** 2.7. (No strong motion instruments were triggered.)

#### **4.2.2 Comparison to 2010 Seismicity**

Overall, the rate of earthquakes induced within 10 km of the injection well decreased in 2011 (117 events) compared to 2010 (156 events), while the magnitude distribution remained about the same. However, the trends are distinctly different for the area within 5 km of the well compared to regions located 5 to 10 km from the well. While the rate and magnitudes of earthquakes occurring within 5 km of the well decreased in 2011 compared to 2010, the rate and magnitudes of earthquakes occurring at distances of 5 to 10 km from the well increased. These trends are shown in **Figure 4-5** and **Figure 4-6** and are discussed below.

The numbers of earthquakes recorded during 2011 and 2010 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 one event 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**.

Both the occurrence rate and maximum event magnitude for earthquakes locating within 5 km of the injection well decreased in 2011 compared to the previous year. The number of earthquakes in this region decreased from 128 in 2010 to 75 in 2011. This decreased rate occurred for most magnitude ranges (**Figure 4-5**, top). The largest near-well earthquake recorded during 2010 had a magnitude of **M** 2.6. The largest near-well earthquake recorded during 2011 had a magnitude of **M** 2.4. Two **M** 2.5+ earthquakes occurred in the near-well region during 2010, but none occurred during 2011.

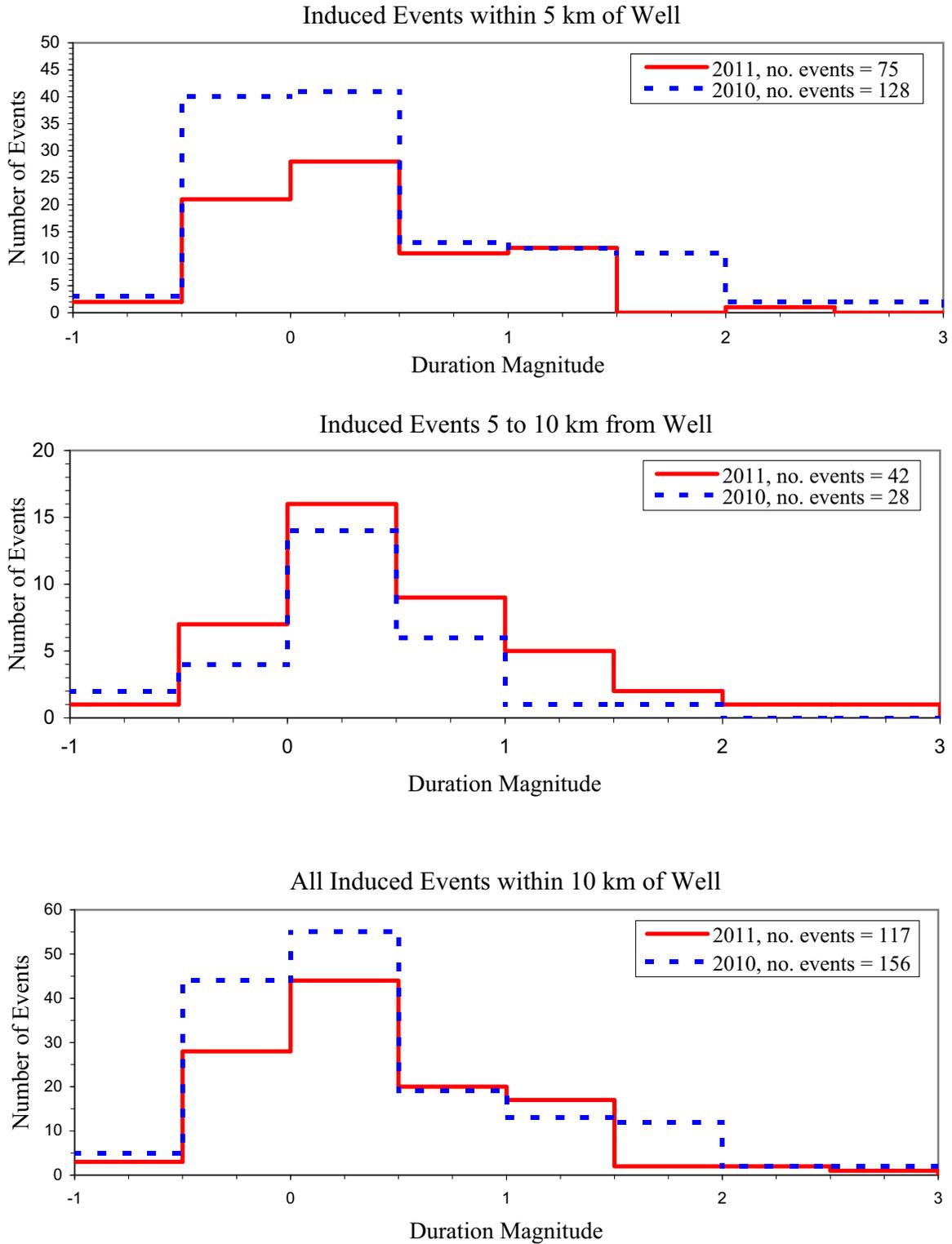


Figure 4-5 Magnitude histograms of induced events recorded within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and in both regions (bottom) during 2011 (solid red lines) and 2010 (dashed blue lines).

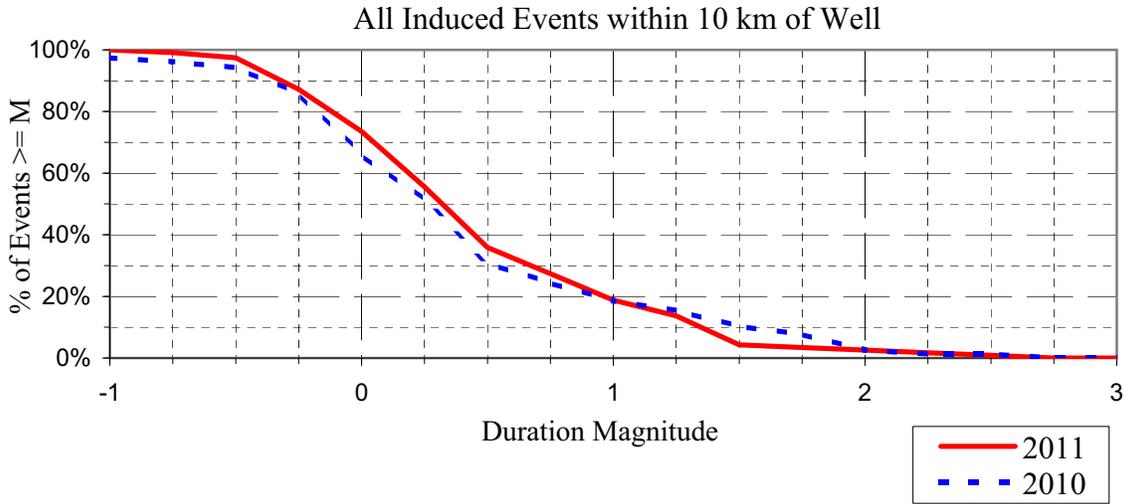
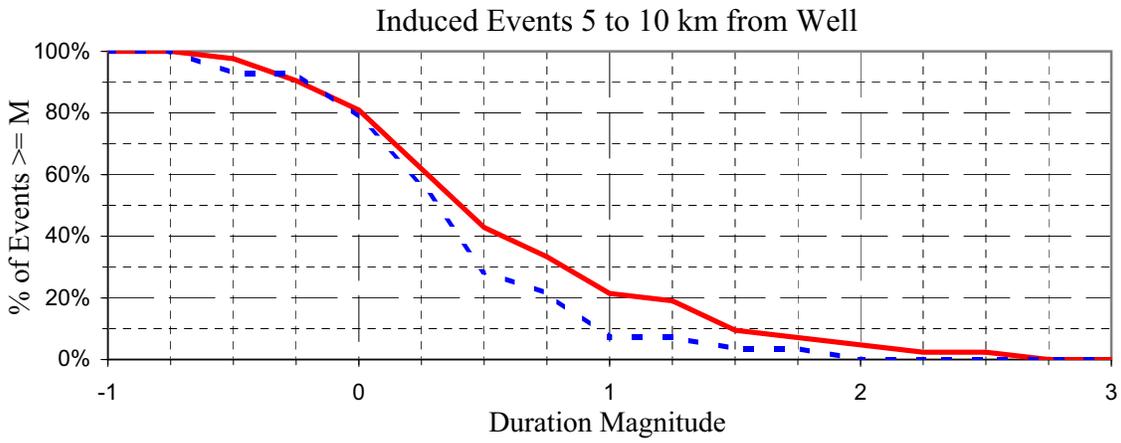
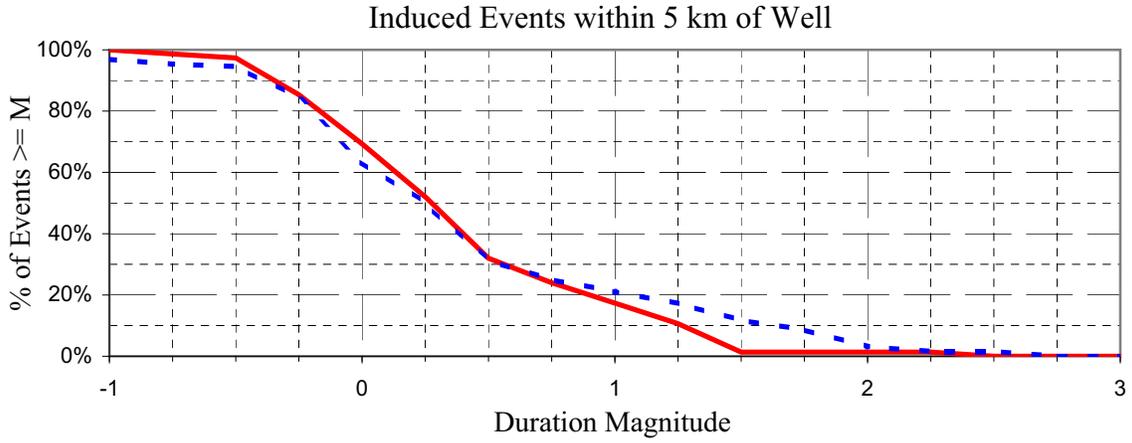


Figure 4-6 Cumulative magnitude-frequency plots of induced events recorded within 5 km of the injection well (top), at distances of 5 to 10 km from the well (middle), and in both areas (bottom) during 2011 (solid red lines) and 2010 (dashed blue lines).

The occurrence rate and maximum event magnitude for earthquakes locating at distances of 5 to 10 km from the injection well increased in 2011 compared to the previous year. The number of earthquakes in this region increased from 28 in 2010 to 42 in 2011. This increased rate occurred for all magnitude ranges  $> M -0.5$  (**Figure 4-5**, middle), with a disproportionately greater increase in the rate of larger-magnitude events. In 2010, only 7% of the earthquakes induced 5 to 10 km from the well had a magnitude greater than  $M 1.0$ ; this value increased to 21% in 2011 (**Figure 4-6**, middle). One earthquake with magnitude  $\geq M 2.5$  occurred in this region during 2011, compared to none the previous year. The largest event recorded during 2011 had a magnitude of  $M 2.7$  (in the NW cluster), whereas the largest event recorded during 2010 had a magnitude of  $M 1.9$  (in the SE cluster).

### 4.3 Northern-Valley Earthquakes

91 of the 113 northern valley earthquakes recorded during 2011 occurred during two swarms of activity, one in April and another in May (**Figure 4-2**). These seismic swarms locate about 3 to 4 km east of station PV04 (**Figure 4-1**). Seismic swarms had been detected at this location three times prior to 2011: 23 earthquakes were recorded over a span of 6 days in September, 2003; 10 earthquakes were recorded during 3 days in October, 2005; and 512 earthquakes were recorded during 16 days in November and December, 2010.

Unfortunately, the first and larger northern valley swarm that occurred in 2011 was not recorded completely. Because of power failures and other technical problems described in section 3.2, the Paradox Valley Seismic Network was offline during part of this swarm activity. The swarm began on April 11th, and 68 events were recorded during 14 hours before the seismic network went down on the 12th. The swarm activity ceased sometime before network operations were restored on the 18th. The swarm that occurred in May lasted just 13.5 hours (on the 25th - 26th). During this time period, 23 earthquakes were recorded.

Of the earthquakes recorded during the April, 2011 swarm, 26% have magnitude  $\geq M 1.0$ , and the largest event has a magnitude of  $M 1.8$ . Of the earthquakes recorded during the May, 2011 swarm, 30% have magnitude  $\geq M 1.0$ , and the largest event has a magnitude of  $M 1.9$ . (This compares to only 18% of the earthquakes recorded during the Nov. - Dec., 2010 swarm having magnitude  $\geq M 1.0$ . The largest earthquake recorded during that swarm has a magnitude of  $M 2.0$ .)

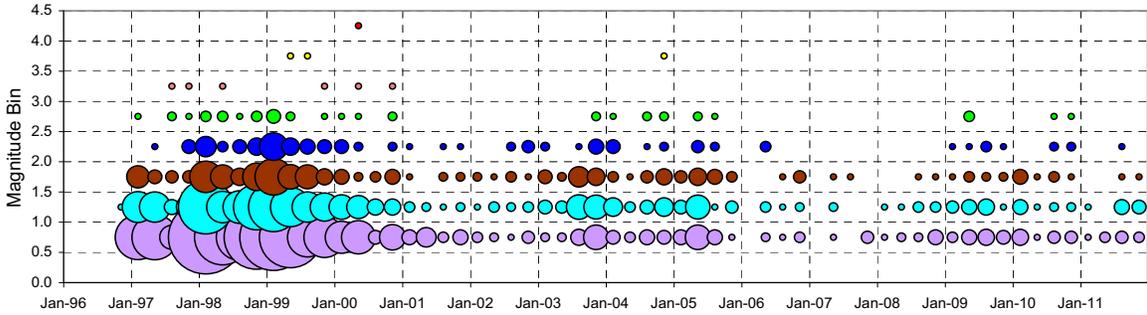
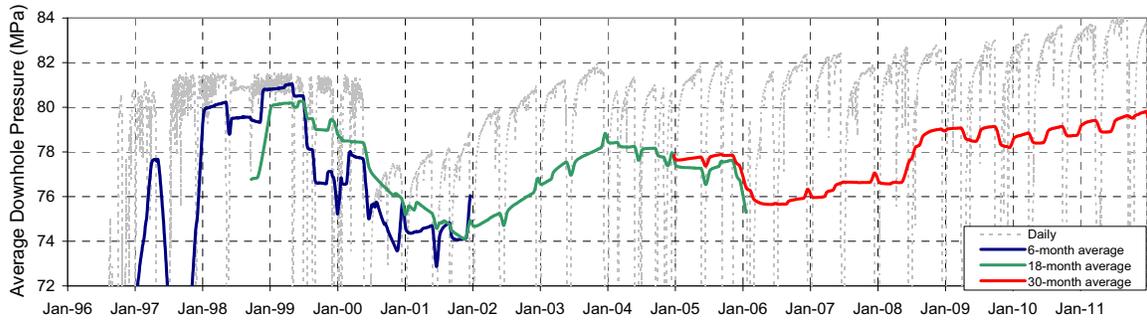
The magnitudes and estimated depths of the 113 northern valley earthquakes recorded during 2011 are comparable to the magnitudes and depths of northern valley events recorded in previous years. Magnitudes of the northern valley earthquakes recorded from 2000 (when they were first detected) through 2010 range from  $M -0.7$  to  $M 2.9$ , with all but one event having magnitude  $\leq M 2.3$ . Magnitudes of the earthquakes that occurred during 2011 range from  $M -0.8$  to  $M 2.0$ . Estimated depths of the northern valley earthquakes recorded in 2011 range from 2.5 to 7.4 km (relative to the ground surface elevation at the injection wellhead), with a median value of 4.4 km. This is comparable to estimated depths of previous northern valley earthquakes having reasonably well-constrained hypocenters.

#### 4.4 Historical Seismicity Trends

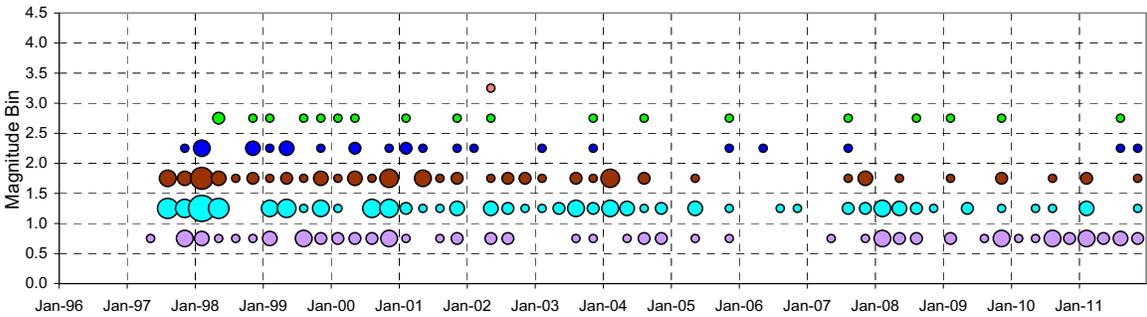
The bubble plots in **Figure 4-7** show the occurrence of shallow seismicity ( $< 8.5$  km depth, relative to the ground surface elevation at the injection wellhead) as a function of date and earthquake magnitude. The area of each circle in these plots is scaled by the number of earthquakes occurring in a given quarter-year and magnitude range. 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.

The uppermost bubble plot shows that the induced seismicity within 5 km of the well, both in terms of occurrence rate and magnitude range, was less active in 2011 compared to 2010 (as discussed earlier in section 4.2.2). However, the change in character from 2010 to 2011 is relatively small compared to longer-term historical trends. Similarly, although the rate and magnitudes of earthquakes occurring 5 to 10 km from the well increased in 2011 compared to 2010, the modest variation is not unusual (middle bubble plot).

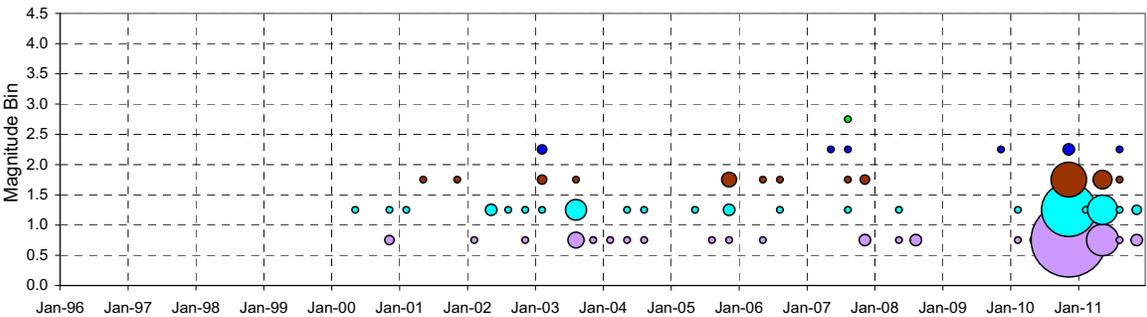
The lower bubble plot, which presents the historical northern valley seismicity, shows that, while the seismicity rate was significantly lower in 2011 compared to 2010, the rate is still anomalously high compared to long-term historical trends. Taking into account the fact that the largest northern valley seismic swarm in 2011 was not completely recorded, the recent departure from historical trends is stronger than represented by the plot in **Figure 4-7**.



Induced Events within 5 km of the Well



Induced Events 5 to 10 km from the Well



Northern Valley Earthquakes

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 2011 are included.

## 5.0 REFERENCES

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APPENDIX A  
PVSN 2011 LOCAL EARTHQUAKE CATALOG

**Table A-1: Local earthquakes recorded by PVSN during 2011**

Date	Time <sup>1</sup>	Latitude (deg.)	Longitude (deg.)	Elevation <sup>2</sup> (km)	Depth <sup>3</sup> (km)	Duration Magnitude	Location Category <sup>4</sup>
1/1/11	20:25:04	38.2774	-108.8289	-2.3	3.8	0.1	SE cluster
1/8/11	4:20:50	38.2793	-108.8091	-2.8	4.4	0.8	other - 1.5 km east of SE cluster
1/12/11	6:18:40	38.4058	-108.8776	-4.6	6.1	1.1	northern valley
1/12/11	22:21:04	38.3171	-108.9752	-2.3	3.8	0.5	NW cluster
1/24/11	19:02:29	38.2776	-108.8270	-2.2	3.7	0.0	SE cluster
1/28/11	23:45:33	38.2957	-108.9147	-2.8	4.3	0.4	near-well
1/31/11	2:47:37	38.2850	-108.8929	-1.8	3.4	-0.4	near-well
1/31/11	9:16:03	38.4034	-108.8711	-4.3	5.8	0.4	northern valley
1/31/11	14:15:43	38.2688	-108.9003	-0.9	2.4	0.7	near-well
2/11/11	6:36:51	38.2894	-108.8717	-4.1	5.6	1.2	near-well
2/13/11	1:08:52	38.3186	-108.9734	-2.5	4.0	0.3	NW cluster
2/25/11	15:05:25	38.2779	-108.8228	-2.3	3.8	0.1	SE cluster
2/28/11	2:59:54	38.2823	-108.8807	-5.1	6.7	0.1	near-well
3/8/11	3:50:26	38.2848	-108.9054	-1.9	3.4	0.2	near-well
3/26/11	12:03:55	38.3245	-108.9737	-2.8	4.3	1.4	NW cluster
3/27/11	1:17:48	38.3246	-108.9730	-2.8	4.3	1.0	NW cluster
3/27/11	1:24:10	38.3221	-108.9722	-2.3	3.8	1.6	NW cluster
3/27/11	4:17:14	38.2781	-108.8271	-2.3	3.9	0.3	SE cluster
3/28/11	2:17:19	38.3246	-108.9721	-2.6	4.2	1.2	NW cluster
3/29/11	4:57:40	38.3225	-108.9714	-2.0	3.5	0.8	NW cluster
3/29/11	19:23:51	38.2777	-108.8273	-2.0	3.6	1.5	SE cluster
3/29/11	19:35:04	38.2784	-108.8267	-2.4	3.9	0.7	SE cluster
3/29/11	21:45:21	38.2758	-108.8213	-2.5	4.0	-0.4	SE cluster
4/1/11	4:53:28	38.4033	-108.8669	-4.5	6.0	0.7	northern valley
4/1/11	4:53:46	38.4034	-108.8669	-4.5	6.1	-0.5	northern valley
4/1/11	20:08:49	38.3634	-108.7616	-2.0	3.6	0.0	other - 6.5 km north-east of PV12
4/2/11	1:32:49	38.2972	-108.9088	-3.1	4.6	0.0	near-well
4/3/11	18:22:49	38.2817	-108.8594	-2.3	3.8	0.6	near-well
4/8/11	2:21:04	38.2741	-108.8321	-1.5	3.0	-0.4	SE cluster
4/11/11	15:25:31	38.4000	-108.8689	-4.2	5.7	1.2	northern valley
4/11/11	15:35:11	38.4013	-108.8683	-4.5	6.0	1.6	northern valley
4/11/11	15:36:03	38.4007	-108.8682	-4.1	5.6	0.1	northern valley
4/11/11	16:06:03	38.4004	-108.8668	-3.9	5.4	0.8	northern valley
4/11/11	16:41:34	38.4014	-108.8697	-4.3	5.8	0.9	northern valley
4/11/11	16:41:55	38.4020	-108.8673	-4.2	5.7	0.0	northern valley
4/11/11	16:44:11	38.4020	-108.8683	-4.2	5.8	-0.1	northern valley
4/11/11	16:44:27	38.4008	-108.8681	-4.0	5.6	0.6	northern valley
4/11/11	16:49:50	38.4009	-108.8674	-4.0	5.5	1.1	northern valley
4/11/11	16:51:42	38.4025	-108.8657	-4.2	5.7	-0.3	northern valley
4/11/11	16:53:12	38.3994	-108.8589	-1.9	3.4	0.0	northern valley
4/11/11	16:53:23	38.4014	-108.8660	-4.2	5.7	-0.5	northern valley
4/11/11	16:53:29	38.4033	-108.8651	-4.3	5.8	-0.7	northern valley
4/11/11	16:54:13	38.4038	-108.8654	-4.1	5.6	-0.1	northern valley
4/11/11	16:54:48	38.4019	-108.8694	-4.4	5.9	-0.7	northern valley
4/11/11	16:57:58	38.4020	-108.8682	-4.3	5.9	1.6	northern valley

**Table A-1: Local earthquakes recorded by PVSN during 2011**

4/11/11	16:59:24	38.3999	-108.8678	-3.9	5.4	0.7	northern valley
4/11/11	16:59:43	38.3919	-108.8637	-1.5	3.0	0.3	northern valley
4/11/11	17:02:28	38.4035	-108.8683	-4.4	6.0	1.3	northern valley
4/11/11	17:02:56	38.4020	-108.8679	-4.1	5.6	-0.8	northern valley
4/11/11	17:27:58	38.4032	-108.8627	-3.3	4.9	0.3	northern valley
4/11/11	17:29:45	38.3964	-108.8600	-2.0	3.6	0.1	northern valley
4/11/11	17:40:29	38.3974	-108.8614	-2.1	3.7	-0.3	northern valley
4/11/11	17:40:41	38.3983	-108.8704	-4.1	5.6	1.3	northern valley
4/11/11	17:41:43	38.4000	-108.8648	-3.5	5.1	-0.2	northern valley
4/11/11	17:43:59	38.4015	-108.8691	-4.2	5.8	0.8	northern valley
4/11/11	18:05:10	38.3979	-108.8685	-3.9	5.4	0.9	northern valley
4/11/11	18:05:51	38.4035	-108.8691	-4.5	6.0	0.1	northern valley
4/11/11	18:08:53	38.4002	-108.8688	-4.1	5.6	0.4	northern valley
4/11/11	18:09:09	38.4011	-108.8688	-4.1	5.6	0.1	northern valley
4/11/11	18:10:03	38.4108	-108.8563	-2.7	4.3	-0.5	northern valley
4/11/11	18:16:39	38.4021	-108.8701	-4.3	5.8	-0.1	northern valley
4/11/11	18:16:51	38.4000	-108.8696	-4.1	5.6	1.4	northern valley
4/11/11	18:24:51	38.4035	-108.8688	-4.4	5.9	1.6	northern valley
4/11/11	18:26:35	38.4050	-108.8595	-2.6	4.1	-0.3	northern valley
4/11/11	18:27:06	38.4018	-108.8679	-3.9	5.4	-0.4	northern valley
4/11/11	19:25:02	38.4007	-108.8599	-3.2	4.7	-0.8	northern valley
4/11/11	19:25:21	38.4003	-108.8707	-4.3	5.8	1.1	northern valley
4/11/11	19:26:16	38.3991	-108.8680	-3.7	5.2	-0.1	northern valley
4/11/11	19:28:07	38.4022	-108.8691	-4.1	5.7	0.0	northern valley
4/11/11	19:29:11	38.4007	-108.8712	-4.3	5.8	1.5	northern valley
4/11/11	19:29:38	38.4009	-108.8682	-4.1	5.6	-0.4	northern valley
4/11/11	19:31:45	38.4026	-108.8686	-4.1	5.7	-0.1	northern valley
4/11/11	19:32:05	38.4024	-108.8668	-4.0	5.5	-0.3	northern valley
4/11/11	19:56:59	38.3986	-108.8694	-3.8	5.3	1.4	northern valley
4/11/11	19:58:28	38.4033	-108.8707	-4.3	5.9	-0.7	northern valley
4/11/11	19:58:35	38.4031	-108.8676	-3.9	5.5	-0.6	northern valley
4/11/11	19:58:59	38.4002	-108.8680	-3.8	5.3	0.1	northern valley
4/11/11	20:00:39	38.4015	-108.8717	-4.5	6.0	1.3	northern valley
4/11/11	20:01:02	38.4001	-108.8699	-3.9	5.5	0.2	northern valley
4/11/11	20:01:22	38.4005	-108.8662	-3.4	4.9	0.5	northern valley
4/11/11	20:12:34	38.4011	-108.8696	-4.1	5.6	1.3	northern valley
4/11/11	20:13:19	38.4046	-108.8688	-4.2	5.7	-0.5	northern valley
4/11/11	20:13:45	38.4013	-108.8688	-3.8	5.3	0.7	northern valley
4/11/11	20:15:02	38.3930	-108.8674	-2.3	3.9	-0.1	northern valley
4/11/11	20:46:29	38.4016	-108.8725	-4.2	5.8	1.3	northern valley
4/11/11	20:51:58	38.4026	-108.8717	-4.5	6.0	1.6	northern valley
4/11/11	21:08:23	38.4014	-108.8707	-4.1	5.6	1.4	northern valley
4/11/11	21:55:06	38.4018	-108.8711	-4.5	6.0	1.8	northern valley
4/11/11	22:49:08	38.4034	-108.8709	-4.1	5.6	0.9	northern valley
4/12/11	0:27:06	38.4030	-108.8694	-4.3	5.8	0.8	northern valley
4/12/11	0:28:16	38.4023	-108.8673	-3.8	5.3	0.2	northern valley
4/12/11	1:06:20	38.4007	-108.8677	-4.0	5.5	0.6	northern valley
4/12/11	1:47:40	38.3997	-108.8690	-3.7	5.2	0.9	northern valley
4/12/11	3:30:50	38.3990	-108.8676	-3.9	5.4	1.3	northern valley
4/12/11	3:31:54	38.4041	-108.8671	-4.4	5.9	-0.7	northern valley
4/12/11	3:45:45	38.4025	-108.8644	-4.0	5.5	0.5	northern valley
4/12/11	5:59:03	38.4074	-108.8504	-1.0	2.5	0.3	northern valley

**Table A-1: Local earthquakes recorded by PVSN during 2011**

4/19/11	15:26:47	38.2790	-108.8267	-2.3	3.8	0.8	SE cluster
4/22/11	20:37:09	38.2791	-108.8284	-3.0	4.5	0.1	SE cluster
4/22/11	22:23:15	38.2782	-108.8290	-2.3	3.8	0.1	SE cluster
5/2/11	3:41:45	38.4135	-108.9967	-4.6	6.1	1.3	northern valley
5/5/11	19:48:34	38.2987	-108.8779	-3.2	4.7	-0.4	near-well
5/12/11	15:18:01	38.2770	-108.9295	-1.1	2.6	0.7	near-well
5/16/11	7:23:01	38.4079	-108.9038	-3.4	4.9	-0.4	northern valley
5/17/11	20:00:15	38.4035	-108.8681	-4.4	5.9	0.8	northern valley
5/18/11	13:01:46	38.2855	-108.8994	-1.9	3.5	0.6	near-well
5/18/11	13:02:51	38.2798	-108.8954	-1.3	2.8	-0.4	near-well
5/19/11	8:13:58	38.3258	-108.9701	-2.8	4.3	0.5	NW cluster
5/20/11	6:29:31	38.3182	-108.9726	-2.7	4.2	0.3	NW cluster
5/25/11	15:18:37	38.4035	-108.8713	-4.4	6.0	0.7	northern valley
5/25/11	15:42:15	38.4035	-108.8711	-4.4	5.9	1.9	northern valley
5/25/11	15:44:28	38.4035	-108.8708	-4.4	6.0	-0.2	northern valley
5/25/11	15:59:33	38.4035	-108.8707	-4.4	5.9	0.7	northern valley
5/25/11	16:00:03	38.4039	-108.8650	-3.7	5.2	-0.8	northern valley
5/25/11	16:13:59	38.4037	-108.8714	-4.3	5.8	1.1	northern valley
5/25/11	17:09:58	38.4034	-108.8715	-4.3	5.9	1.7	northern valley
5/25/11	17:11:34	38.4035	-108.8714	-4.4	5.9	0.0	northern valley
5/25/11	17:28:00	38.4034	-108.8718	-4.4	5.9	0.7	northern valley
5/25/11	17:28:10	38.4034	-108.8718	-4.3	5.9	0.6	northern valley
5/25/11	17:47:20	38.4033	-108.8711	-4.3	5.8	1.2	northern valley
5/25/11	17:49:33	38.4109	-108.8720	-3.5	5.0	-0.6	northern valley
5/25/11	17:49:36	38.4034	-108.8727	-4.4	6.0	0.2	northern valley
5/25/11	17:49:54	38.4034	-108.8721	-4.4	5.9	-0.1	northern valley
5/25/11	17:53:51	38.4033	-108.8722	-4.3	5.9	1.1	northern valley
5/25/11	20:21:04	38.4033	-108.8721	-4.4	5.9	0.7	northern valley
5/25/11	21:52:38	38.4033	-108.8721	-4.3	5.8	0.3	northern valley
5/25/11	21:54:04	38.4087	-108.9062	-4.3	5.8	-0.2	northern valley
5/25/11	21:58:48	38.4033	-108.8717	-4.3	5.8	0.3	northern valley
5/25/11	22:21:04	38.4035	-108.8723	-4.3	5.8	0.2	northern valley
5/26/11	0:49:38	38.4034	-108.8717	-4.3	5.8	0.0	northern valley
5/26/11	3:24:18	38.4032	-108.8714	-4.3	5.8	1.2	northern valley
5/26/11	4:46:12	38.4034	-108.8721	-4.3	5.8	0.5	northern valley
6/1/11	9:19:53	38.2768	-108.8362	-2.5	4.0	0.0	SE cluster
6/4/11	15:20:24	38.4222	-108.9438	-4.7	6.2	1.2	northern valley
6/8/11	22:05:44	38.3028	-108.9338	-2.1	3.7	0.4	near-well
6/9/11	1:12:15	38.2859	-108.9199	-1.3	2.9	0.0	near-well
6/10/11	16:47:36	38.2757	-108.8838	0.4	1.1	0.3	near-well
6/21/11	11:44:22	38.4025	-108.8806	-2.4	3.9	0.8	northern valley
6/21/11	11:51:53	38.4056	-108.8822	-2.8	4.3	1.3	northern valley
6/21/11	11:52:09	38.4055	-108.8913	-3.2	4.7	0.5	northern valley
6/21/11	11:56:17	38.4045	-108.8856	-3.0	4.5	1.4	northern valley
6/21/11	11:57:01	38.4029	-108.8620	-1.6	3.2	-0.2	northern valley
6/21/11	22:17:10	38.3028	-108.9331	-2.4	3.9	0.4	near-well
6/27/11	19:14:00	38.2955	-108.9003	-2.2	3.7	-0.1	near-well
7/3/11	9:40:44	38.4020	-108.9331	-3.7	5.2	2.0	northern valley
7/5/11	17:43:36	38.4038	-108.9339	-3.8	5.3	1.3	northern valley
7/8/11	11:03:06	38.2916	-108.8222	-13.7	15.2	1.4	other - 2 km northeast of SE cluster
7/9/11	18:39:17	38.2771	-108.8286	-2.0	3.5	-0.2	SE cluster

**Table A-1: Local earthquakes recorded by PVSN during 2011**

7/12/11	1:39:03	38.4029	-108.9335	-3.8	5.3	1.7	northern valley
7/17/11	6:48:24	38.4015	-109.0056	-3.7	5.3	0.6	northern valley
7/17/11	7:44:30	38.2773	-108.8288	-2.3	3.8	0.6	SE cluster
7/21/11	5:54:48	38.2778	-108.8292	-2.2	3.7	0.9	SE cluster
7/22/11	22:45:14	38.2853	-108.8948	-1.8	3.4	-0.3	near-well
7/23/11	14:26:55	38.2856	-108.8935	-1.8	3.3	0.2	near-well
7/26/11	12:02:02	38.2763	-108.8744	-0.9	2.4	0.2	near-well
7/29/11	16:13:03	38.2845	-108.8945	-1.9	3.4	-0.2	near-well
7/31/11	5:43:46	38.3262	-108.9833	-2.9	4.4	2.2	NW cluster
7/31/11	11:30:05	38.3264	-108.9829	-3.0	4.5	2.7	NW cluster
7/31/11	18:22:22	38.3243	-108.9853	-3.1	4.6	0.2	NW cluster
7/31/11	18:38:13	38.2854	-108.8941	-1.8	3.3	0.5	near-well
7/31/11	18:38:51	38.2848	-108.8938	-2.3	3.8	-0.3	near-well
8/1/11	4:45:55	38.3028	-108.9341	-2.4	3.9	0.4	near-well
8/1/11	4:46:21	38.3065	-108.9357	-2.9	4.4	-0.9	near-well
8/1/11	23:17:32	38.2860	-108.8938	-1.9	3.4	0.8	near-well
8/13/11	19:26:50	38.2966	-108.8940	-2.6	4.2	0.0	near-well
8/13/11	19:30:20	38.3001	-108.9294	-2.1	3.7	0.3	near-well
8/21/11	2:33:03	38.3043	-108.9148	-2.4	3.9	1.1	near-well
8/21/11	2:33:35	38.3052	-108.9115	-2.4	3.9	0.1	near-well
8/21/11	2:37:58	38.3058	-108.9110	-2.4	3.9	-0.1	near-well
8/21/11	10:39:17	38.3033	-108.9135	-2.4	4.0	1.5	near-well
8/21/11	17:51:53	38.3031	-108.9137	-2.5	4.0	1.3	near-well
8/22/11	10:26:50	38.3032	-108.9137	-2.7	4.2	1.4	near-well
8/26/11	5:13:50	38.2982	-108.8950	-2.6	4.1	0.1	near-well
9/2/11	21:49:03	38.2768	-108.8821	-0.8	2.3	-0.3	near-well
9/2/11	21:49:11	38.2761	-108.8831	0.4	1.1	-0.1	near-well
9/2/11	23:10:39	38.3024	-108.9293	-2.2	3.7	-0.4	near-well
9/3/11	8:48:30	38.2777	-108.8848	0.3	1.2	-0.4	near-well
9/4/11	11:24:12	38.2971	-108.8962	-2.4	4.0	0.8	near-well
9/4/11	11:53:33	38.2973	-108.8962	-2.4	3.9	1.4	near-well
9/5/11	9:57:09	38.2985	-108.8947	-2.5	4.0	0.4	near-well
9/7/11	0:58:44	38.2969	-108.8937	-2.6	4.1	0.3	near-well
9/7/11	2:13:31	38.2840	-108.8351	-2.5	4.0	0.5	SE cluster
9/7/11	8:43:32	38.2770	-108.8303	-2.0	3.6	0.3	SE cluster
9/9/11	22:37:42	38.2865	-108.9119	-1.9	3.4	0.1	near-well
9/10/11	12:40:07	38.2983	-108.8938	-2.5	4.0	0.2	near-well
9/10/11	13:04:53	38.2981	-108.8940	-2.5	4.1	0.5	near-well
9/10/11	14:58:39	38.2981	-108.8932	-2.5	4.0	0.3	near-well
9/10/11	15:54:40	38.2980	-108.8939	-2.6	4.2	0.0	near-well
9/12/11	1:52:53	38.2866	-108.9117	-2.0	3.5	1.4	near-well
9/12/11	11:36:42	38.3042	-108.9338	-3.3	4.8	2.4	near-well
9/15/11	2:01:25	38.2982	-108.8938	-2.6	4.1	0.1	near-well
9/15/11	2:01:24	38.2982	-108.8932	-2.6	4.1	-0.6	near-well
9/15/11	4:08:02	38.3063	-108.9338	-3.6	5.2	1.2	near-well
9/21/11	11:34:46	38.2758	-108.8784	-0.9	2.4	0.3	near-well
9/30/11	21:55:51	38.3160	-108.8644	-0.7	2.2	-0.1	other - 3.5 km north-east of inj. well
10/4/11	20:31:36	38.3236	-108.9768	-2.7	4.3	1.5	NW cluster
10/5/11	13:02:33	38.3236	-108.9763	-2.7	4.2	0.7	NW cluster
10/7/11	10:36:00	38.3238	-108.9766	-2.6	4.2	0.2	NW cluster
10/9/11	11:47:48	38.2740	-108.8795	2.3	-0.7	0.7	near-well

**Table A-1: Local earthquakes recorded by PVSN during 2011**

10/9/11	11:48:24	38.2750	-108.8756	-1.4	2.9	0.2	near-well
10/16/11	8:00:37	38.3240	-108.9462	-2.9	4.4	0.7	NW cluster
10/19/11	23:25:19	38.3034	-108.9348	-2.2	3.7	-0.3	near-well
10/24/11	3:14:08	38.3222	-108.9846	-2.6	4.2	2.0	NW cluster
10/26/11	10:50:04	38.3129	-108.9658	-2.4	3.9	0.2	NW cluster
10/28/11	20:48:23	38.3225	-108.9842	-2.7	4.2	1.3	NW cluster
10/29/11	4:02:29	38.3139	-108.9716	-2.6	4.1	0.0	NW cluster
10/30/11	19:40:43	38.4216	-108.9394	-5.4	6.9	1.2	northern valley
11/2/11	9:24:21	38.4044	-109.0128	-4.1	5.6	0.7	northern valley
11/4/11	15:04:42	38.2854	-108.9150	-1.5	3.1	0.2	near-well
11/4/11	15:56:48	38.2880	-108.9143	-1.5	3.0	1.0	near-well
11/6/11	4:50:41	38.2622	-108.8695	2.2	-0.7	0.3	near-well
11/12/11	23:03:28	38.3005	-108.7516	-8.6	10.1	-0.1	other - 5 km southeast of PV12
11/13/11	4:36:48	38.3236	-108.9843	-2.3	3.8	0.2	NW cluster
11/20/11	9:54:28	38.3117	-108.9674	-1.7	3.2	-0.6	NW cluster
11/20/11	9:54:38	38.3116	-108.9675	-1.1	2.6	-0.3	NW cluster
12/4/11	0:16:29	38.3199	-108.7484	-5.5	7.0	1.4	other - 5 km east of PV12
12/9/11	10:17:36	38.2820	-108.9037	-1.9	3.4	1.0	near-well
12/11/11	13:57:29	38.2819	-108.8838	-3.0	4.6	1.1	near-well
12/12/11	10:52:20	38.4077	-108.9361	-4.2	5.8	0.6	northern valley
12/13/11	3:03:50	38.4077	-108.9361	-4.2	5.8	1.0	northern valley
12/14/11	16:13:05	38.2847	-108.9051	-1.6	3.1	1.5	near-well
12/15/11	9:47:15	38.2844	-108.9049	-1.6	3.1	1.3	near-well
12/15/11	9:52:02	38.2848	-108.9045	-1.7	3.2	0.3	near-well
12/15/11	9:53:01	38.2848	-108.9043	-1.7	3.3	0.2	near-well
12/15/11	10:02:11	38.2844	-108.9047	-1.6	3.2	1.2	near-well
12/15/11	10:09:52	38.2848	-108.9045	-1.7	3.2	0.5	near-well
12/16/11	1:17:58	38.2848	-108.9042	-1.7	3.2	0.7	near-well
12/16/11	17:36:39	38.4050	-108.8707	-3.5	5.0	0.6	northern valley
12/17/11	1:29:26	38.2849	-108.9044	-1.6	3.1	0.9	near-well
12/17/11	9:47:54	38.2846	-108.9046	-1.6	3.2	0.0	near-well
12/18/11	3:09:36	38.2846	-108.9057	-1.7	3.2	0.0	near-well
12/19/11	6:20:21	38.2844	-108.9052	-1.8	3.3	0.4	near-well
12/20/11	11:34:13	38.2848	-108.9045	-1.7	3.2	-0.2	near-well
12/29/11	2:51:06	38.3255	-108.9798	-2.9	4.4	0.4	NW cluster

<sup>1</sup> Time listed is Coordinated Universal Time, UTC (Mountain Standard Time = UTC – 7 hours)

<sup>2</sup> Elevation is given with respect to mean sea level.

<sup>3</sup> Depth is referenced to the surveyed elevation of the injection wellhead, 1.524 km.

<sup>4</sup> 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 very near areas of recurring seismicity along the northern edge of Paradox Valley

other: local earthquake not associated with any of the other location categories.

**APPENDIX B**

**2011 SITE VISIT REPORTS**

## Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2011-1

**Departure Date:** 4/25/2011

**Return Date:** 5/3/2011

**Purpose:** Site preparations for new stations; Station maintenance.

**Work Summary:** Site preparations necessary to install digital broadband seismographs were completed at five new stations and one existing station. This work included excavation and installation of seismometer vaults, tower bases, conduit, and grounding rods. An *Octans* gyrocompass was used to inscribe True North orientation lines on the frosted-glass floors of new seismometer vaults, with an accuracy of < 0.1 degrees. Power supplies were reset at two offline digital stations, and a GPS antenna was reset at a third. Minor maintenance was completed at two analog stations.

**Action Items:**

1	Plan for a trip in July or August to build out and complete the six new digital stations
2	Complete the acquisition of a right-of-way for the one remaining proposed site on USFS lands.
3	Plan field trips in September or October to perform site preps and install a seventh station.
4	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
3	Steve Angster	US Geological Survey, Golden
4	Steve Ploetz	US Geological Survey, Albuquerque
5	Steve Roberts	US Geological Survey, Albuquerque

**Work by Site:**

	Site	Work Accomplished
1	Hopkins Field	Check servers and disks
	PV02	Troubleshoot bad connector in analog mux cabling.
2	PV10	Reset seismometer power supply with tripped fusible link.
3	PV14	Reset seismometer power supply with tripped fusible link.
4	PV15	Test and adjust analog station and radio. Perform site preparations to convert station to broadband digital, including: install new seismometer vault with 1/2-inch frosted glass base, install new Rohn tower base, install buried conduit, install three 8-foot ground rods, inscribe North arrow using Octans gyrocompass.
5	BR-1	Perform site preparations to install new broadband digital seismograph station, including: install new seismometer vault with 1/2-inch frosted glass base, install new Rohn tower base, install buried conduit, install three 8-foot ground rods, inscribe North arrow using Octans gyrocompass.
6	BR-3	Perform site preparations to install new broadband digital seismograph station, including: install new seismometer vault with 1/2-inch frosted glass base, install new Rohn tower base, install buried conduit, install three 8-foot ground rods, inscribe North arrow using Octans gyrocompass.
7	BR-5	Perform site preparations to install new broadband digital seismograph station, including: install new seismometer vault with 1/2-inch frosted glass base, install new Rohn tower base, install buried conduit, install three 8-foot ground rods, inscribe North arrow using Octans gyrocompass.
8	BR-6	Perform site preparations to install new broadband digital seismograph station, including: install new seismometer vault with 1/2-inch frosted glass base, install new Rohn tower base, install buried conduit, install three 8-foot ground rods, inscribe North arrow using Octans gyrocompass.
9	BR-8	Perform site preparations to install new broadband digital seismograph station, including: install new seismometer vault with 1/2-inch frosted glass base, install new Rohn tower base, install buried conduit, install three 8-foot ground rods.



Clockwise from upper left: (1) Excavation for seismometer vault extends through layer of soil into bedrock, and is carefully cleaned out before pouring concrete. (2) Wire reinforcement is added to the initial pour of concrete. (3) Seismometer vault (yellow barrel) is installed and leveled. Screw-on lid and seal (not shown) provides a water-tight enclosure. (4) A 1/2-inch frosted glass plate is installed to provide electrical insulation and a level base for the seismometer. (5) Glass plate is placed and leveled while concrete is still wet. (6 and 7) Precision *Octans* gyrocompass is used to establish True North within < 0.1 degrees, and does not depend on magnetic north. (8) Spring flowers.





Clockwise from upper left: (1 and 2) A 3-foot antenna tower base is set into a circular excavation through soil and bedrock, and cemented into place after leveling. (3 and 4) After the concrete cures, a 20-foot tower, solar panel, communications and GPS antennas, and an instrumentation enclosure will be attached to the base. Flexible steel conduit is installed between the tower base and seismometer vault for instrumentation and grouting cables. (5) Spring flowers. (6) View towards the northeast across Paradox Valley and the Delores River Canyon. Uncompaghre Butte is in the background. Photo taken from the trail to PV16.

## Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2011-2    **Departure Date:** 7/15/2011    **Return Date:** 7/22/2011

**Purpose:** Construction and installation of new stations.

**Work Summary:** Installation of digital broadband seismograph stations was completed at five new sites and one existing site. This work included installation of an antenna mast, solar panel, system enclosure, GPS and communications antennas, cabling, conduit, grounding, surge protection, break-out-boxes, radio, and a digital broad-band seismometer.

**Action Items:**

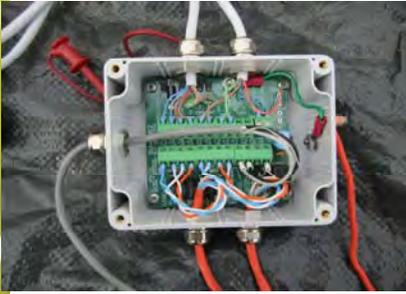
1	Plan for a trip in September or October to complete cable and radio testing of the six new digital stations
2	Complete the acquisition of a right-of-way for the one remaining proposed site on USFS lands.
3	Plan field trips in September or October to perform site preps and install a seventh station.
4	Upgrade server disk array at Hopkins Field during next maintenance trip.
5	Perform maintenance on analog equipment at PV02, PV11, and PV16 if time permits

**Personnel:**

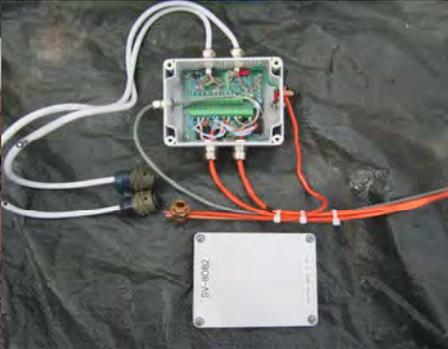
	Name	Organization
1	Chris Wood	Reclamation, Seismotectonics & Geophysics, 86-68330
2	Justin Schwarzer	Reclamation, Seismotectonics & Geophysics, 86-68330
3	Mark Meremonte	US Geological Survey, Golden

**Work by Site:**

	Site	Work Accomplished
4	PV15	Install mast, solar panel, equipment enclosure, GPS and communications antennas, cabling, conduit, break-out boxes, seismometer vault fittings and equipment, grounding, surge protection, seismometer, and radio.
5	PV-18 (BR-3)	Install mast, solar panel, equipment enclosure, GPS and communications antennas, cabling, conduit, break-out boxes, seismometer vault fittings and equipment, grounding, surge protection, seismometer, and radio.
6	PV-19 (BR-1)	Install mast, solar panel, equipment enclosure, GPS and communications antennas, cabling, conduit, break-out boxes, seismometer vault fittings and equipment, grounding, surge protection, seismometer, and radio.
7	PV-20 (BR-8)	Install mast, solar panel, equipment enclosure, GPS and communications antennas, cabling, conduit, break-out boxes, seismometer vault fittings and equipment, grounding, surge protection, seismometer, and radio.
8	PV-21 (BR-5)	Install mast, solar panel, equipment enclosure, GPS and communications antennas, cabling, conduit, break-out boxes, seismometer vault fittings and equipment, grounding, surge protection, seismometer, and radio.
9	PV-22 (BR-6)	Install mast, solar panel, equipment enclosure, GPS and communications antennas, cabling, conduit, break-out boxes, seismometer vault fittings and equipment, grounding, surge protection, seismometer, and radio.



Clockwise from upper left: (1) Digital broadband seismometer on frosted glass plate with inscribed North line. (2) Sensor-vault break-out-box (SV-BOB) is used to provide a cabling interface and surge protection. (3) Seismometer vault (yellow barrel) with seismometer and insulating foam installed. (4) Seismometer is leveled and oriented to True North. (5) Glass plate in seismometer vault provides electrical insulation and a surface for easy leveling. (6) Sensor-vault BOB cabling. Ground wire is run from main enclosure to avoid ground loops. (7) Seismometer vault is sealed with a waterproof screw-top lid, then covered with 12-16 inches of soil for additional thermal insulation.





Clockwise from upper left: (1 and 2) A 20-foot triangular lattice mast set into concrete provides a stable base for the enclosure, solar panel, and antennas. (3) All external cabling is protected from damage by flexible steel conduit. (4) A quick-release mounting system allows easy replacement of the GPS antenna. (5) Completed station. (6) Surge protectors, fusible links, and low-voltage-disconnects are provided in DIN-mounted circuit boards for the solar panel and batteries. A solar-panel regulator provides a readout of the system load (0.6 amp @ 12 VDC). Thermostat-controlled fans are used to cool the enclosure during summer months. (7) Seismometer (orange) and GPS (grey) cables are terminated in a GPS break-out-box (GPS-BOB) which also provides surge protection and power isolation. (8) Testing of the digital seismometer and radio with a laptop.

## Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2011-3    **Departure Date:** 10/1/2011    **Return Date:** 10/8/2011

**Purpose:** Construction and installation of new stations; Repair of lightning damage; Station Maintenance

**Work Summary:** Installation of the final planned digital broadband seismograph station (PV23) was completed, following issuance of a special use permit by the USFS on October 1. This work included site preps, as well as installation of all equipment. Substantial lightning damage at PV02 was repaired, including repairing the seismometer vault, and replacing all nearby electronic components and cabling. Moderate lightning damage at PV11 was repaired, including replacing the radio and seismometer. Additional grounding was installed at both PV02 and PV11. The solar panel surge protector at PV03 was replaced.

**Action Items:**

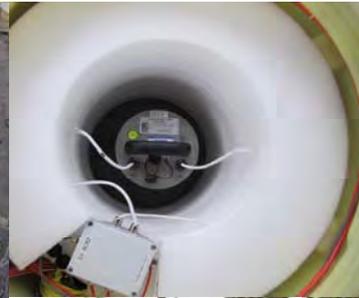
1	Plan for a trip in October to perform additional repairs at PV02, and to perform maintenance at PV05, PV11, and PV23.
2	Plan field trips for October to perform maintenance and final testing of the seven newly installed stations.
3	Initiate a review and possible redesign of the grounding and lightning protection system, and plan to install any necessary equipment next April and May, before the next lightning season.
4	Schedule use of the USGS's Octans gyrocompass to orient all seismometers not already oriented
5	Upgrade server disk array at Hopkins Field.
6	Perform maintenance on analog equipment at PV11 if time permits

**Personnel:**

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

**Work by Site:**

	Site	Work Accomplished
4	PV23 (BR-9)	Perform site preparations to install new broadband digital seismograph station, including: install new seismometer vault with 1/2-inch frosted glass base, install new Rohn tower base, install buried conduit, install three 8-foot ground rods. Install locked gate on access road per USFS stipulation.
5	PV23 (BR-9)	Install mast, solar panel, equipment enclosure, GPS and communications antennas, cabling, conduit, break-out boxes, seismometer vault fittings and equipment, grounding, surge protection, seismometer, and radio.
6	PV02	Repair damage from lightning strike, including: repair concrete in seismometer vault and install 1/2-inch frosted glass plate, replace seismometer cables and surge protection, replace foam insulation, replace seismometer, replace radios, replace DM24 BOB, replace antenna cables and PolyPhasers, replace antennas, replace GPS BOB, replace GPS receiver, replace discharged batteries, install additional grounding rods, install air terminal.
7	PV11	Repair damage from lightning strike, including: replace seismometer, replace radio, replace sensor vault BOB, install additional grounding rods, install air terminal.
8	PV03	Replace solar panel lightning protection blocks.



Installation of PV23. Clockwise from upper left: (1) Excavation for seismometer vault (yellow barrel). (2) Seismometer vault concreted into bedrock, with a 1/2-inch frosted glass plate for seismometer base set into the concrete. (3) Seismometer vault with seismometer and insulating foam installed. (4) Construction of antenna mast and solar panel array. (5) Equipment enclosure detail showing lightning protection for GPS (GPS BOB), batteries and solar panel (DIN blocks). (6) Locked gate installed on access road (7) Completed station showing antenna mast, solar panel, and equipment enclosure (tan box).





PV02 lightning damage and repair. Clockwise from upper left: (1) Top antenna has been vaporized by lightning strike - only the gold-colored aluminum base remains. (2) GPS BOB surge protector completely destroyed. (3) Sensor Vault BOB surge protector completely destroyed. (4) Damage to concrete and wire mesh damage in seismometer vault. Seismometer (silver cylinder) was also damaged. (5) Repaired seismometer vault with 1/2-inch frosted glass plate for electrical insulation. (6) Fully repaired seismometer vault, with new seismometer, cabling, SV BOB, and foam. (7) Repaired enclosure with new GPS BOB, and new solar panel and battery surge protector blocks. (8) New antennas with Omni antenna (white) relocated lower on mast. Air terminal installed on top of mast is connected to a new grounding system (buried).



## Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2011-4

**Departure Date:** 10/17/2011

**Return Date:** 10/21/2011

**Purpose:** Station maintenance and testing

**Work Summary:** Troubleshoot radio problems at PV02, PV05, PV11, and PV13. Perform annual maintenance. Replace defective components at PV03 and PV23.

**Action Items:**

1	Assess whether extensive damage to the analog equipment at PV02 is worth repairing
2	Plan field trip for November to further troubleshoot low sensitivity issue at PV02 and perform maintenance at other stations.
3	Complete the review and possible redesign of the grounding and lightning protection system, and plan to install any necessary equipment next April and May, before the next lightning season.
4	Schedule use of the USGS's Octans gyrocompass to orient all seismometers not already oriented
5	Upgrade server disk array at Hopkins Field.
6	Perform maintenance on analog equipment at PV11 if time permits

**Personnel:**

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

**Work by Site:**

	Site	Work Accomplished
4	PV02	Test new antennas and troubleshoot loss of sensitivity. Assess damage to analog equipment. Remove several trees blocking antenna.
5	PV03	Replace solar panel surge protector (second in 2 months).
6	PV05	Perform annual maintenance of system, and reprogram radio to associate with new PV02 radio.
7	PV11	Replace digital radio. Test and repair analog instrumentation.
8	PV13	Perform annual maintenance of system. Check antenna orientation. Reprogram radio to associate with new PV02 radio.
9	PV23	Replace DM24 BOB.

## Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2011-5

**Departure Date:** 11/16/2011

**Return Date:** 11/20/2011

**Purpose:** Station maintenance and testing

**Work Summary:** Troubleshoot digital radio sensitivity issues at PV02. Perform annual maintenance at hub sites. Replace defective components at PV14 and PV23. Test and adjust equipment at Hopkins Field

**Action Items:**

1	Assess whether extensive damage to the analog equipment at PV02 is worth repairing
2	Consider raising PV02 mast or removing more trees to improve reception.
3	Complete the review and possible redesign of the grounding and lightning protection system, and plan to install any necessary equipment next April and May, before the next lightning season.
4	Schedule use of the USGS's Octans gyrocompass to orient all seismometers not already oriented
5	Upgrade server disk array at Hopkins Field, and replace KVM.

**Personnel:**

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

**Work by Site:**

	Site	Work Accomplished
4	PV02	Troubleshoot loss of sensitivity due to reducing antenna height. Assess damage to analog equipment. Removed additional trees blocking antenna (RSSI improved about 6 dB).
5	PV04	Perform annual station maintenance.
7	PV11	Troubleshoot low-voltage disconnect issue on digital station. Test analog station.
	PV12	Perform annual station maintenance.
8	PV14	Replace DM24-BOB with unit rated for higher current
9	PV23	Replace DM24-BOB with unit rated for higher current
9	Hopkins Field	Test analog receivers and antenna splitters. Troubleshoot servers and KVM.