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Technical Memorandum No. 86-68330-2010-07

# 2009 Annual Report
# Paradox Valley Seismic Network
# Paradox Valley Project, Colorado

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

May 2010

**U.S. Department of the Interior**
**Mission Statement**

**The mission of the Department of the Interior is to protect and provide access to our Nations's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.**

**Bureau of Reclamation**
**Mission Statement**

**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*

**Lisa Block**

**U.S. Department of the Interior**
**Bureau of Reclamation**
**Technical Service Center**
**Denver, Colorado**

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**Seismotectonics and Geophysics Group**

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# 2009 Annual Report
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# Paradox Valley Project, Colorado

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# 1.0 INTRODUCTION

The Paradox Valley Seismic Network (PVSN) monitors earthquakes induced by injection operations at 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 2009. 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 2009 are presented, including discussions of maintenance and upgrades of seismic stations and data acquisition systems, network performance, and data management activities. The earthquake data recorded during 2009 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 brine is pumped from 9 extraction wells located within Paradox Valley near the Dolores River, which flows from southwest to northeast across the valley (**Figure 2-2**). 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 (t.d.) of 4.88 km (approximately 16,000 ft). The well was built to 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 rock at the surface through Precambrian rock at t.d. and has a minor drift to the east and slightly to the north. 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 Inconel 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 2-3**.

## 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 Environmental Protection Agency (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.

### *2.2.1 Phase I (July 22, 1996 - July 25, 1999)*

During this initial phase of continuous injection, PVU injected at a maximum flow rate of ~1290 l/min (~345 gpm), at ~33 MPa (~4,900+ psi ) surface pressure. This corresponds to ~80 MPa (~11,600 psi) downhole pressure at 4.3 km (14,080 ft) depth. To maintain this 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

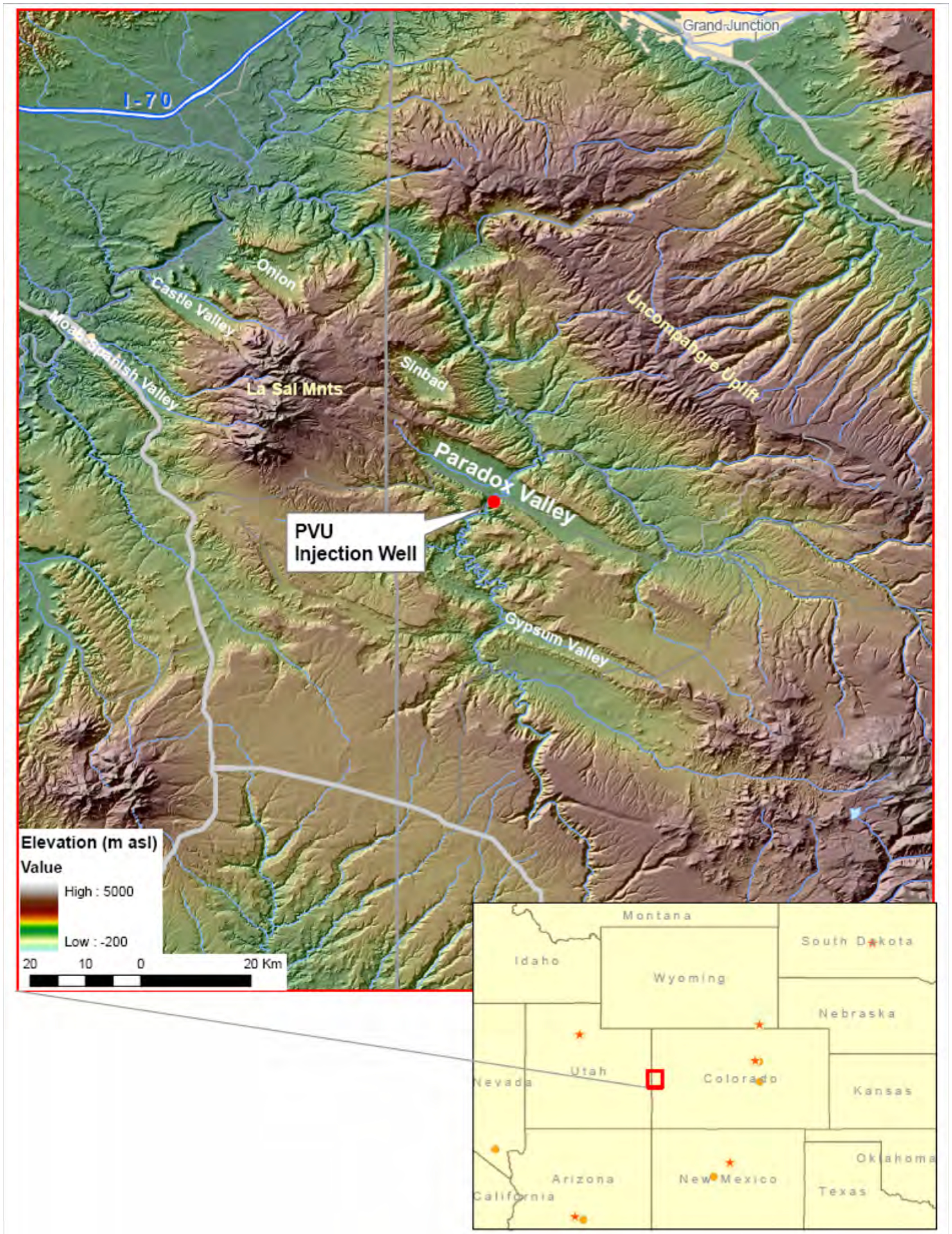


*Figure 2-1 Location of the deep injection well at Reclamation's Paradox Valley Unit in western Colorado.*

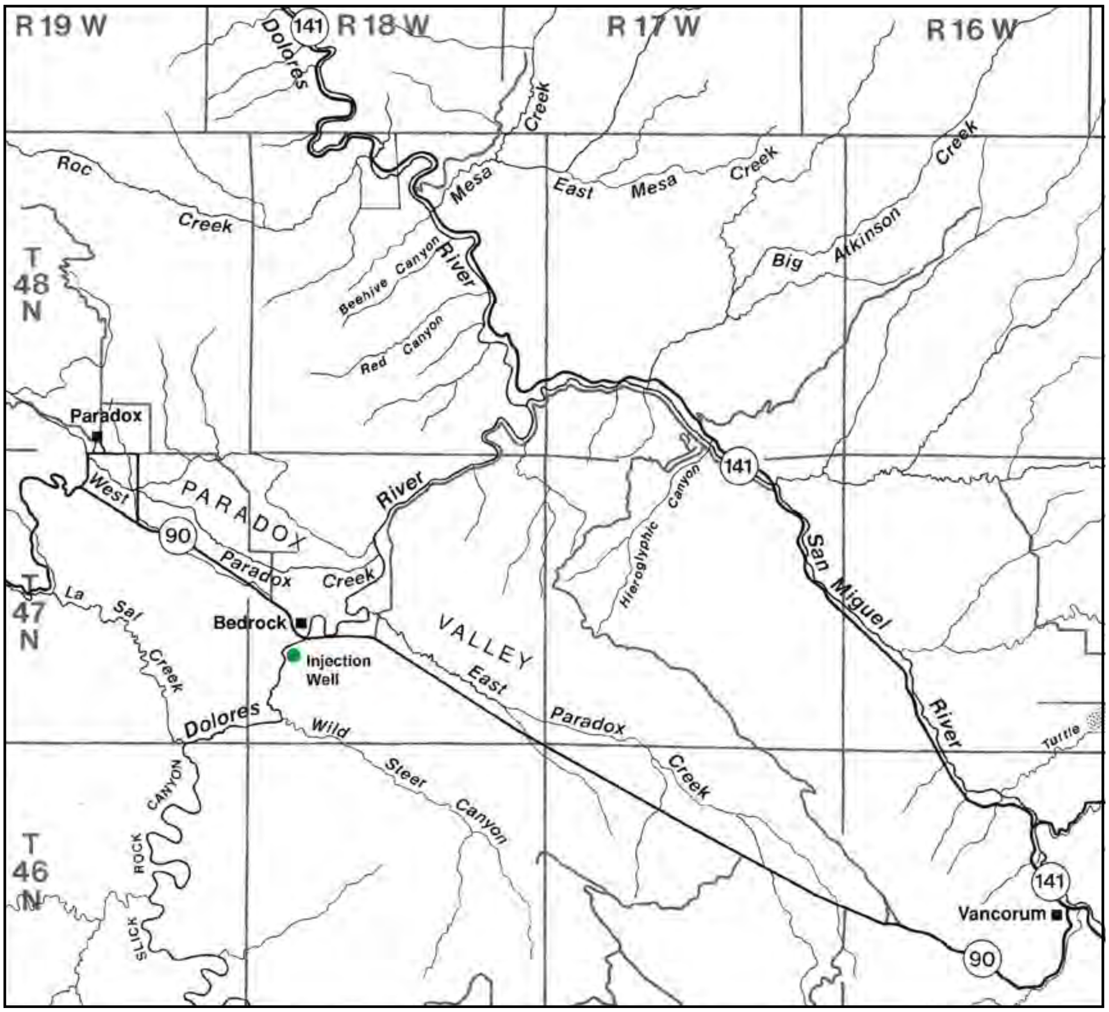


*Figure 2-2 Location of the Paradox Valley Unit injection well (green dot) and local geography. Figure is adapted from Parker (1992). Each square is approximately 10 km by 10 km.*

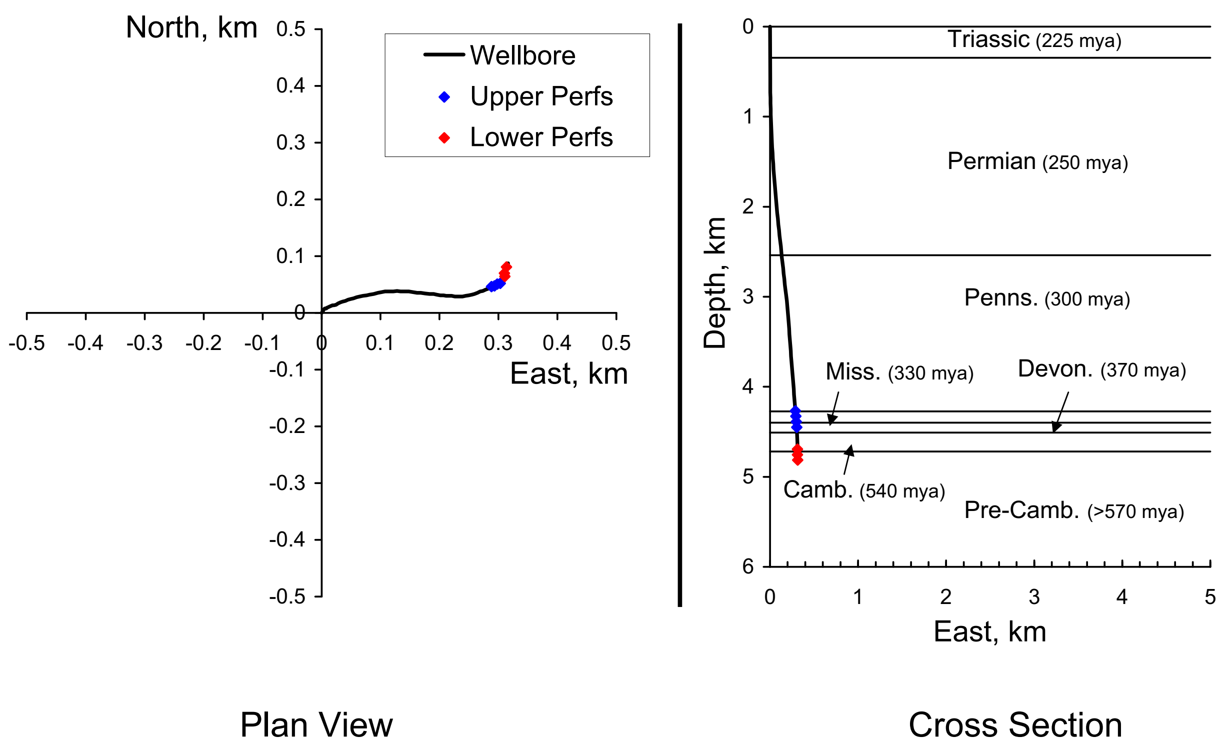


*Figure 2-3 PVU injection well in plan view (left) and north-viewing vertical cross section (right). Figures include the near-wellbore stratigraphy and locations of the upper and lower casing perforations.*

lasted for minutes, hours, or a few days. Maintenance shutdowns lasted for a few weeks up to a maximum of 71 days in mid-1997. The shutdowns resulted in an overall average injection rate for *phase I* of ~300 gpm. 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, we had 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 shut-downs 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 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 ~870 l/min (~230 gpm). 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 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 about 8 tons of calcium sulfate per day. To put this amount into perspective, injecting 100% PVB at 230 gpm gives a daily injection mass of approximately 1613 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* ( ~870 l/min; ~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%:30% mix. No discernible affect on the induced seismicity has been seen.

## 2.3 Seismic Monitoring

### *2.3.1 Paradox Valley Seismic Network*

During 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 two more were added in 1999 (PV16) and 2005 (PV17), bringing the total number of stations to its current compliment of 16. 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 is becoming increasingly difficult to maintain, with modern digital broad-band instrumentation. In November, 2005, a new digitally-telemetered station (PV17) was installed that employs a broad-band triaxial seismometer. Seven other existing stations have been converted from analog short-period to digital broad-band instrumentation since 2005: PV12 in November, 2005, PV04 in May, 2007, PV14 in June 2007, and PV02, PV03, PV10, and PV11 in October, 2008. As discussed in section 3.0, digital broad-band instrumentation was installed at five additional existing stations in 2009 (PV01, PV05, PV07, PV13, and PV16). These are expected to come online in May, 2010, bringing to 13 the number of digital stations.

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 2-4**. More detailed information about the stations is provided in **Table 2-1,** including installation date, station type, and number of components. **Table 2-2** lists descriptive information about the telemetered stations, including a legal descriptions of the station locations.

### *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.

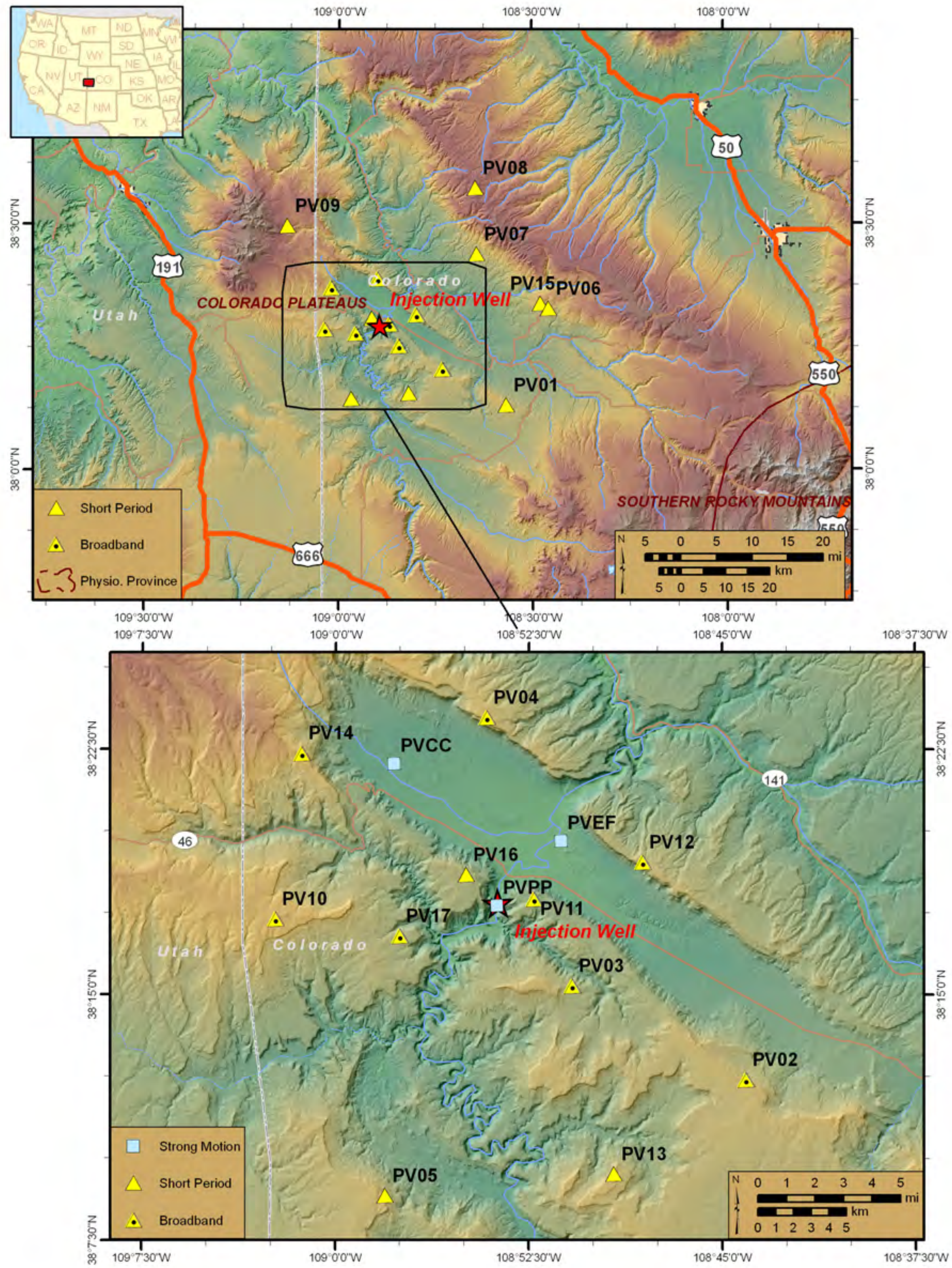


*Figure 2-4 Locations of the Paradox Valley Seismic Network stations and the Paradox Valley Unit injection well. PVCC, PVEF & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Physiographic provinces from Fenneman and Johnson (1946).*

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

| Station Name | Latitude deg., N | Longitude deg., W | Elev. m | Dates of Operation | Station Type | Sensor Direction |
|---|---|---|---|---|---|---|
| PV01 | 38.13 | 108.57 | 2191 | 5/83-present | short-period | vertical |
| PV02 | 38.21 | 108.74 | 2177 | 5/83-present<br>10/08-present | short-period<br>broad-band | vertical<br>triaxial |
| PV03 | 38.25 | 108.85 | 1972 | 5/83-present<br>10/08-present | short-period<br>broad-band | vertical<br>triaxial |
| PV04 | 38.39 | 108.90 | 2176 | 5/83-6/06<br>5/07-present | short-period<br>broad-band | vertical<br>triaxial |
| PV05 | 38.15 | 108.97 | 2142 | 5/83-present | short-period | vertical |
| PV06 | 38.33 | 108.46 | 2243 | 5/83-8/94 | short-period | vertical |
| PV07 | 38.44 | 108.64 | 2040 | 6/83-present | short-period | vertical |
| PV08 | 38.58 | 108.65 | 2950 | 6/83-9/89<br>9/89-10/03<br>10/07-present | short-period<br>short-period<br>short-period | triaxial<br>vertical<br>triaxial |
| PV09 | 38.50 | 109.13 | 2662 | 6/83-present | short-period | vertical |
| PV10 | 38.29 | 109.04 | 2266 | 6/83-present<br>10/08-present | short-period<br>broad-band | vertical<br>triaxial |
| PV11 | 38.30 | 108.87 | 1882 | 12/89-present<br>10/08-present | short-period<br>broad-band | triaxial<br>triaxial |
| PV12 | 38.32 | 108.80 | 2092 | 12/89-7/05<br>11/05-present | short-period<br>broad-band | vertical<br>triaxial |
| PV13 | 38.16 | 108.82 | 2158 | 12/89-present | short-period | vertical |
| PV14 | 38.37 | 109.02 | 2234 | 12/89-4/02<br>6/07-present | short-period<br>broad-band | vertical<br>triaxial |
| PV15 | 38.34 | 108.48 | 2234 | 6/95-present | short-period | vertical |
| PV16 | 38.31 | 108.92 | 2025 | 7/99-present | short-period | triaxial |
| PV17 | 38.28 | 108.96 | 1991 | 11/05-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: Table lists network configuration as of 12/31/2009. 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  Current PVSN Telemetered Sites - Legal Descriptions

| Station Desig. | Station Name | Legal Description |
|---|---|---|
| PV01 | The Burn | T45N R15W S19 C,NM |
| PV02 | Monogram Mesa | T46N R17W S27 C,NM |
| PV03 | Wild Steer | T46N R18W S10 C,NM |
| PV04 | Carpenter Flats | T48N R18W S30 C,NM |
| PV05 | E. Island Mesa | T45N R19W S16 C,NM |
| PV07 | Long Mesa | T48N R16W S9 C,NM |
| PV08 | Uncompahgre Butte | T50N R16W S22 C,NM |
| PV09 | North LaSalle | T26S R25E S35 U,SLC |
| PV10 | Wray Mesa | T47N R20W S35 C,NM |
| PV11 | Davis Mesa | T47N R18W S29 C,NM |
| PV12 | Saucer Basin | T47N R18W S24 C,NM |
| PV13 | Radium Mtn | T45N R18W S14 C,NM |
| PV14 | Lion Creek | T48N R20W S36 C,NM |
| PV15 | Pinto Mesa | T47N R15W S11 C,NM |
| PV16 | Nyswonger Mesa | T47N R19W S24 C,NM |
| PV17 | Wray Mesa East | T47N R19W S34 C,NM |

To date, PVSN has recorded over 4,600 induced earthquakes, generally those with magnitudes **M**0 or larger. The largest induced seismic event was a magnitude **M**4.3 earthquake, which occurred on May 27, 2000. The induced earthquakes locate in two spatially-separated seismic source zones: a primary zone asymmetrically surrounding the injection well to a maximum radial distance of approximately 3.5 km and a smaller secondary zone centered about 7.5 km northwest of the injection well. From the western boundary of the primary zone, the secondary zone lies along the direction of the local major fault trend, the Wray Mesa Fault system.

# 3.0 PVSN OPERATIONS IN 2009

## 3.1 Network Maintenance and Upgrades

### *3.1.1 Seismic Stations*

During 2009, new broad-band digital seismic stations were installed at five existing sites: PV01, PV05, PV07, PV13, and PV16. In April, 2009, new infrastructure was installed at these sites, including seismometer vaults, conduit, and antenna tower bases. The following October, all remaining equipment was installed and tested, with the exception of the digital seismometers. Equipment installed in October included antenna masts, solar panels, antennas, cabling, station enclosures, batteries, and radios. Unfortunately, the digital seismometers needed to bring these five new digital stations online were not delivered by the vendor until January, 2010, approximately four months late. The seismometers will be installed and these stations brought online as soon as weather conditions permit - likely May, 2010.

Upgrades were also performed at four existing broad-band digital stations: PV04, PV12, PV14, and PV17. These were the first four digital stations installed in the Paradox Valley Seismic Network, and some of the equipment at these sites did not conform to the current design specifications. The upgrades were performed in April and September, 2009, and included installing new seismometer vaults, conduit, station enclosures, solar panels, cabling, lightning protection, and electronics. These station upgrades were required to make the stations compatible with the upgraded digital radio communications system discussed below.

Because of the significant effort to replace the remaining obsolete analog stations with digital ones as soon as possible, minimal resources were devoted in 2009 to their routine maintenance. Instead, maintenance efforts were focused on the digital stations, including replacing malfunctioning digital seismometers at stations PV10 and PV12, and replacing a malfunctioning GPS clock at station PV17. Limited maintenance was done at analog stations PV02, PV11, and PV15, and at Hopkins Field to address communication problems.

Reconnaissance of potential new sites for digital seismograph stations to replace analog stations PV08 and PV09 (because the current locations of these stations are not optimal), as well as for a few additional stations to improve monitoring coverage of some critical areas, was performed during several trips in the fall of 2009. Several sites were found that satisfy the necessary criteria (network geometry, spatial relation to seismicity, bedrock outcrop, access, solar exposure, radio coverage, and public land ownership). Locations for potential sites were initially determined using GIS overlays of existing stations, earthquake epicenters, geologic units, radio coverage, aerial photographs, and roads. Final selection was made by visiting the areas identified using GIS methods and then selecting the sites that best met the criteria. Final sites were then staked, photographed, documented, and GPS coordinates and access tracks were determined. The process for acquiring permits from the Bureau of Land Management and the U.S. Forest Service for installation of these stations on public land was begun in early 2010. These permits are needed before the final round of digital station upgrades can be performed. This final round of upgrades will include upgrading analog station PV15 at it's current location, updating PV08 and PV09 at new locations, and installing between 3 and 5 additional stations to improve coverage of earthquakes occurring in the primary and secondary zones of induced seismicity and those occurring near the northern end of Paradox Valley.

#### *3.1.2 Digital Radio Communication System*

The digital radio communication system, which carries seismic signals from the digital stations to the server at Hopkins Field in Nucla, underwent a major upgrade in 2009. This change was necessary in order for the system to be able to accomodate the five new digital stations installed in 2009, as well as those planned for 2010. In addition, the upgraded system eliminates the occasional data drop-outs that had been observed for the digital seismic stations and allows for redundant telemetry paths to make the radio communications more robust. The upgrade included performing work at Hopkins Field and at every existing digital seismic station. Because of the extensive work required at multiple sites, the eight existing digital seismic stations had to be taken offline for approximately one week in September in order to complete the first phase of the upgrade. Additional trips were required in October and November to replace malfunctioning components and optimize radio and antenna operation. All digital seismic stations remained online during these subsequent trips, with the exception of station PV04. Because of an electronics design flaw, digital station PV04 was offline from the time of the initial radio upgrade in mid-September until new electronics were installed in mid-November.

#### *3.1.3 Data Acquisition System*

In order to improve reliability of the data acquisition computer systems, the data acquisition software, *Earthworm*, was migrated from an obsolete unix-based computer system (located in the offices of the Bureau of Reclamation in Denver) to a new Linux-based system. The latest Reclamation version of *Earthworm*, which dates from 2001, was ported and compiled for a current version of Linux in mid-2009. After several months of testing and running in parallel with the old version, the new version of *Earthworm* was brought into production use on an updated Linux-based computer system in January, 2010. At the same time, a redundant data acquisition server was installed at Hopkins Field in Nucla, and the Linux version of *Earthworm* was brought into production. The incoming seismic data streams are therefore processed on two parallel data acquisition systems - at Reclamation’s office in Denver and at Hopkins Field. This improves the reliability of the seismic monitoring network by allowing data acquisition to continue without loss of data even if the wide-area network (WAN) link between Denver and Hopkins Field goes down, or if some problem occurs with computer systems in Denver, such as a prolonged power failure.

Another improvement in the reliability of PVSN’s data acquisition was the installation of an environmental monitor in the Hopkins Field server room. This monitoring system provides continuous remote monitoring of temperature, humidity, and air flow, and also sends email and pager alerts if conditions exceed designated thresholds. The main air conditioning system at Hopkins Field was also replaced in 2009, and a back-up air-conditioning system was installed. The old air conditioning system had been unreliable for cooling the data acquisition system, and it completely failed during July, 2009.

### 3.2 Network Performance

PVSN performed very well during most of 2009. We’ve characterized the annual network performance by two aspects: performance of individual seismic stations (i.e., how well individual stations functioned throughout the year) and performance of network data acquisition (i.e., the continuity of data acquisition and recording).

**Figure 3-1** indicates the performance of the individual seismic stations during 2009. Each horizontal line across the plot represents one seismic data channel, as indicated on the left-hand side of the plot. Each data channel name consists of the station name (e.g., PV01), the component identifier (V = vertical; E - east-west; N = north-south), and a label indicating whether it is an analog (a) or digital (d) station. Thick blue lines in **Figure 3-1** indicate that the data channel was installed and functioning normally. Thin red lines in **Figure 3-1** 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. (Note that the chart in **Figure 3-1** only indicates whether the individual seismic data channels were functioning properly and not whether they were being recorded by the acquisition system.) The reasons for problems with individual station performance are variable. Details of the performance of the digital seismic stations are given in **Table 3-1**, while the performance of the analog stations is summarized in **Table 3-2**. The majority of the station performance issues did not significantly degrade the performance of the seismic network. The only time period when performance of individual seismic stations likely affected PVSN's event detection capabilities was the week in September when the eight digital stations were intentionally taken offline for the digital radio communication system upgrade. Because data were not being acquired at two of the station sites close to the injection well (digital stations PV11 and PV17 were offline; analog station PV11 was experiencing problems), PVSN's ability to detect very small events (**M** < about 0.5) was likely affected.

The performance of PVSN data acquisition during 2009 is represented by the graph shown in **Figure 3-2**. 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, including the servers located at Hopkins Field in Nucla, the dedicated telephone line from Nucla to Denver, and the data acquisition and recording system in Denver were all operating properly. Hence, during these times, all seismic events above the detection threshold were being identified and the corresponding seismic data streams were being saved for analysis. 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. (Because this graph represents daily values, periodic shut-downs for routine equipment maintenance lasting less than two hours are ignored in this performance rating.) During 2009, PVSN data acquisition was completely shut down for two time periods. The first shut-down lasted about 4 days, from April 12 to 15. The shut-down was caused by a LAN switch failure that occurred over a weekend. The second network shut-down lasted approximately 2 1/2 days over the Labor Day weekend (Sept. 5-8). It was caused by a lightning strike which struck a utility pole at Hopkins Field in Nucla and caused a power failure. Accounting for the periods when the network was offline, PVSN acquired approximately 358.5 days' worth of seismic data, out of a 365-day calendar year, which is equivalent to 98.2% uptime. PVSN uptime for 2009 is compared to that for previous years in **Table 3-3**.

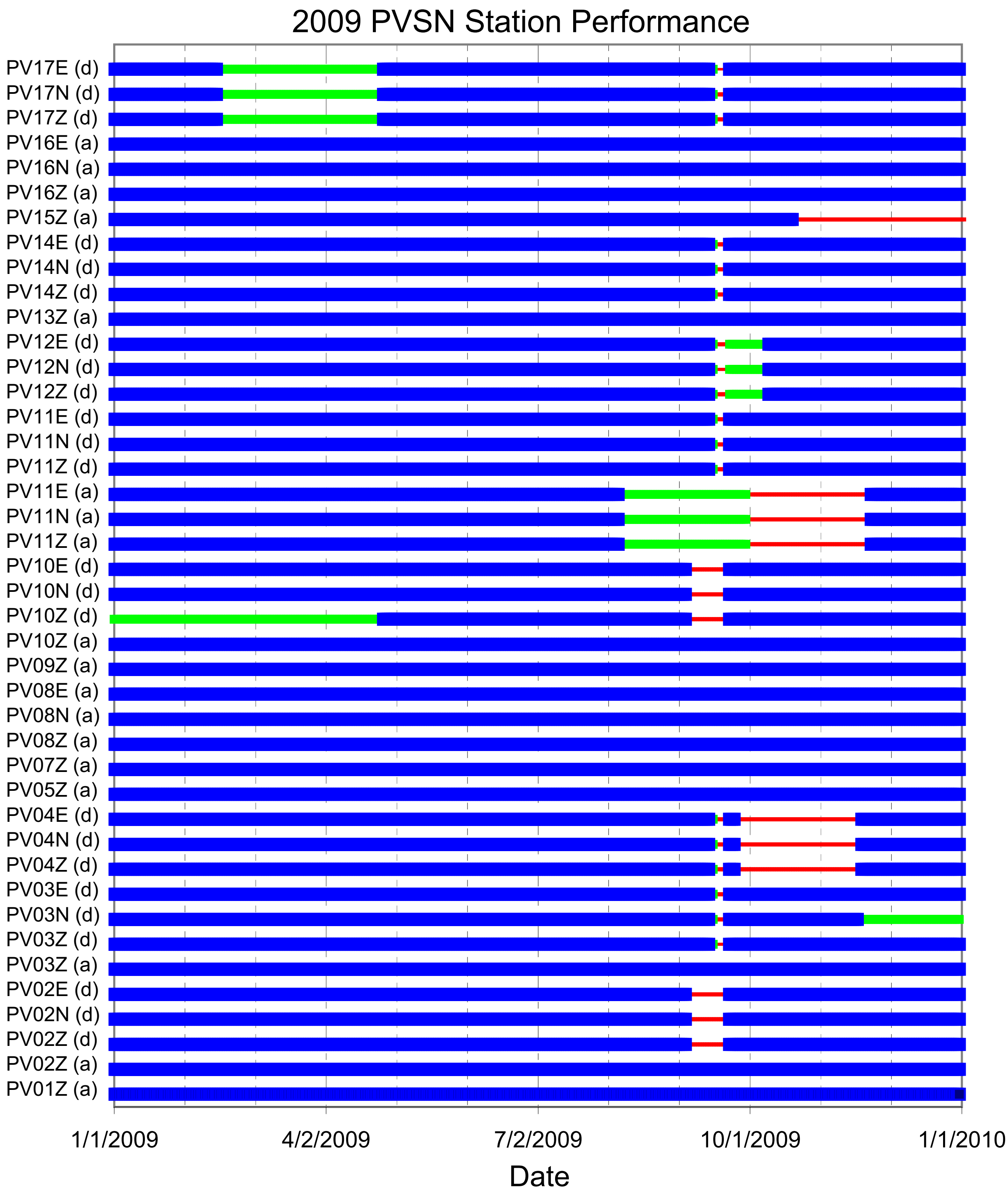


*Figure 3-1 Performance of PVSN seismic data channels during 2009. The letter in parentheses indicates whether the data channel is analog (a) or digital (d). Thick blue lines indicate that the channel was installed and functioning well. Thin red lines indicate that the channel was offline. Intermediate-thickness green lines indicate that the channel was online but experiencing some type of problem; see text for explanations.*

**Table 3-1 Performance of digital seismic stations during 2009**

| Station | Performance |
|---|---|
| PV02 | Taken offline by lightning strike at Hopkins Field on Sept. 5; brought back online on Sept. 23 after digital radio upgrade (vertical-component analog station PV02 continued to provide data) |
| PV03 | Intentionally offline intermittently on Sept. 15-16 and completely offline on Sept. 17-22 for digital radio upgrade (vertical-component analog station PV03 continued to provide data); North component began failing in mid-November, but East component still provides useable S-wave arrival times |
| PV04 | Intentionally offline intermittently on Sept. 15-16 and completely offline on Sept. 17-22 for digital radio upgrade; electronics failure took station offline on Sept. 26; new electronics installed and station brought back online on Nov. 19 (no analog station at this site) |
| PV10 | Noisy vertical component Jan. 1- Apr. 26; new seismometer installed on Apr. 27; Taken offline by lightning strike at Hopkins Field on Sept. 5; brought back online on Sept. 23 after digital radio upgrade (vertical-component analog station PV10 continued to provide data) |
| PV11 | Intentionally offline intermittently on Sept. 15-16 and completely offline on Sept. 17-22 for digital radio upgrade (vertical-component analog station PV11 was experiencing problems and did not consistently provide data during this week.) |
| PV12 | Intentionally offline intermittently on Sept. 15-16 and completely offline on Sept. 17-22 for digital radio upgrade; data recorded from Sept. 23 to Oct. 9 contain a significant level of electrical noise due to problems with new circuit boards, but station still provided useable arrival times; circuit boards replaced Oct. 10 (no analog station at this site) |
| PV14 | Intentionally offline intermittently on Sept. 15-16 and completely offline on Sept. 17-22 for digital radio upgrade (no analog station at this site) |
| PV17 | Bad GPS clock Feb. 15 - Apr. 26 - no absolute arrival times but S-P times useable; intentionally offline intermittently on Sept. 15-16 and completely offline on Sept. 17-22 for digital radio upgrade (no analog station at this site) |

**Table 3-2 Performance of analog seismic stations during 2009**

| Station | Performance |
|---|---|
| PV01 | online and functioning normally throughout 2009 |
| PV02 | online and functioning normally throughout 2009 |
| PV03 | online and functioning normally throughout 2009 |
| PV05 | online and functioning normally throughout 2009 |
| PV07 | online and functioning normally throughout 2009 |
| PV08 | online and functioning normally throughout 2009 |
| PV09 | online and functioning normally throughout 2009 |
| PV10 | online and functioning normally throughout 2009 |
| PV11 | Intermittently offline early Aug. - Sept.; completely offline Oct. - mid-Nov; station repaired and functioning normally since mid-Nov. |
| PV13 | online and functioning normally throughout 2009 |
| PV15 | Mostly offline from mid-Oct. to the end of the year, due to deterioration of old analog equipment |
| PV16 | online and functioning normally throughout 2009 |

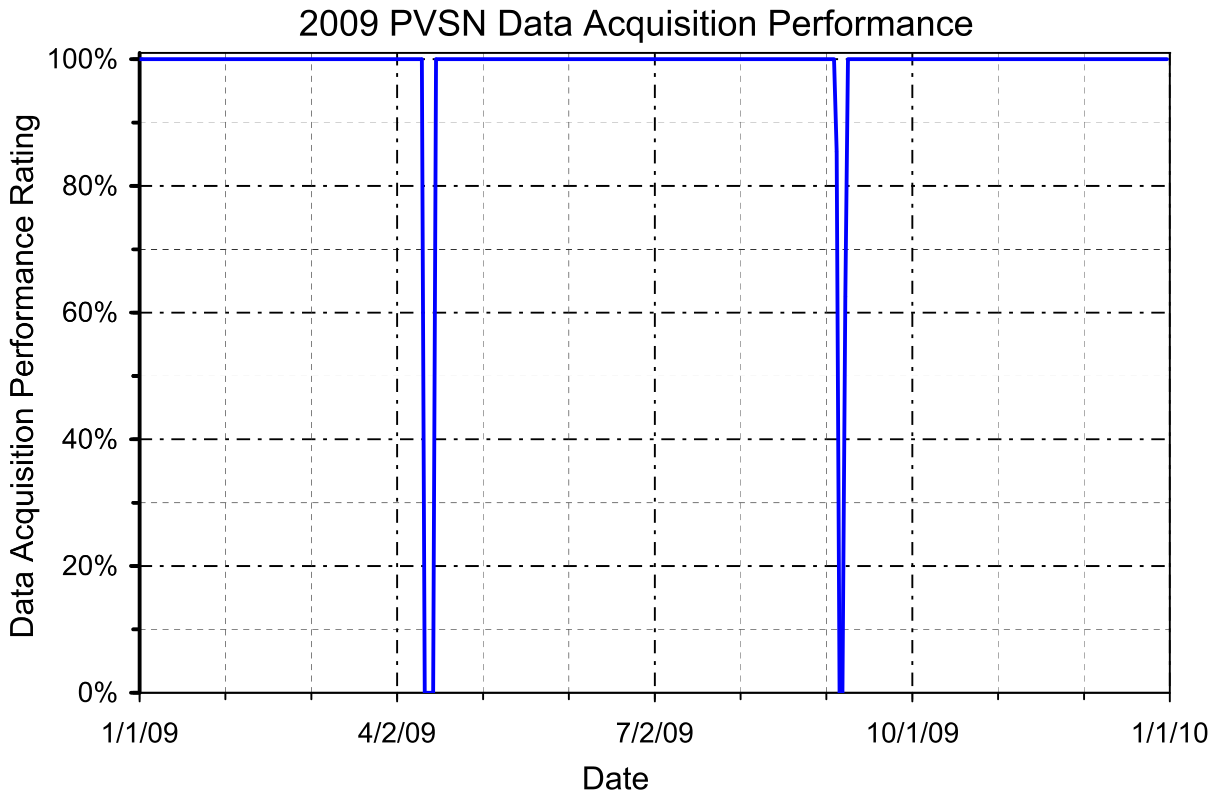


*Figure 3-2  Performance of PVSN data acquisition during 2009.  A rating of 100% indicates that PVSN was continuously triggering on seismic events above the detection threshold and properly recording the seismic datafiles. A rating of 0% indicates that some part of the data acquisition, transmission, or recording system was down and no data were recorded.  See text for further explanations.*

### 3.3  Review of Historic Seismic Data Files

A comprehensive review and re-organization of PVSN's historic seismic data files was begun in the summer of 2008 and largely completed in 2009.  (A few remaining tasks were completed in early 2010.)  The goal was to create a data repository that is as complete and internally consistent as possible and to reverse an accumulation of small errors that had occurred over twenty-five years of data acquisition.

During the first phase of review, all available PVSN data files were characterized and entered into a database, including data restored from over 100 computer backup tapes. Database utilities were created to associate the approximately 190,000 PVSN data files into about 39,000 unique events, and to identify data files having management discrepancies such as incorrect timing, inconsistent naming, or incomplete analysis. Automatic processing utilities were developed to correct these discrepancies. The U.S. Geological Survey seismic data files (acquired prior to 1990, when data acquisition was moved from the USGS to the Bureau of Reclamation) were converted to the current format. Timing problems were corrected on approximately 300 Reclamation-recorded events. Component picks (picks on individual traces from 3-component stations) were merged

**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 % |
| **not tabulated in 2001 | | |

into station picks (single P-wave and S-wave pick for each 3-component station) on over 9,000 events recorded prior to 2000, to be consistent with current analysis software. Over 7,000 unprocessed events were identified and automatically processed. Many of these previously-unprocessed events were noise events that apparently had been only partially deleted from the system during initial processing. However, unprocessed regional, teleseismic, and local events were also found, including 104 induced events (one of which was an **M** 2.6 event from March, 1998).

During the second phase of review, manual re-classification of all PVSN data files was performed, including both events that had been processed previously and unprocessed events restored from backup tapes. The classification of each event was checked and changed if needed, both in terms of whether it was designated as a teleseismic, regional, or local event and whether local events were properly identified as earthquakes or explosions. Manual picking and locating of previously-unprocessed local events was performed, as well as any previously-processed local events that had obvious picking or location errors. (Manual picking and locating of previously-unprocessed regional and teleseismic events was not performed because it was considered both impractical with the available resources and having relatively little benefit.) When the manual processing of all PVSN data files was complete, maps were created and any questionable individual events were then double-checked. Special consideration was given to whether local events were classified as earthquakes or explosions, with such classification being independently checked by two seismologists.

During the third and final phase of review, additional timing problems were corrected on over 2,000 events, additional unprocessed events were identified and processed, remaining explosions that had been mischaracterized as earthquakes were identified and reclassified, events without supporting waveform data were identified and removed from the main catalog, all event files were renamed using a consistent naming convention, event IDs were assigned, and a final catalog was produced.

The final revised PVSN catalog shows that there were far fewer earthquakes occurring in the Paradox Valley region than the original dataset had indicated (**Figure 3-3**). This difference is largely the result of correctly identifying explosions, which had originally been designated as earthquakes. Also, several regional and teleseismic events, occurring far outside the boundaries of PVSN, were originally incorrectly classified as local earthquakes and given bogus locations in the Paradox Valley region. (Many of these were likely classified and located by the auto-picker and never manually processed.) These have been re-classified and removed from the database of local earthquakes. The revised and much more accurate database of the earthquakes that have occurred in the Paradox Valley region in the years before and during PVU injection operations will enable better analysis of the induced and naturally-occurring seismicity.

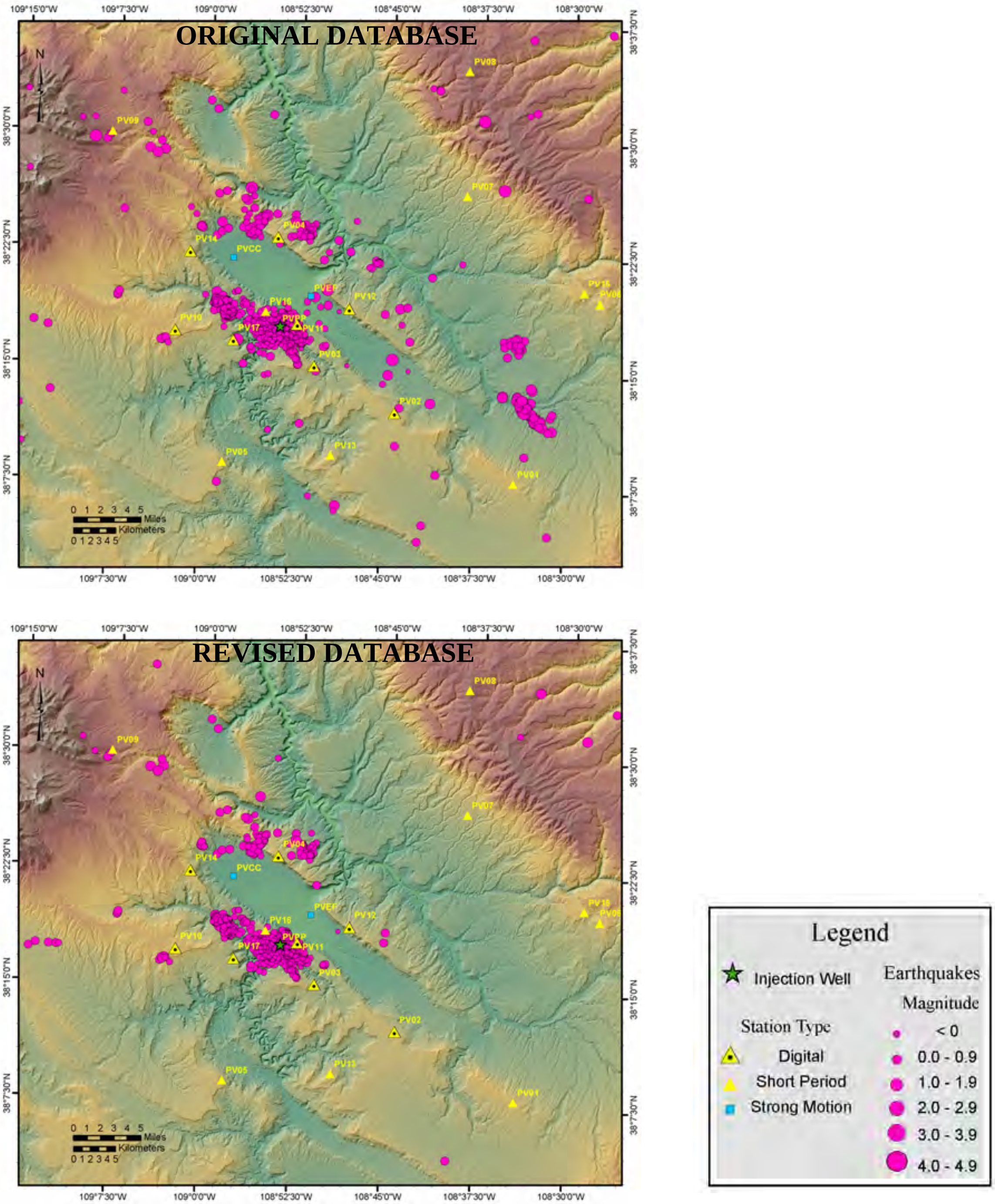


*Figure 3-3 Comparison of local earthquakes in the original PVSN database (top) and in the final revised PVSN database (bottom).*

# 4.0 SEISMIC DATA RECORDED IN 2009

## 4.1 Annual Summary

123 earthquakes were recorded within the perimeter of PVSN during 2009. The dates and times of occurrence, latitudes, longitudes, elevations, depths (referenced to the ground surface elevation at the injection well), and computed duration magnitudes of these events are listed in **Table 4-1**. The beginning and ending dates of the 20-day shut-ins of the injection well are also indicated in the table. The last column in **Table 4-1** indicates the general geographical area in which the earthquakes occurred, defined by four location categories: “near-well” - event occurred in the primary zone of induced seismicity immediately surrounding the injection well; “NW cluster” - event occurred in the secondary zone of induced seismicity that is centered approximately 7.5 km northwest of the injection well; “northern valley” - event is located in or near areas of recurring seismicity at the northern end of Paradox Valley (several events have been recorded in this region by PVSN every year since 2000); and “other” - local seismic event, currently interpreted as a naturally-occurring earthquake, not associated with any of the other three categories listed above. The numbers and magnitudes of the events recorded by PVSN during 2009 for each of these four location categories are summarized in **Table 4-2**, and the average daily seismicity rates for each event location category are listed in **Table 4-3**. The earthquake locations are plotted on the map in **Figure 4-1.**

**Table 4-1 Local earthquakes recorded by PVSN during 2009. The four earthquakes outlined in bold are large-magnitude events that triggered PVSN strong motion instruments. The color-shaded events are foreshocks and aftershocks associated with each main event.**

| Date | Time[1] | Latitude (deg.) | Longitude (deg.) | Elevation[2] (km) | Depth[3] (km) | Duration Magnitude | Location Category[4] |
|---|---|---|---|---|---|---|---|
| Injection resumed on January 7 (pressure: 1246 psi). | | | | | | | |
| 1/8/2009 | 13:49:04 | 38.2914 | -108.9265 | -1.2 | 2.8 | 1.2 | near-well |
| 1/11/2009 | 22:12:51 | 38.2843 | -108.9078 | -1.8 | 3.3 | 1.8 | near-well |
| 1/11/2009 | 22:15:00 | 38.2844 | -108.9076 | -1.8 | 3.3 | 0.5 | near-well |
| 1/15/2009 | 12:38:43 | 38.3187 | -108.9778 | -2.6 | 4.1 | 1.5 | NW cluster |
| 2/4/2009 | 14:54:59 | 38.3075 | -108.8851 | -3.1 | 4.6 | 0.7 | near-well |
| 2/14/2009 | 10:07:21 | 38.2974 | -108.9287 | -2.6 | 4.1 | 1.5 | near-well |
| 2/14/2009 | 10:08:00 | 38.2974 | -108.929 | -2.6 | 4.1 | 1.5 | near-well |
| 2/14/2009 | 10:25:16 | 38.2974 | -108.9286 | -2.6 | 4.1 | 0.7 | near-well |
| 2/14/2009 | 10:25:29 | 38.2974 | -108.9283 | -2.5 | 4.1 | 1.2 | near-well |
| 2/16/2009 | 15:57:45 | 38.2819 | -108.9081 | -1.6 | 3.1 | 1.3 | near-well |
| 2/21/2009 | 18:25:58 | 38.3217 | -108.9825 | -2.8 | 4.3 | 1.3 | NW cluster |
| 2/21/2009 | 18:28:33 | 38.3215 | -108.9824 | -2.7 | 4.3 | 1.1 | NW cluster |
| 2/21/2009 | 21:00:47 | 38.3216 | -108.9823 | -2.7 | 4.3 | 0.6 | NW cluster |
| 2/21/2009 | 23:29:30 | 38.3213 | -108.9809 | -3 | 4.5 | 2.6 | NW cluster |
| 3/16/2009 | 20:27:51 | 38.2738 | -108.8751 | -1.4 | 2.9 | 0.6 | near-well |
| 3/16/2009 | 20:28:13 | 38.274 | -108.8667 | -1.2 | 2.8 | -0.1 | near-well |
| 3/22/2009 | 4:18:11 | 38.2818 | -108.898 | -1.6 | 3.1 | 0 | near-well |
| 3/22/2009 | 5:26:25 | 38.2842 | -108.897 | -2 | 3.5 | 0.4 | near-well |
| 3/22/2009 | 9:26:24 | 38.2838 | -108.897 | -2 | 3.5 | 0.4 | near-well |
| 3/29/2009 | 5:43:44 | 38.2819 | -108.9081 | -1.7 | 3.2 | 1.4 | near-well |
| Injection well was shut in on April 1 (pressure: 4753 psi) | | | | | | | |
| 4/6/2009 | 6:17:34 | 38.3193 | -108.9838 | -2.7 | 4.2 | 1.6 | NW cluster |

**Table 4-1 Local earthquakes recorded by PVSN during 2009. The four earthquakes outlined in bold are large-magnitude events that triggered PVSN strong motion instruments. The color-shaded events are foreshocks and aftershocks associated with each main event.**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 4/6/2009 | 6:18:03 | 38.318 | -108.9895 | -1.1 | 2.6 | -0.9 | NW cluster |
| 4/6/2009 | 11:54:32 | 38.3191 | -108.9844 | -2.7 | 4.2 | 1.4 | NW cluster |
| 4/18/2009 | 7:31:17 | 38.3071 | -108.8895 | -3 | 4.5 | 2.1 | near-well |
| 4/18/2009 | 7:34:54 | 38.3077 | -108.8905 | -3 | 4.5 | 0.2 | near-well |
| 4/18/2009 | 23:58:04 | 38.3077 | -108.8906 | -3 | 4.5 | -0.8 | near-well |
| 4/18/2009 | 23:58:07 | 38.308 | -108.889 | -2.7 | 4.3 | 2.8 | near-well |
| 4/19/2009 | 0:15:30 | 38.3097 | -108.8912 | -3.8 | 5.3 | -0.1 | near-well |
| 4/19/2009 | 10:05:45 | 38.3073 | -108.8876 | -3 | 4.6 | 1.6 | near-well |
| 4/19/2009 | 13:34:52 | 38.2845 | -108.9077 | -1.7 | 3.2 | 2.7 | near-well |
| 4/19/2009 | 13:51:35 | 38.2845 | -108.9076 | -1.8 | 3.3 | 1 | near-well |
| 4/19/2009 | 13:54:30 | 38.285 | -108.9068 | -1.7 | 3.3 | 0.6 | near-well |
| 4/19/2009 | 16:13:45 | 38.2849 | -108.9069 | -1.8 | 3.3 | 1.4 | near-well |
| 4/19/2009 | 17:19:41 | 38.2841 | -108.9089 | -1.6 | 3.1 | 1.1 | near-well |
| 4/19/2009 | 17:22:07 | 38.2807 | -108.919 | -0.6 | 2.2 | -0.8 | near-well |
| 4/19/2009 | 17:22:16 | 38.2842 | -108.9087 | -1.6 | 3.1 | -0.8 | near-well |
| 4/19/2009 | 19:12:03 | 38.2841 | -108.909 | -1.6 | 3.1 | 0.8 | near-well |
| 4/20/2009 | 11:24:32 | 38.2824 | -108.9054 | -1.6 | 3.2 | 0.5 | near-well |
| 4/20/2009 | 11:24:42 | 38.2827 | -108.9085 | -1.7 | 3.2 | -0.6 | near-well |
| 4/21/2009 | 1:30:03 | 38.2836 | -108.9085 | -1.5 | 3 | -0.2 | near-well |
| 4/21/2009 | 5:15:08 | 38.3077 | -108.8851 | -3.2 | 4.7 | 2 | near-well |
| 4/21/2009 | 5:15:41 | 38.3077 | -108.8869 | -3.2 | 4.8 | -0.2 | near-well |
| 4/21/2009 | 13:40:21 | 38.2844 | -108.9076 | -1.8 | 3.3 | 0.9 | near-well |
| 4/22/2009 | 11:49:57 | 38.2843 | -108.9081 | -1.8 | 3.3 | 1 | near-well |
| Injection resumed on April 23 (pressure: 1157 psi). | | | | | | | |
| 4/27/2009 | 23:45:05 | 38.2843 | -108.9081 | -1.8 | 3.3 | 1.5 | near-well |
| 4/30/2009 | 8:50:34 | 38.2841 | -108.9082 | -1.8 | 3.3 | 2.7 | near-well |
| 4/30/2009 | 8:54:43 | 38.2841 | -108.9087 | -1.7 | 3.2 | 1.5 | near-well |
| 4/30/2009 | 9:09:39 | 38.2839 | -108.9091 | -1.6 | 3.1 | 0.5 | near-well |
| 4/30/2009 | 10:08:07 | 38.2839 | -108.9091 | -1.7 | 3.2 | 1.6 | near-well |
| 4/30/2009 | 10:27:16 | 38.2841 | -108.909 | -1.6 | 3.1 | 0.5 | near-well |
| 4/30/2009 | 10:27:40 | 38.2828 | -108.9097 | -1.1 | 2.6 | -0.8 | near-well |
| 4/30/2009 | 21:46:44 | 38.2841 | -108.9092 | -1.6 | 3.1 | 0.7 | near-well |
| 5/2/2009 | 13:12:41 | 38.2818 | -108.9083 | -1.7 | 3.2 | 1.4 | near-well |
| 5/4/2009 | 19:25:57 | 38.2841 | -108.9086 | -1.6 | 3.1 | 1.1 | near-well |
| 5/9/2009 | 6:51:29 | 38.3128 | -108.7517 | -7.1 | 8.6 | 1.4 | other |
| 5/21/2009 | 13:14:15 | 38.2982 | -108.9297 | -2.3 | 3.8 | 0.4 | near-well |
| 5/27/2009 | 22:05:24 | 38.4068 | -108.9213 | -4 | 5.5 | -0.1 | northern valley |
| 6/1/2009 | 9:49:59 | 38.2845 | -108.9073 | -1.8 | 3.3 | 1.5 | near-well |
| 6/5/2009 | 18:50:36 | 38.2817 | -108.9086 | -1.6 | 3.2 | -0.1 | near-well |
| 6/24/2009 | 1:26:47 | 38.2819 | -108.9084 | -1.7 | 3.2 | 1.4 | near-well |
| 6/27/2009 | 15:16:41 | 38.2961 | -108.9169 | -2.6 | 4.1 | 0 | near-well |
| 6/28/2009 | 14:53:55 | 38.3083 | -108.9583 | -2.3 | 3.8 | 0 | NW cluster |
| 7/6/2009 | 6:07:34 | 38.2838 | -108.9095 | -1.6 | 3.2 | 2.1 | near-well |
| 7/7/2009 | 16:40:30 | 38.2814 | -108.9082 | -1.5 | 3 | -0.2 | near-well |
| 7/12/2009 | 10:37:33 | 38.2818 | -108.9084 | -1.7 | 3.2 | 1.8 | near-well |
| 7/12/2009 | 18:29:30 | 38.2846 | -108.9072 | -1.8 | 3.3 | 1.9 | near-well |
| 7/16/2009 | 16:46:17 | 38.2846 | -108.907 | -1.8 | 3.3 | 0.8 | near-well |
| 7/18/2009 | 8:21:38 | 38.2839 | -108.9098 | -1.6 | 3.1 | 0 | near-well |
| 8/9/2009 | 21:38:32 | 38.2837 | -108.8935 | -1.6 | 3.1 | 1.3 | near-well |
| 8/11/2009 | 12:53:04 | 38.297 | -108.8953 | -2.6 | 4.1 | 0.9 | near-well |

**Table 4-1 Local earthquakes recorded by PVSN during 2009. The four earthquakes outlined in bold are large-magnitude events that triggered PVSN strong motion instruments. The color-shaded events are foreshocks and aftershocks associated with each main event.**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8/11/2009 | 16:08:27 | 38.2968 | -108.896 | -2.5 | 4.1 | 0.1 | near-well |
| 8/11/2009 | 20:16:25 | 38.2968 | -108.8946 | -2.5 | 4.1 | 1.6 | near-well |
| 8/12/2009 | 16:22:10 | 38.2969 | -108.8955 | -2.5 | 4.1 | 1.2 | near-well |
| 8/13/2009 | 7:23:19 | 38.2909 | -108.9146 | -2.5 | 4 | 1 | near-well |
| 8/13/2009 | 8:24:11 | 38.2912 | -108.9137 | -2.5 | 4 | 2.1 | near-well |
| 8/14/2009 | 11:03:02 | 38.2913 | -108.9128 | -2.5 | 4 | 0.5 | near-well |
| 8/15/2009 | 0:27:45 | 38.2914 | -108.9126 | -2.5 | 4.1 | 1.4 | near-well |
| 8/15/2009 | 3:06:24 | 38.2913 | -108.9127 | -2.5 | 4 | 1 | near-well |
| 8/15/2009 | 9:38:24 | 38.2912 | -108.9132 | -2.5 | 4.1 | 1.4 | near-well |
| 8/26/2009 | 4:39:43 | 38.2819 | -108.9057 | -1.6 | 3.1 | 0.6 | near-well |
| 8/29/2009 | 7:58:15 | 38.2817 | -108.8637 | -2.1 | 3.6 | 1.2 | near-well |
| 8/29/2009 | 7:58:58 | 38.2814 | -108.8639 | -1.9 | 3.4 | 0.2 | near-well |
| 9/1/2009 | 11:24:24 | 38.2969 | -108.8957 | -2.6 | 4.2 | 2 | near-well |
| 9/1/2009 | 11:41:38 | 38.2968 | -108.8953 | -2.6 | 4.1 | 0.7 | near-well |
| 9/16/2009 | 7:46:58 | 38.3189 | -108.9707 | -2.6 | 4.1 | 0.9 | NW cluster |
| 9/20/2009 | 22:43:42 | 38.2967 | -108.8943 | -2.6 | 4.2 | 1 | near-well |
| 9/26/2009 | 7:40:27 | 38.2967 | -108.8931 | -2.6 | 4.1 | 0.7 | near-well |
| 9/27/2009 | 17:11:41 | 38.2972 | -108.8931 | -2.6 | 4.1 | 0.3 | near-well |
| 9/27/2009 | 22:35:19 | 38.2968 | -108.8959 | -2.5 | 4.1 | 1.3 | near-well |
| Injection well was shut in on September 29 (pressure: 4884 psi) | | | | | | | |
| 10/3/2009 | 14:01:04 | 38.3086 | -108.9618 | -2.2 | 3.7 | 1.8 | NW cluster |
| 10/3/2009 | 14:01:08 | 38.3068 | -108.9652 | -2.8 | 4.3 | 1.6 | NW cluster |
| 10/3/2009 | 14:12:24 | 38.3089 | -108.9633 | -2.1 | 3.6 | 0.4 | NW cluster |
| 10/3/2009 | 15:28:31 | 38.3082 | -108.9628 | -2.1 | 3.7 | 2 | NW cluster |
| 10/3/2009 | 15:29:11 | 38.3123 | -108.967 | -1.8 | 3.4 | 0.9 | NW cluster |
| 10/4/2009 | 13:17:44 | 38.3092 | -108.9607 | -2.2 | 3.7 | 1.3 | NW cluster |
| 10/4/2009 | 13:19:11 | 38.3095 | -108.9618 | -2.8 | 4.3 | -0.4 | NW cluster |
| 10/14/2009 | 22:53:48 | 38.2824 | -108.9045 | -1.6 | 3.1 | 1.7 | near-well |
| 10/21/2009 | 0:00:24 | 38.3049 | -108.8863 | -2.9 | 4.4 | 0.9 | near-well |
| 10/26/2009 | 4:18:57 | 38.2819 | -108.9084 | -1.7 | 3.2 | 2.2 | near-well |
| Injection resumed on October 29 (pressure: 970 psi). | | | | | | | |
| 11/1/2009 | 7:10:25 | 38.2825 | -108.9047 | -1.7 | 3.3 | 0.8 | near-well |
| 11/10/2009 | 18:04:36 | 38.3069 | -108.9661 | -2.1 | 3.6 | 2.5 | NW cluster |
| 11/10/2009 | 18:26:26 | 38.3067 | -108.9653 | -2.1 | 3.6 | 1.1 | NW cluster |
| 11/10/2009 | 18:46:42 | 38.307 | -108.965 | -2.1 | 3.7 | 0.9 | NW cluster |
| 11/12/2009 | 14:14:18 | 38.308 | -108.963 | -2.1 | 3.6 | 1 | NW cluster |
| 11/17/2009 | 19:10:35 | 38.3067 | -108.969 | -2.2 | 3.8 | -0.9 | NW cluster |
| 11/17/2009 | 19:44:39 | 38.3064 | -108.9672 | -2.1 | 3.6 | 2.9 | NW cluster |
| 11/18/2009 | 22:13:57 | 38.2855 | -108.9066 | -1.8 | 3.4 | -0.2 | near-well |
| 11/21/2009 | 8:13:55 | 38.2808 | -108.9115 | -1.1 | 2.6 | 1.8 | near-well |
| 11/25/2009 | 22:43:09 | 38.2828 | -108.9043 | -1.8 | 3.3 | 0.1 | near-well |
| 11/26/2009 | 12:10:38 | 38.4003 | -109.0078 | -5.3 | 6.8 | 2.1 | northern valley |
| 11/27/2009 | 3:48:47 | 38.276 | -108.8324 | -2.4 | 3.9 | 0.1 | near-well |
| 11/29/2009 | 15:18:15 | 38.3047 | -108.886 | -2.9 | 4.4 | -0.4 | near-well |
| 12/5/2009 | 16:45:06 | 38.2843 | -108.915 | -1.5 | 3 | -0.3 | near-well |
| 12/14/2009 | 0:05:07 | 38.2841 | -108.8972 | -2 | 3.6 | 1.2 | near-well |
| 12/14/2009 | 0:05:17 | 38.2836 | -108.8978 | -2 | 3.6 | 0.1 | near-well |
| 12/16/2009 | 13:29:47 | 38.2841 | -108.8972 | -2 | 3.5 | 0.8 | near-well |
| 12/16/2009 | 14:20:14 | 38.284 | -108.897 | -2 | 3.5 | 1.1 | near-well |
| 12/16/2009 | 14:20:33 | 38.2838 | -108.8977 | -2.1 | 3.6 | -0.1 | near-well |

**Table 4-1 Local earthquakes recorded by PVSN during 2009. The four earthquakes outlined in bold are large-magnitude events that triggered PVSN strong motion instruments. The color-shaded events are foreshocks and aftershocks associated with each main event.**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12/16/2009 | 14:20:52 | 38.2839 | -108.897 | -2 | 3.5 | 0.9 | near-well |
| 12/16/2009 | 14:22:11 | 38.2839 | -108.8969 | -2 | 3.5 | 0.5 | near-well |
| 12/17/2009 | 0:44:37 | 38.2838 | -108.8969 | -2 | 3.5 | 0.4 | near-well |
| 12/20/2009 | 12:36:06 | 38.2844 | -108.8977 | -2.1 | 3.6 | 1.1 | near-well |
| 12/30/2009 | 0:51:44 | 38.5363 | -109 | -8.8 | 10.3 | 1.4 | other |

[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 approximately 5 km of the injection well (induced by fluid injection)
NW cluster: located within the zone of induced seismicity that is centered approximately 7.5 km northwest of the injection well (induced by fluid injection)
northern valley: located in or very near areas of recurring seismicity at the northern end of Paradox Valley
other: local earthquake not associated with any of the other three location categories

The local earthquakes recorded during 2009 are plotted as a function of date and earthquake magnitude in **Figure 4-2.** Earthquakes in each location category are plotted with different symbols. Also shown on this chart are times when the seismic network was down (green marks across the top of the chart) and injection well shut-ins (blue marks at the top of the chart).

**Table 4-2 Summary of events recorded during 2009 in the four defined location categories**

| Location Category[1] | Number of Earthquakes | Magnitude Range | Median Magnitude |
|---|---|---|---|
| near-well | 96 | -0.8 to 2.8 | 0.90 |
| NW cluster | 23 | -0.9 to 2.9 | 1.10 |
| all induced events | 119 | -0.9 to 2.9 | 0.90 |
| | | | |
| northern valley | 2 | -0.1 to 2.1 | 1.00 |
| other | 2 | 1.4 | 1.40 |
| TOTAL | 123 | -0.9 to 2.9 | 0.95 |

[1] See footnote #4 in Table 4-1 for definition of location categories.

**Table 4-3 Average daily seismicity rates of local earthquakes recorded by PVSN during 2009. These rates were computed using the approximate number of days the network was operational, 358.5, 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 induced events | 96 | 0.268 | 67 | 0.187 |
| NW-cluster induced events | 23 | 0.064 | 18 | 0.050 |
| all induced events | 119 | 0.332 | 85 | 0.237 |
| | | | | |
| northern valley events | 2 | 0.006 | 1 | 0.003 |
| other (isolated local earthquake) | 2 | 0.006 | 2 | 0.006 |
| | | | | |
| TOTAL | 123 | 0.343 | 88 | 0.245 |

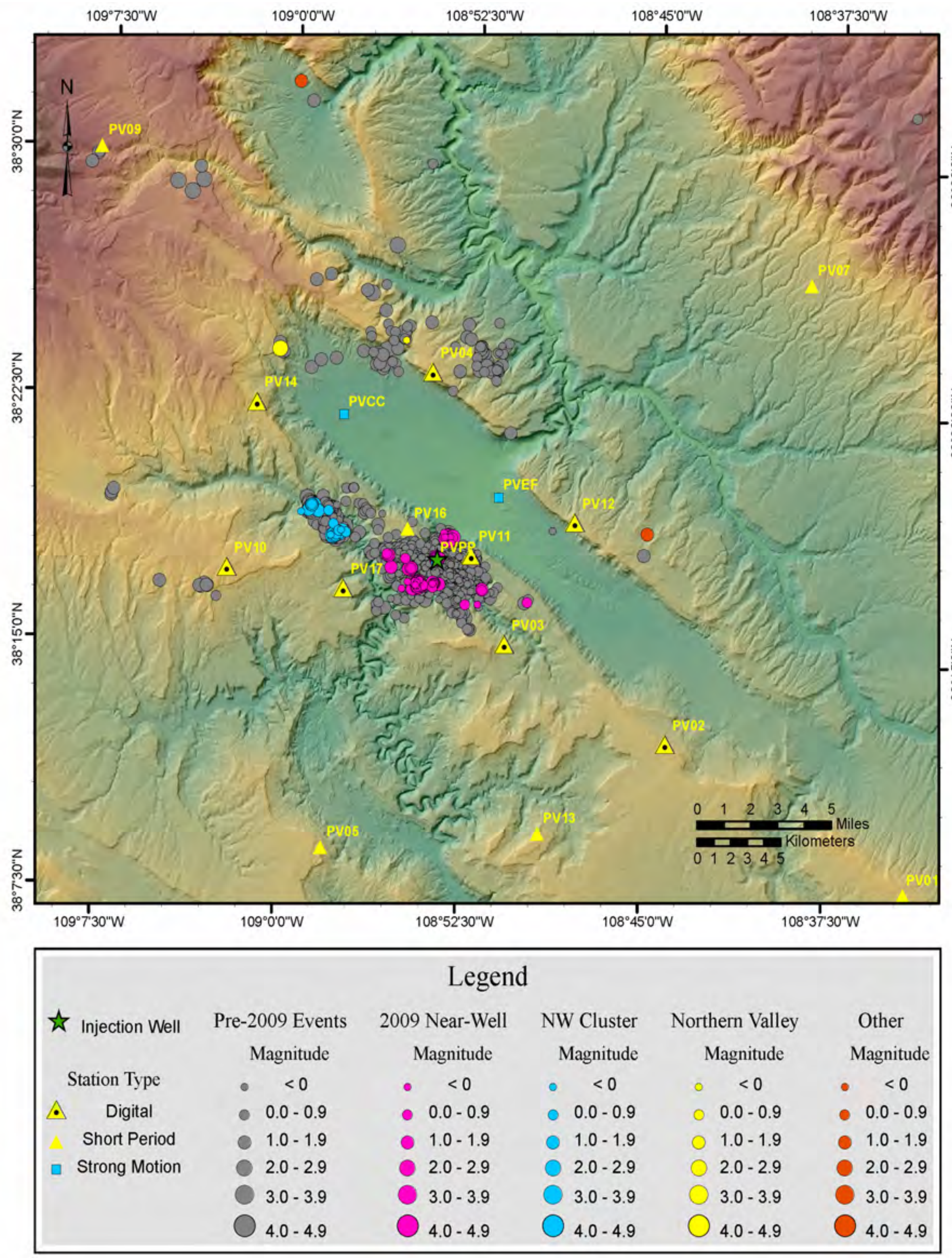


*Figure 4-1 Locations of local earthquakes recorded by PVSN during 2009 (colored circles) and previous years (gray circles).*

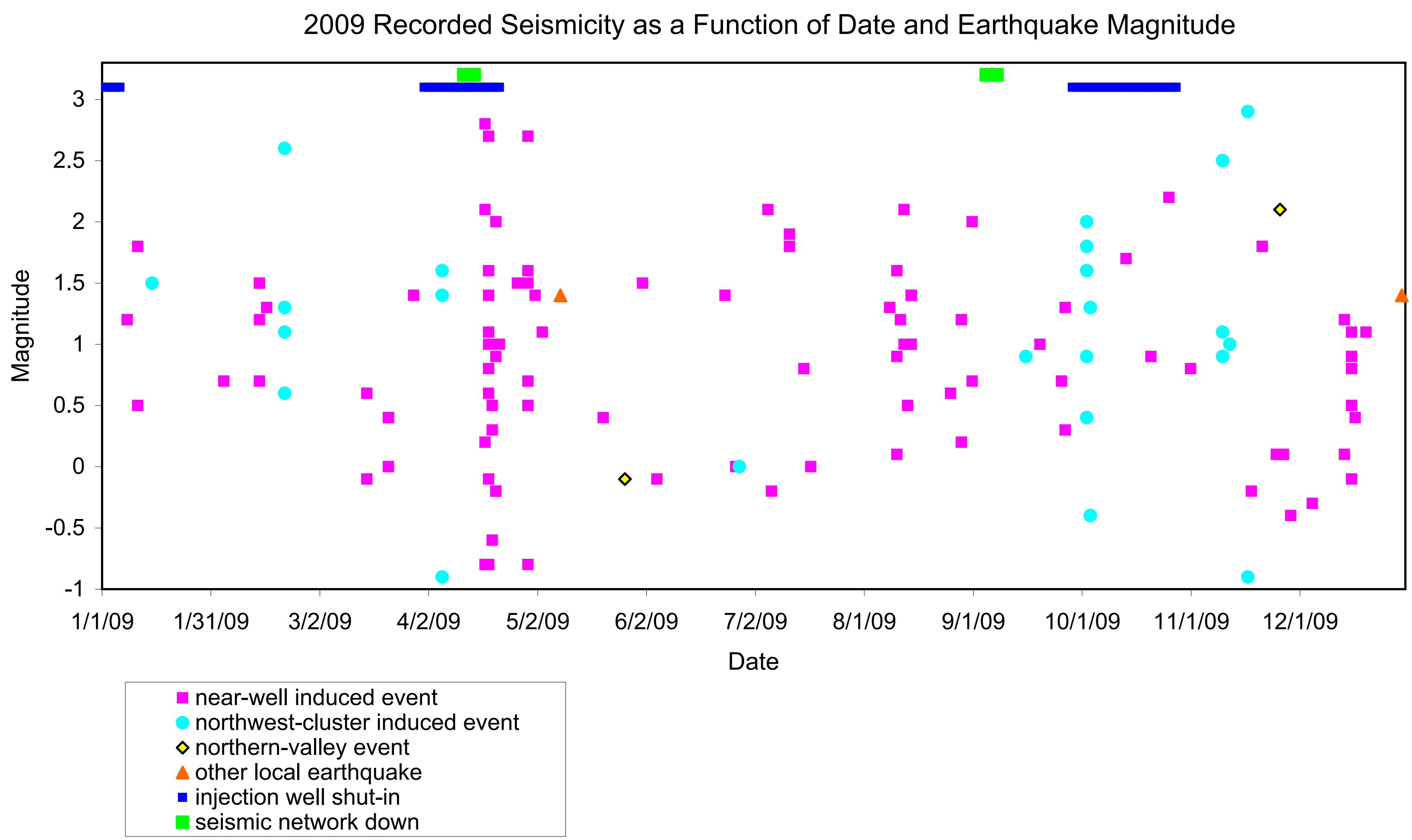


*Figure 4-2 Earthquakes recorded by PVSN during 2009, plotted as a function of date, magnitude, and event location category. The dates of network down-times and injection well shut-ins are included as indicated by the legend.*

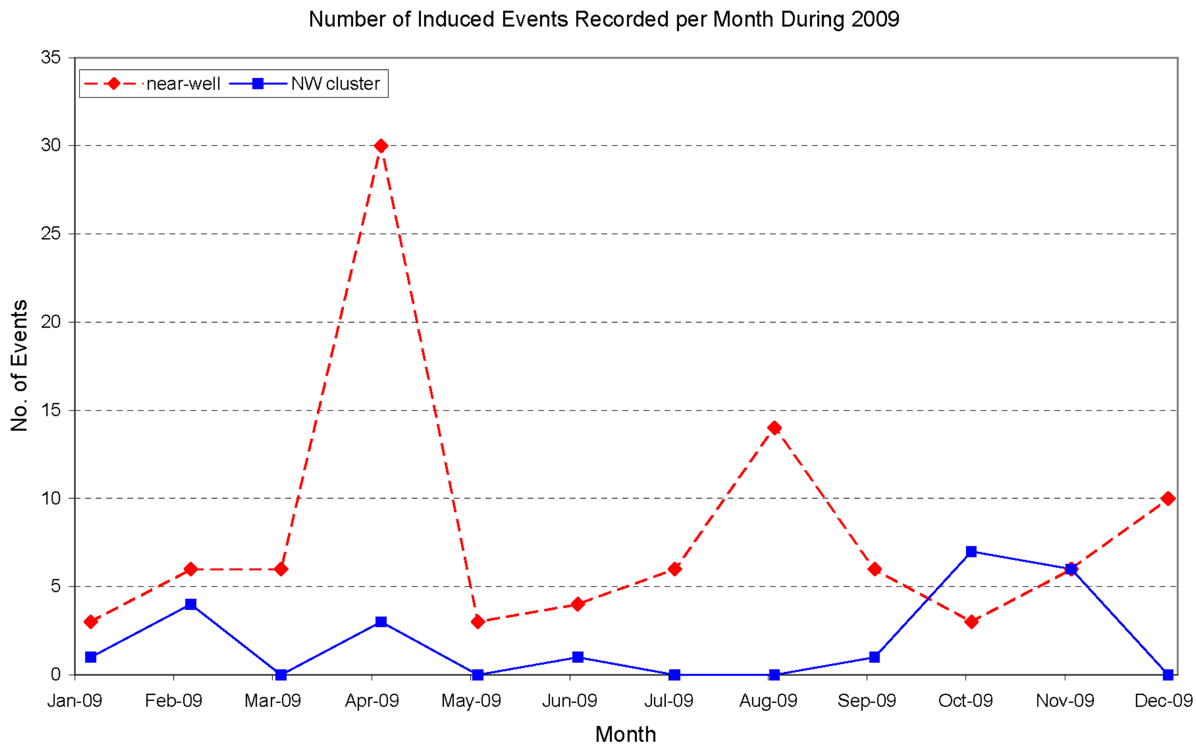


*Figure 4-3 Number of earthquakes detected in the near-well (dashed red line) and NW-cluster (solid blue line) regions per month during 2009.*

## 4.2 Injection-Induced Earthquakes

### *4.2.1 2009 Seismicity*

**Figure 4-2** shows that the induced seismicity was rather sporadic during 2009, especially in the near-well region. During some months, such as April and August, the seismicity rate was relatively high. During other months, such as May to July, the seismicity rate was very low. The rate of induced seismicity was higher in the near-well region than in NW cluster during most of the year, except in October and November when the seismicity rate in the NW cluster increased (**Figure 4-3**).

The magnitudes of the induced events occurring in the near-well and NW-cluster regions during 2009 were of similar magnitude, as can be seen in the event summary in **Table 4-2**. Magnitudes of the near-well events range from **M** -0.8 to **M** 2.8, with a median value of **M** 0.90. Magnitudes of the NW-cluster events range from **M** -0.9 to **M** 2.9, with a median value of **M** 1.10. Six events with magnitude greater than or equal to **M** 2.5 (**M** 2.5+) were recorded during 2009, three in the near-well region and three in the NW cluster. This magnitude threshold is significant because it represents the approximate threshold for human detection in the nearby communities of Paradox and Bedrock. Four of the **M** 2.5+ events triggered strong motion instruments located at the injection well, the brine extraction field, and the Paradox community center (although not all strong

**Table 4-4 Peak ground motion accelerations recorded for four large-magnitude induced earthquakes that occurred in April and November, 2009.**

| Date | UTC Time | Event Duration Magnitude | Strong Motion Station[1] | Component | Peak Acceleration (g) |
|---|---|---|---|---|---|
| 4/18/2009 | 23:57:56 | 2.8 | PVEF | Vertical | 0.012 |
| | | | | North | 0.022 |
| | | | | East | 0.016 |
| 4/19/2009 | 13:34:41 | 2.7 | PVEF | Vertical | 0.004 |
| | | | | North | 0.010 |
| | | | | East | 0.005 |
| | 13:34:42 | | PVCC | Vertical | 0.005 |
| | | | | North | 0.008 |
| | | | | East | 0.004 |
| 4/30/2009 | 8:50:22 | 2.7 | PVEF | Vertical | 0.004 |
| | | | | North | 0.006 |
| | | | | East | 0.005 |
| 11/17/2009 | 19:44 | 2.9 | PVPP | Vertical | 0.026 |
| | | | | North | 0.041 |
| | | | | East | 0.005 |
| | 19:44 | | PVEF | Vertical | 0.007 |
| | | | | North | 0.011 |
| | | | | East | 0.010 |

[1] The locations of the strong motion stations are shown on the map in Figure 4-1.

motion instruments were triggered for any single event). Ground motion accelerations recorded for these four events are listed in **Table 4-4**. The earthquake locations are shown in **Figures 4-4** and **4-5**.

The majority of the induced earthquakes recorded during 2009 locate in areas of previous seismic activity, as seen in the expanded-scale map presented in **Figure 4-4** and the vertical cross sections in **Figure 4-5**. In these figures, the earthquakes that occurred during 2009 and those that occurred in previous years are each separated into two categories based on how reliable the computed hypocenters are. (The earthquakes with the "best locations" meet the following criteria in the event relative location: number of stations with cross-correlation time differences >= 6; maximum azimuthal gap in ray coverage <= 100 degrees, and the horizontal distance from the earthquake epicenter to the closest station with observed time differences divided by the earthquake (focal) depth is <= 1.0.) As can be seen, the majority of induced earthquakes recorded during 2009 occur on or very near previously-active fractures, especially those with the best-constrained locations.

Three areas of anomalous seismic activity in 2009 are identified by dashed circles on the map in **Figure 4-4.** Several earthquakes were induced approximately 1.5 km north-northeast of the injection well (dashed yellow circle), including a magnitude 2.8 event on April 18. Most of the other

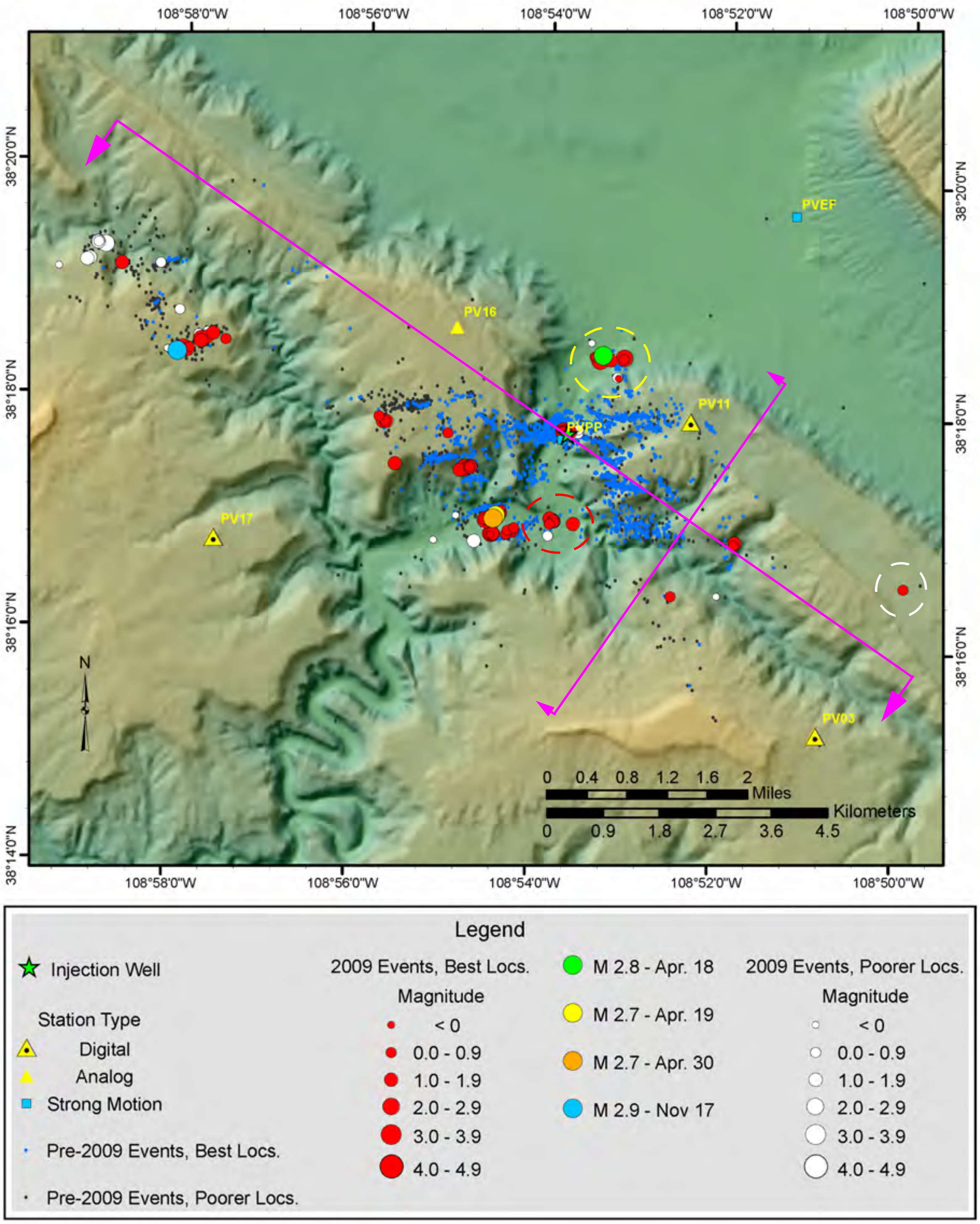


*Figure 4-4 Map showing the locations of induced earthquakes recorded in 2009, compared to the locations of previously-induced events. The four earthquakes that triggered strong motion instruments in 2009 are identified as shown in the legend. (The **M** 2.7 April 19 and April 30 events co-locate.) The dashed circles indicate areas of recent seismic activity that is anomalous compared to historical trends. The magenta lines indicate the orientations of the cross sections presented in Figure 4-5.*

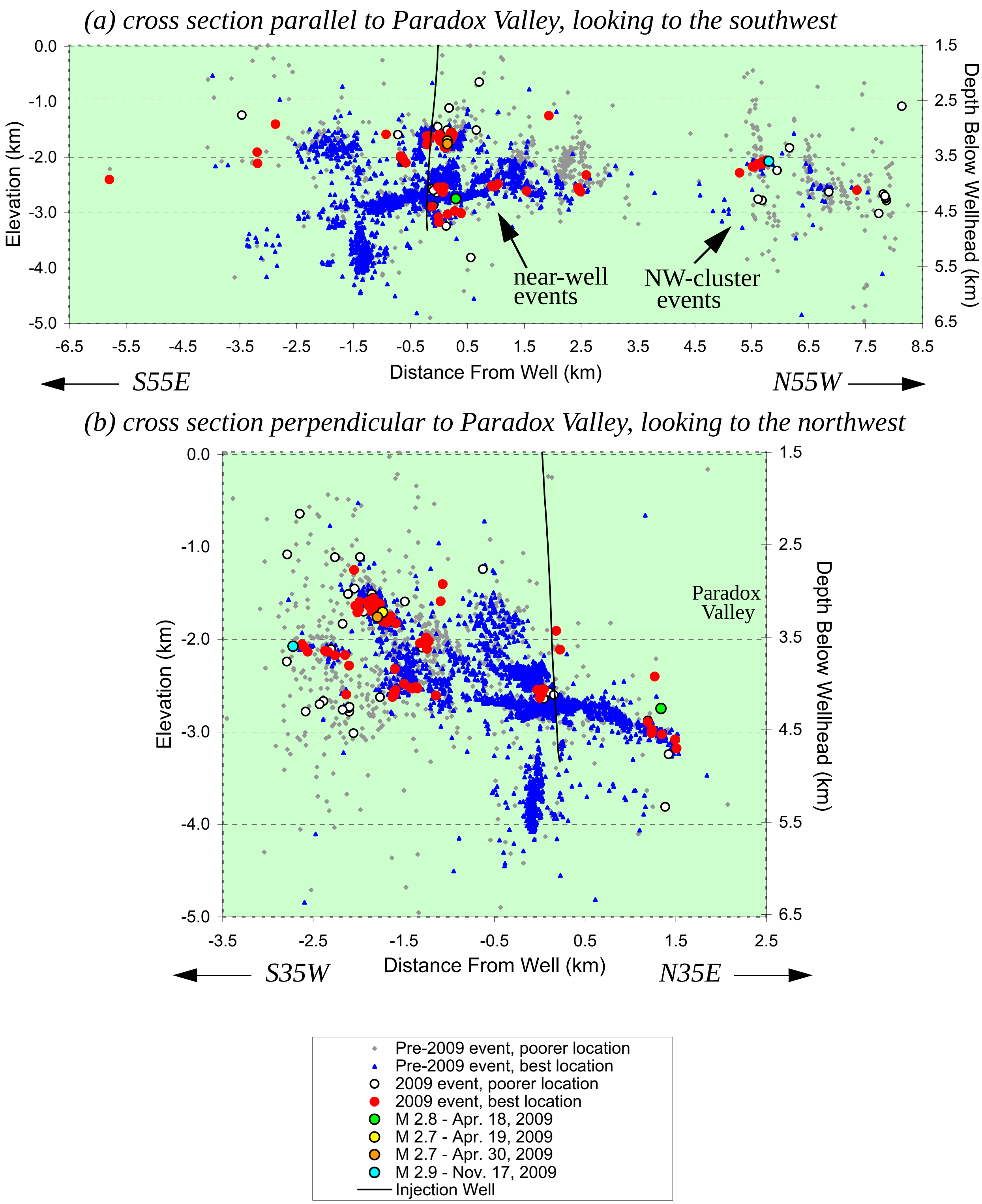


*Figure 4-5 Vertical cross sections showing the locations of induced earthquakes recorded in 2009, compared to the locations of previously-induced events: (a) section parallel to Paradox Valley (b) section perpendicular to Paradox Valley. The orientations of the cross sections are indicated by the magenta lines in Figure 4-4. (The depths of events locating shallower than approximately 2.5 km are poorly constrained.)*

events that occurred in this area are foreshocks or aftershocks associated with the April 18th main shock, including two events with magnitude >= **M** 2.0. Although there have been events detected in this area during continuous injection operations as far back as 1998, there have been relatively few of them and most of them have been fairly small (all but one less than **M** 2.0). Hence, the magnitudes of the events observed in this area in 2009 are anomalously large compared to historical trends. In another area, several earthquakes, mostly in the magnitude range **M** 0.5 - **M** 1.5, occurred in a cluster located approximately 1.5 km south of the injection well (red circle in **Figure 4-4**). Most of these occurred during a one-week period in mid-December, 2009. With the exception of a few events with a similar magnitude range as the 2009 events that occurred during 2003 and 2004, this area has been largely aseismic in the past. Lastly, one isolated earthquake occurred nearly 6 km southeast of the injection well in November, 2009 (white dashed circle in **Figure 4-4**). This event locates well outside the nominal 4-km radius that generally defines the near-well region of induced seismicity. Although the magnitude of this event is small (**M** 0.1), it's computed location is believed to be reliable. Two other earthquakes occurred at nearly the same location in the past: an **M** 0.6 event in November, 2004 and an **M** 1.0 event in May, 2008. In addition, two more earthquakes have occurred in this area in early 2010: an **M** 0.8 event in March and an **M** 1.5 event in April. The occurrence of three earthquakes in this area in a 5-month time frame, compared to only two events in the previous 13 years of continuous injection operations, indicates that stress conditions in this region are changing. This in turn suggests that recent injection operations may be driving fluid further to the southeast than in the past.

### *4.2.2 Comparison to 2008 Seismicity*

The seismicity induced by PVU operations during 2009 increased in both rate and magnitude compared to the previous year. The numbers of induced earthquakes recorded during 2009 and 2008 are plotted as a function of magnitude in **Figure 4-6.** Individual histograms are shown for earthquakes induced in the primary near-well region and in the secondary seismic zone northwest of the injection well, as well as for the total of all induced events. Cumulative histograms of the same data are presented in **Figure 4-7**

The number of earthquakes recorded in the near-well region increased from 59 in 2008 to 96 in 2009. The number of events with magnitude less than **M** 0.5 is comparable for both years; the increase in near-well seismicity in 2009 compared to 2008 is only for events with magnitude > **M** 0.5 (**Figure 4-6**). The number of larger-magnitude near-well events as a fraction of the total number of near-well events increased substantially in 2009 compared to 2008. In 2008, only 14% of the near-well events had magnitude > **M** 1.0, whereas in 2009, 41% of the near-well events had magnitude > **M** 1.0 (**Figure 4-7**). The largest near-well earthquake induced during 2008 had a magnitude of **M** 1.3. The largest near-well earthquake recorded during 2009 had a magnitude of **M** 2.8. Three **M** 2.5+ earthquakes occurred in the near-well region during 2009 (compared to none in 2008).

In contrast to the increase in the seismicity rate of near-well induced earthquakes, the number of earthquakes induced in the NW cluster decreased from 38 in 2008 to 23 in 2009. However, this overall decrease is due solely to a decrease in the seismicity rate of events with magnitude < **M** 1.0 (**Figure 4-6**). For events with magnitude > **M** 1.0, both the absolute number of events and the number of events as a fraction of the total increased in 2009 compared to 2008. In 2009, 57% of

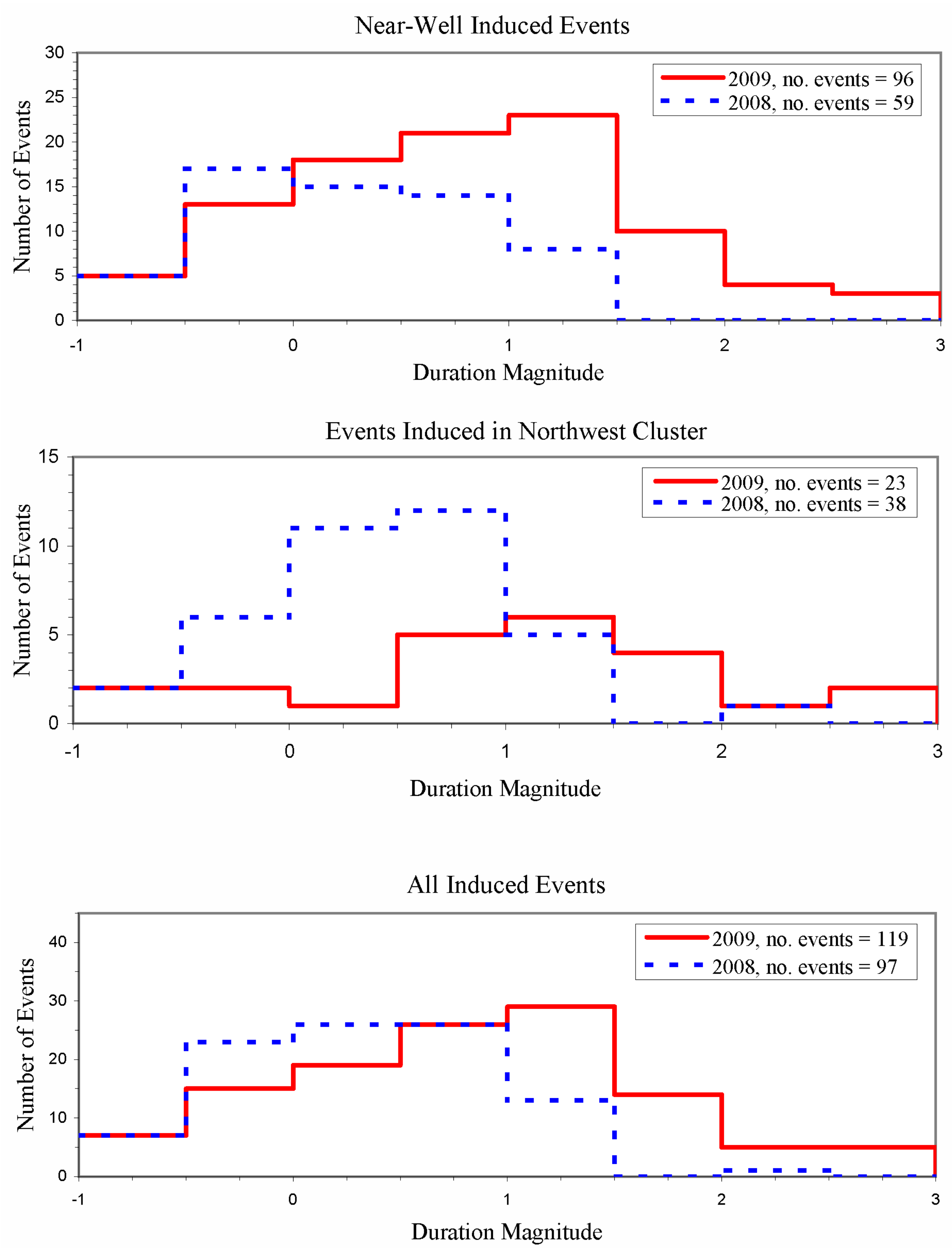


*Figure 4-6 Magnitude histograms of induced events recorded in the near-well region (top), in the northwest zone of induced seismicity (middle), and in both zones (bottom) during 2009 (solid red lines) and 2008 (dashed blue lines).*

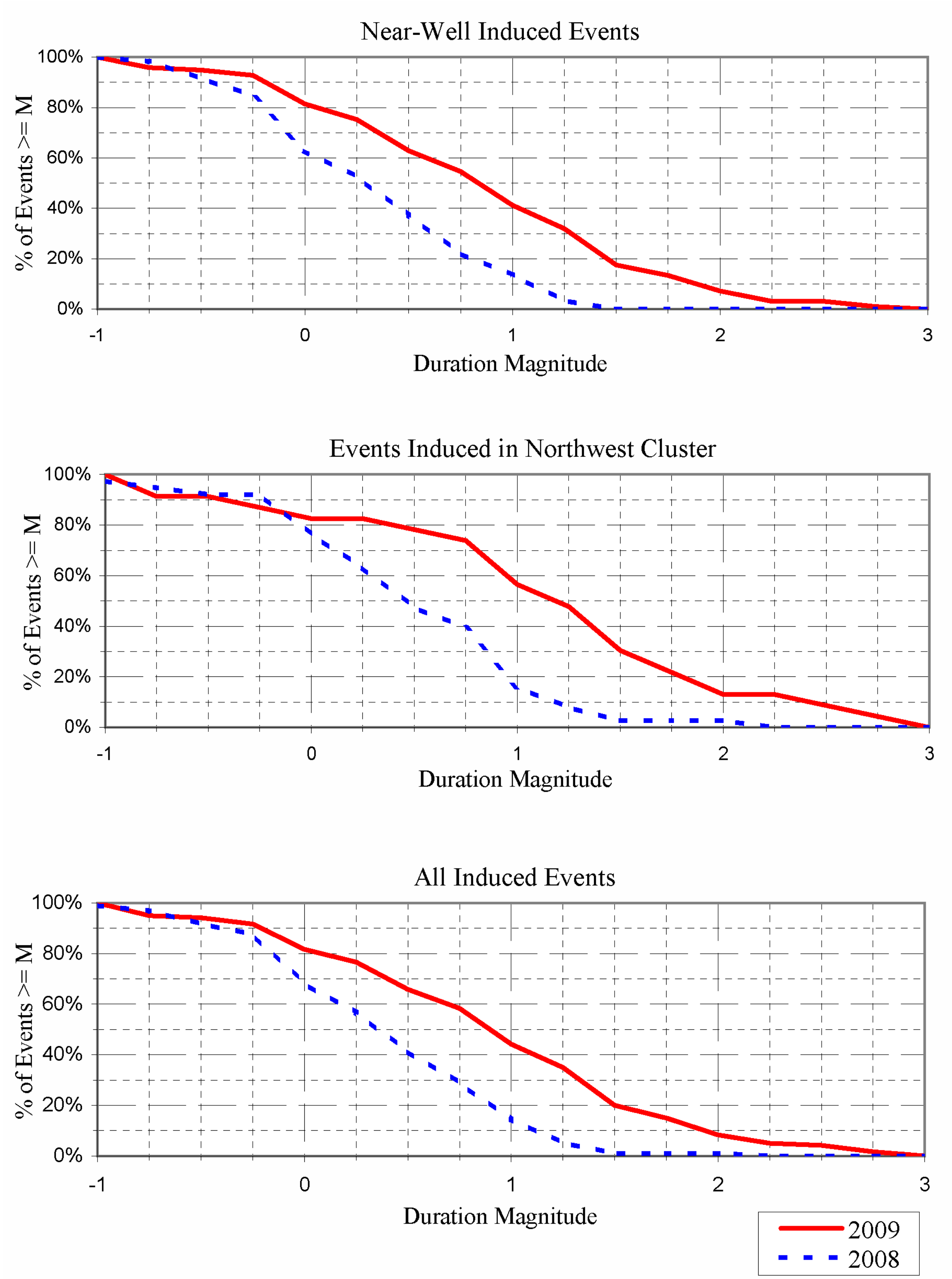


*Figure 4-7 Cumulative magnitude histograms of induced events recorded in the near-well region (top), in the northwest zone of induced seismicity (middle), and in both zones (bottom) during 2009 (solid red lines) and 2008 (dashed blue lines).*

the NW-cluster earthquakes had a magnitude > **M** 1.0, compared to only 16% in 2008 **(Figure 4-7**). Only one NW-cluster earthquake with magnitude >= **M** 2.0 occurred during 2008; four such events were recorded during 2009, including three **M** 2.5+ events. The largest NW-cluster event recorded during 2008 had a magnitude of **M** 2.1, whereas the largest NW-cluster event recorded during 2009 had a magnitude of **M** 2.9.

### *4.2.3 Historical Seismicity Trends*

The PVU-induced seismicity recorded during 2009 was characterized by a marked increase in the number of **M** 2.5+ events compared to the previous eight years (2001-2008). Six induced **M** 2.5+ events were recorded during 2009, compared to a total of four such events from 2001 through 2008 (an average of only 0.5 events per year). The 2009 rate of occurrence of **M** 2.5+ events has been exceeded in only one other year since PVU injection operations began - seven such events were recorded during 1999, prior to the decrease in injection flow rate by one-third in mid-2000. In contrast to the increased rate of **M** 2.5+ events, the current overall rate of induced seismicity remains relatively low compared to historic rates - only 85 induced events with magnitude greater than or equal to **M** 0.5 were recorded during 2009, compared to 658 such events recorded in 1999.

The increase in the rate of production of larger-magnitude events in 2009, as well as the relatively low rate of production observed for smaller-magnitude events, initiated a re-examination of the historical seismicity induced by PVU continuous injection operations. The goal was to obtain a better understanding of how the induced seismicity has changed over time and how these changes may be related to injection operations. The analysis was based on simple empirical exploration of the data rather than a rigorous mathematical analysis and therefore is largely qualitative rather than quantitative. The analysis procedures and results are documented in Technical Memorandum No. 86-68330-2009-22 (Block and Wood, 2009). A summary of the most significant results are presented here.

#### *Near-Well Seismicity*

The near-well seismicity induced by continuous injection operations at PVU, beginning in July, 1996, has experienced three periods of relatively high activity: 1997-2000, 2003-2005, and mid-2008-present, as seen in **Figure 4-8**. The middle plot in this figure shows the near-well earth-quake data (events occurring within 4 km of the injection well) plotted as a function of date and magnitude. The area of each circle in the plot is proportional to the total number of events for that quarter of the year that fall within the given magnitude range. The three relative high-activity periods are separated by two distinctly quieter periods that have lower seismicity rates and a scar-city of events with magnitudes of **M** 2.0 or greater (2001-2002 and 2006-mid-2008).

For each successive near-well high-activity period, the seismicity rate is lower than the previous high-activity period. This is best illustrated in the lower plot of **Figure 4-8,** which shows the number of near-well events with **M** >= 0.5 recorded per quarter. It is also shown by the decreasing size of the circles in the middle plot for successive high-activity periods.

The seismicity rate of smaller-magnitude events in the near-well region has decreased over time more than the rate of the larger-magnitude events, as indicated by the size of the circles in the middle plot of **Figure 4-8**. To clarify the trend in relative magnitudes over time, we computed a

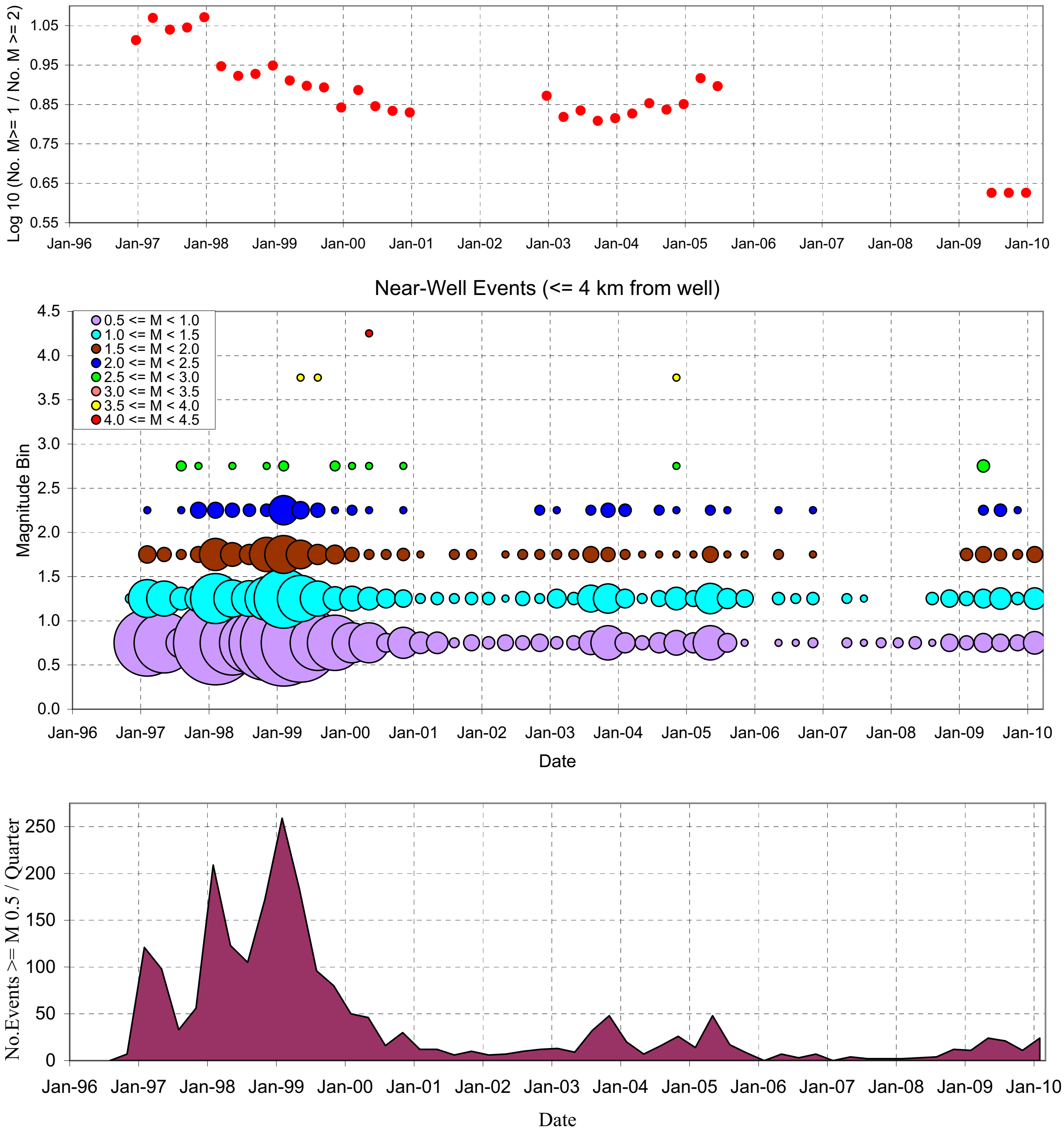


*Figure 4-8 Occurrence of induced earthquakes in the near-well region (within 4 km of the injection well) as a function of date. The lower plot shows the number of near-well events with magnitude >=* ***M*** *0.5 recorded per quarter. In the middle plot, the quarterly rate of seismicity is shown as a function of magnitude. The area of each circle is scaled by the number of earthquakes occurring in that quarter-year and magnitude range. The upper plot shows a measure of the ratio of smaller- to larger-magnitude events, computed for those time periods for which sufficient data are available. Each data point in the upper plot was computed as the log (base 10) of the ratio of the number of* ***M*** *1.0+ events to the number of* ***M*** *2.0+ events, for data within running time windows of up to 2 years.*

measure of the ratio of smaller- to larger-magnitude events as a function of time. We show this measure in the upper plot of **Figure 4-8**. Higher values in this upper plot indicate relatively higher ratios of smaller- to larger-magnitude events. No ratios are indicated for some of the time periods shown because of the lack of sufficient data (i.e., the seismicity rate is too low to compute a reliable ratio). This upper plot indicates that the ratio of smaller- to larger-magnitude events was greatest prior to 1998. The ratio gradually declined from 1998 through 2000. The ratio maintained this lower level from 2003 to mid-2005 (a time period for which we have sufficient data to compute reliable ratios). The limited data we have for the most recent years indicate that the ratio has decreased substantially in 2009 compared to 2003-2005.

Based on the above observations of the historical trends of near-well induced seismicity, it is clear that the near-well seismicity is currently experiencing it's third period of relatively high activity, which began in mid-2008. However, there is also a longer-term trend in the near-well data indicating that overall seismicity rates are declining with time. The decline is disproportionately greater for smaller-magnitude events. Hence, the current seismicity rate for smaller-magnitude events (< ~**M** 2.0) is lower than rates experienced during the two previous high-activity periods, while the current seismicity rate for larger-magnitude events (~**M** 2.0 to ~**M** 3.0) is more comparable to rates experienced during the previous high-activity periods.

### *NW-Cluster Seismicity*

In contrast to the near-well region, the seismicity rate in the secondary zone of induced seismicity northwest of the injection well (NW cluster) shows no distinct patterns over time (**Figure 4-9**). (The apparent minor decrease in seismicity rate in 2006 may be an artifact of seismic monitoring due to deteriorating network conditions that persisted until mid-2007.) Unlike the near-well region, the ratio of smaller- to larger-magnitude earthquakes in the NW cluster also appears to have remained relatively constant with time, as seen in the upper plot of **Figure 4-9**.

### *Correlation of Induced Seismicity with Injection Operations*

There appears to be a gross correlation between the three periods of increased near-well seismic activity and periods of increased time-averaged injection pressures (**Figure 4-10**). To produce the upper plot in **Figure 4-10**, the daily downhole injection pressures were averaged over 6-month, 18-month, and 30-month time periods. The response time of the near-well seismicity to injection operations has increased over time. In the early years of continuous injection operations (1996 to ~2000), the patterns in the occurrence of near-well seismicity correlate best with injection pressures averaged over a time period of 6 months or less. In later years (~2001 to ~2005), the seismicity pattern matches the 18-month average pressure curve fairly well. In the most recent years, (2006 to 2009), the response time of the near-well seismicity to injection operations appears to be on the order of 2 to 3 years.

The majority of the near-well earthquakes that have occurred since 2000 (including all events with magnitudes > **M** 2.5) locate more than 1 km from the injection well. Averaging the injection pressures over long time periods (18 to 30 months) simulates the time required for changes in pressures at the injection well to propagate out to these seismically active areas. The scarcity of induced earthquakes with magnitude > **M** 2.0 during periods of time that correlate with relatively low long-term averaged injection pressures (2001 - 2002 and 2006 - mid-2008) suggests that

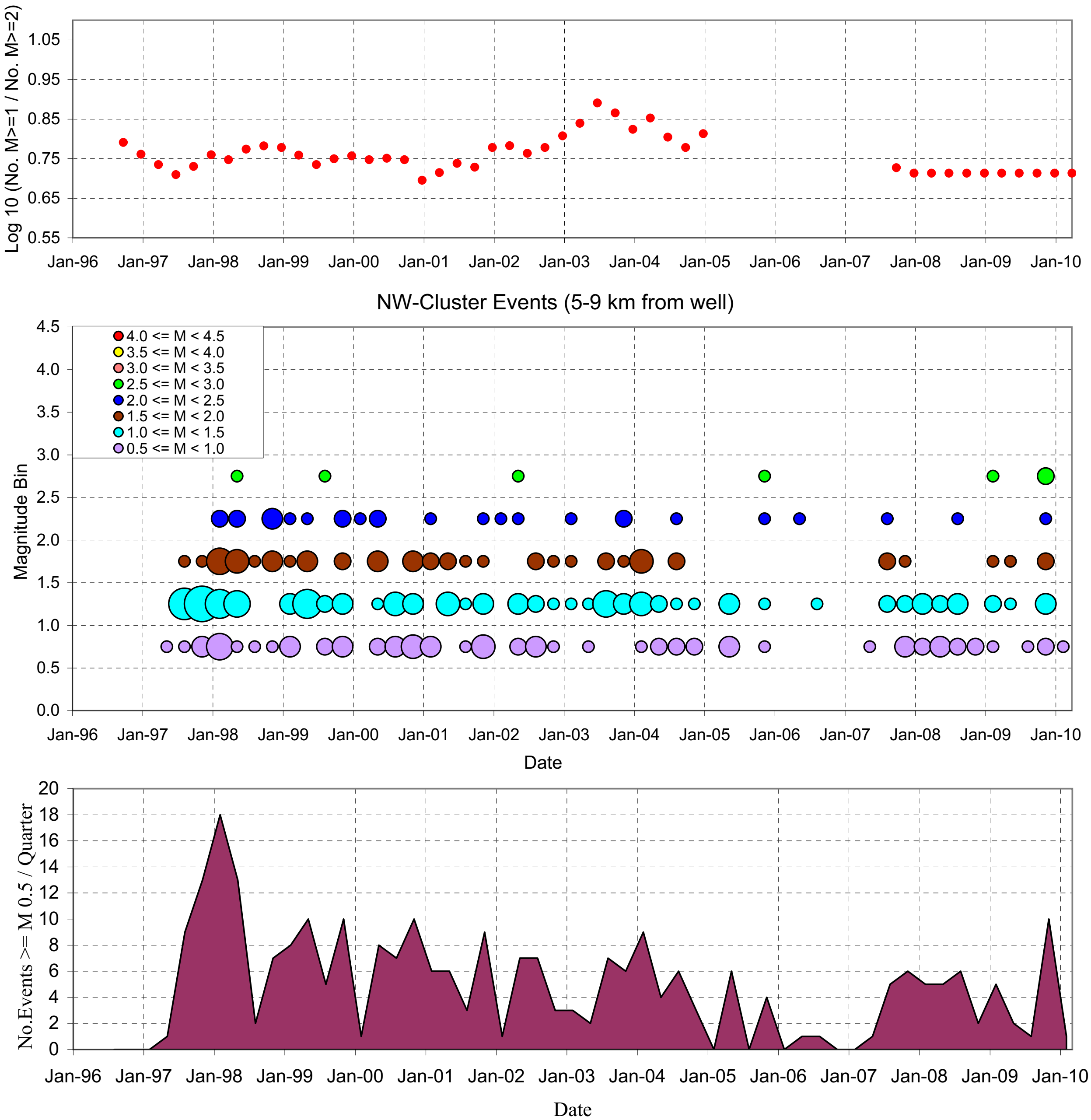


*Figure 4-9 Occurrence of induced earthquakes in the NW cluster (5-9 km from the injection well) as a function of date. The lower plot shows the number of NW-cluster events with magnitude >= **M** 0.5 recorded per quarter. In the middle plot, the quarterly rate of seismicity is shown as a function of magnitude. The area of each circle is scaled by the number of earthquakes occurring in that quarter-year and magnitude range. The upper plot shows a measure of the ratio of smaller- to larger-magnitude events, computed for those time periods for which sufficient data are available. Each data point in the upper plot was computed as the log (base 10) of the ratio of the number of **M** 1.0+ events to the number of **M** 2.0+ events, for data within running time windows of up to 6 years. (Longer time windows were required for the NW cluster data compared to the near-well data because of the relatively lower seismicity rate in the NW cluster.)*

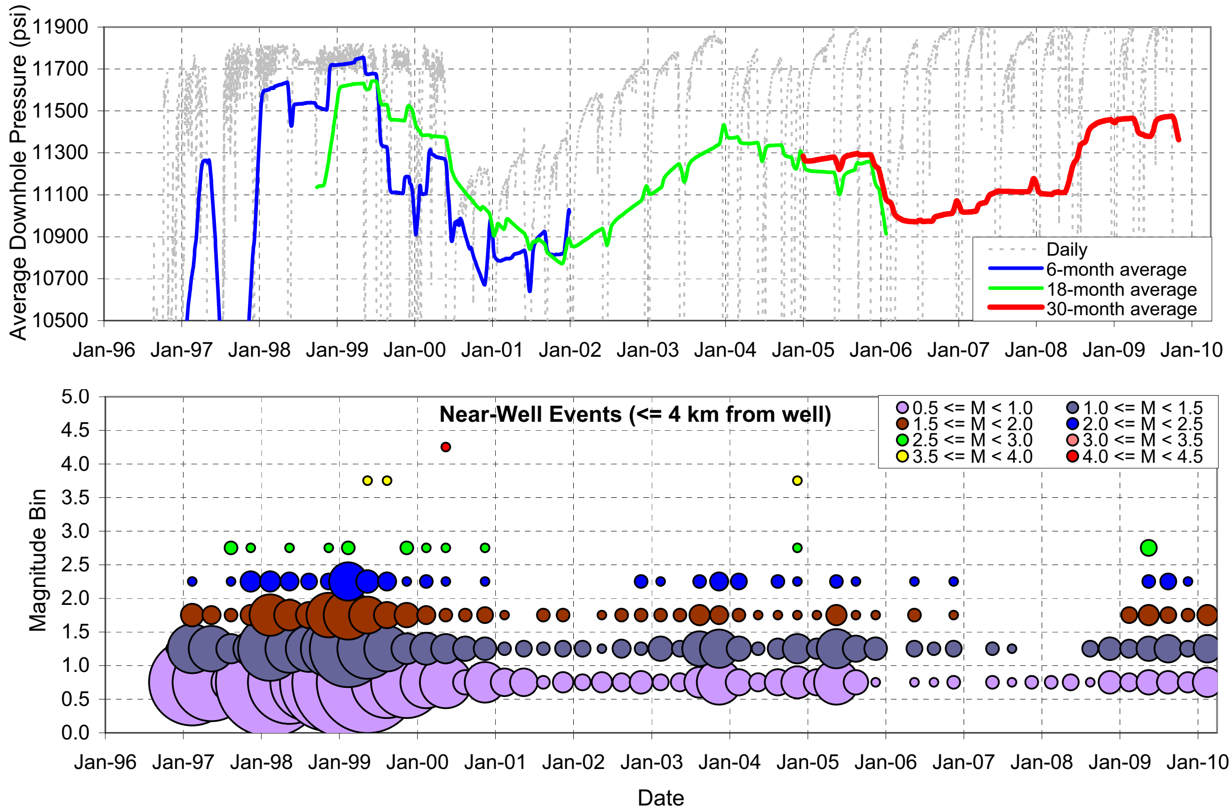


*Figure 4-10 Average downhole pressure data for daily, 6-month, 18-month, and 30-month time periods (top) and occurrence over time of near-well seismicity (bottom).*

when reservoir pressures fall below some critical threshold, the likelihood of producing larger-magnitude earthquakes is greatly reduced. Conversely, when reservoir pressures in the seismically active areas exceed this threshold level, corresponding to periods of time of relatively high long-term averaged injection pressures (1997 - 2000, 2003 - 2005, and mid-2008 - present), the likelihood of inducing larger-magnitude earthquakes is increased.

## 4.3 Northern-Valley Earthquakes

Two earthquakes were detected in the northern Paradox Valley region during 2009. A magnitude **M** -0.1 earthquake occurred northwest of seismic station PV04 in May, 2009. The computed depth of this earthquake is about 6.2 km below local ground surface. A magnitude **M** 2.1 earthquake occurred northeast of station PV14 in November, 2009. This event locates approximately 7.3 km below local ground surface. It is the largest earthquake that has been detected in the northern Paradox Valley region since August, 2007.

## 4.4 Other Local Earthquakes

Two local earthquakes, not associated with the northern valley events discussed above, were recorded by PVSN during 2009. In May, a local earthquake occurred approximately 4.5 km east-southeast of station PV12, at a computed depth of 8.8 km relative to the local ground surface. It has a computed duration magnitude of 1.4. In December, a magnitude 1.4 earthquake occurred near the northern edge of PVSN. It's computed location is about 13 km east-northeast of station PV14, at a depth of 10.5 km below local ground surface. Because it occurred near the edge of the seismic network, however, it's computed location and depth are not well-constrained.

## 5.0 REFERENCES


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# APPENDIX A

# 2009 SITE VISIT REPORTS

# Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2009-2 **Departure Date:** 4/20/2009 **Return Date:** 4/28/2009

**Purpose:** Perform site infrastructure upgrades (seismometer vaults, antenna tower bases, and steel conduit) at seven stations (PV01, PV05, PV07, PV12, PV13, PV16, and PV17). Replace seismometer at PV10; Install an environmental monitor at Hopkins Field.

**Work Summary:** Installed new seismometer vaults, conduit, and antenna-tower bases at PV01, PV05, PV07, PV13, and PV16, which are currently analog-only sites. Installed new seismometer vaults and conduit at PV12 and PV17, which had been upgraded to digital before 2007, but which used obsolete seismometer vaults; the old vaults were incompatible with the new equipment enclosures required for a communications upgrade planned for later this year. Replaced the digital broad-band seismometer at PV10, which had a bad vertical component. Installed an environmental monitor in the Hopkins Field server room to remotely monitor the air-conditioning system and provide alert messages in the event of overheating; also reconfigured IP address and other parameters.

**Action Items:**

| | |
|---|---|
| 1 | Need to test all 7 spare Guralp seismometers - most seem to now have one or more bad components. |
| 2 | Requisition additional digital radios needed for communications upgrade later this summer. |
| 3 | Prepare for communications upgrade required to convert entire network to digital (install new enclosures, solar panels, batteries, and radios at PV04, PV12 and PV17; replace radios at PV02, PV03 PV10, PV11, and PV14; replace radios at Hopkins field and configure security infrastructure). |
| 4 | Evaluate whether/how to accelerate completion of digital upgrades at these sites to FY09 - had originally been planned for FY10. |
| 5 | Complete station infrastructure upgrades at these sites by installing towers, enclosures, batteries, solar panels, antennas, cabling, etc. (requires approx. one day field work for three people, per site). Install, configure, and test digital broad-band seismometer and digital radios (requires 1/2 day of field work for two people, per site). |

**Personnel:**

| | Name | Organization |
|---|---|---|
| 1 | Chris Wood | Reclamation, Seismotectonics & Geophysics, 86-68330 |
| 2 | Mark Meremonte | USGS, Golden |
| 3 | Jeff Fox | USGS, Golden |
| 4 | Zeb Maharrey | USGS, Golden |
| 5 | Martin Messmer | USGS, Golden |

**Work by Site:**

| | Site | Work Accomplished |
|---|---|---|
| 1 | PV01 | Installed 3-ft Rohn tower base, poly-overpack seismometer vault, ground rods, and 1-1/2" Sealtite conduit with pull-rope. |
| | PV05 | Installed 3-ft Rohn tower base, poly-overpack seismometer vault, ground rods, and 1-1/2" Sealtite conduit with pull-rope. |
| | PV07 | Installed 3-ft Rohn tower base, poly-overpack seismometer vault, ground rods, and 1-1/2" Sealtite conduit with pull-rope. |
| | PV10 | Replaced Guralp CMG-40TD seismometer, and tested. |
| | PV12 | Installed poly-overpack seismometer vault, ground rods, and 1-1/2" Sealtite conduit with pull-rope. |
| 2 | PV13 | Installed 3-ft Rohn tower base, poly-overpack seismometer vault, ground rods, and 1-1/2" Sealtite conduit with pull-rope. |
| 3 | PV16 | Installed 3-ft Rohn tower base, poly-overpack seismometer vault, ground rods, and 1-1/2" Sealtite conduit with pull-rope. |
| 4 | PV17 | Installed poly-overpack seismometer vault, ground rods, and 1-1/2" Sealtite conduit with pull-rope. |
| 5 | Hopkins Field | Installed Netbotz environmental monitor and configured. Reset IP addresses of switch and KVM. Re-configured server. |

# Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2009-3 **Departure Date:** 9/13/2009 **Return Date:** 9/24/2009

**Purpose:** Upgrade existing digital stations and radios to a new system that will allow for digital upgrades of the remaining 8 analog stations, eliminate data dropouts, and provide redundant telemetry paths.

**Work Summary:** New GE-MDS iNet-II wireless Ethernet bridges were installed at PV02, PV03, PV04, PV10, PV11, PV12, PV14, PV17, and Hopkins Field. Hubs were established at PV02, PV04, PV12, and Hopkins Field, and a backhaul network between the hubs and Hopkins Field was set up. Because the new radios require more power to operate, and have an interface that is incompatible with the original 4 digital stations (PV04, PV12, PV14, and PV17), these stations were essentially rebuilt from the ground up using the current generation enclosures, solar panels, and electronics. Stations PV12 and PV17 also had old style seismometer vaults, which were upgraded to the new vaults, and the seismometers were relocated. Only minor changes were required to install the radios at PV02, PV03, PV10, and PV11.

**Action Items:**

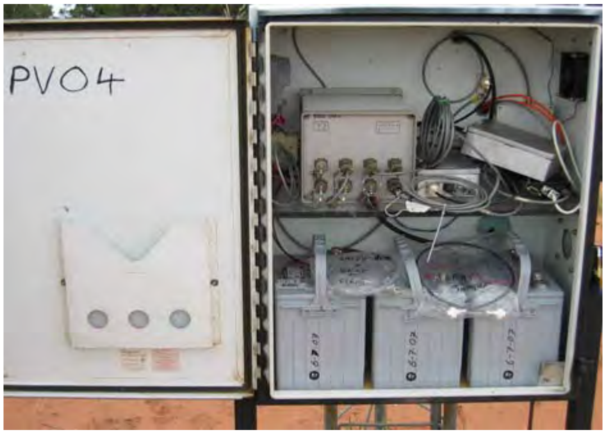
| | |
|---|---|
| 1 | Tune remote sites in order to optimize power consumption while maintaining good signal levels. |
| 2 | Replace used batteries with new batteries when supplier receives new stock (need 12 batteries). |
| 3 | Configure additional security measures (RADIUS authentication) once basic operation and reliability have been established |
| 4 | Prepare a final security plan and formally bring the new communications network into production mode. |
| 5 | Optimize hub antenna position at PV02 once there are remote sites transmitting through PV02. |

**Personnel:**

| | Name | Organization |
|---|---|---|
| 1 | Chris Wood | Reclamation, Seismotectonics & Geophysics, 86-68330 |
| 2 | Mark Meremonte | USGS, Golden |
| 4 | Zeb Maharrey | USGS, Golden |

**Work by Site:**

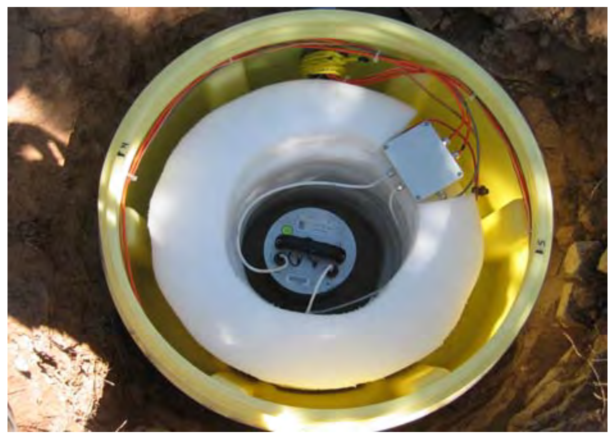
| | Site | Work Accomplished |
|---|---|---|
| 1 | PV02 | Installed battery enclosure and 3 additional batteries (used), second solar panel, hub and backhaul radios, antennas and cables. |
| 2 | PV03 | Installed new radio and cables. |
| 3 | PV04 | Removed old solar panel, station enclosure, electronics, seismometer cable, and conduit. Installed new station enclosure, dual solar panels, battery enclosure, 6 batteries (new), hub and backhaul antennas and cabling, new radios, new conduit, new cabling. Validated GPS and seismometer cables with automatic tester. |
| 4 | PV10 | Installed new radio and cables. |
| 5 | PV11 | Installed new radio and cables. Reoriented antenna. |
| 6 | PV12 | Removed old tower, enclosure, solar panel, electronics, seismometer vault, seismometer conduit and cables. Installed new station enclosure, battery enclosure and 3 additional batteries (used), dual solar panels, antennas, cables, electronics and radios. Replaced bad seismometer and relocated to new vault. Validated GPS and seismometer cables with automatic tester. |
| 7 | PV14 | Removed old enclosure, solar panel, electronics, seismometer conduit and cables. Installed new station enclosure, solar panel, antenna, cables, electronics and radio. Validated GPS and seismometer cables with automatic tester. |
| 8 | PV17 | Removed old tower, enclosure, solar panel, electronics, seismometer vault, seismometer conduit and cables. Installed new station enclosure, solar panel, antennas, cables, electronics and radios. Replaced bad seismometer and relocated to new vault.Validated GPS and seismometer cables with automatic tester. |
| 9 | Hopkins Field | Removed old digital radios. Reconfigured antennas and added new hub antenna. Installed 2 backhaul radios and 1 hub radio. Reconfigured data acquisition server. |




Old PV04 digital station enclosure, obsolete combiner-repeater, and serial radios


New PV04 digital station enclosure, low-noise electronics, and wireless Ethernet bridges

New (left) and old (right) seismometer vaults at PV17



Seismometer installed in new vault at PV17.

# Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2010-1 **Departure Date:** 10/8/2009 **Return Date:** 10/13/2009

**Purpose:** Work on Phase-2 of digital radio upgrade, including optimizing radio and antenna operation, troubleshooting new equipment, and installing new solar batteries. Site reconnaissance for new and replacement stations.

**Work Summary:** Configuration of the Phase-1 digital radio system was based on theoretical path-loss calculations. Actual performance can vary significantly from theoretical predictions, requiring tuning and reconfiguration. To reduce costs, several antennas and other components from the previous system had been reused during Phase-1 installation, pending detailed performance measurements during Phase 2. For this Phase-2 work, radio and antenna operation was optimized, including making RF measurements of the radio, feedline, surge supressor, and antenna. Poorly-performing components were replaced. Directional antenna alignment was fine-tuned to optimize received signal strength. New circuit-board designs were used for for the surge supression, GPS antenna system, and regulated power system for the CMG40T seismometer and DM24 data logger. Several design defects in these new components were discovered under actual field conditions, and temporary work-arounds were devised. All remaining old solar batteries were replaced. Two potential sites for new/replacement seismic stations were identified, surveyed, photographed, and staked.

**Action Items:**

| | |
|---|---|
| 1 | Have Matrix-5 modify the GPS BOB circuit board design to better isolate clean and dirty power, provide additional surge protection, and redesign the 1 PPS GPS LED driver. |
| 2 | Have Matrix-5 modify the DM24 BOB circuit board design to use higher-rated fusible links that will not trip from the DM24 start-up or other normal current spikes. |
| 3 | Have Matrix-5 modify the Sensor-vault BOB design to provide a stiffer power-conditioning capacitor to better handle normal current spikes from the DM24. |
| 4 | Have Matrix-5 quickly produce enough of the modified BOBs for the 5 stations to be installed later this month (PV03, PV05, PV07, PV13 and PV16), replacements for the 4 upgraded stations (PV04, PV12, PV14, and PV17), and at least 1 spare. |
| 5 | Purchase sufficient number of antennas to replace all reused antennas. |

**Personnel:**

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

**Work by Site:**

| | Site | Work Accomplished |
|---|---|---|
| 1 | PV02 | Installed 6 new solar batteries. Tested Omni antenna (used) for access point - found to be bad. Installed replacement Omni (used) - still marginal. Remotely reprogrammed PV10 (only site currently using PV02 access point) to route signals through PV12 access point until new antennas can be installed. |
| 2 | PV04 | Found design problem with new DM24 BOB that can cause fusible link on clean power supply to trip after some period of normal operation. Temporarily jumpered over input (dirty power) fusible link. Output (clean power) links may still trip, but it's too risky to the DM24 to jumper over all the power fuses. Other three stations with new BOBs, but shorter seismometer-cable runs, seem to be unaffected. Alignment of back-haul antenna to Hopkins Field fine tuned to optimize RSSI. Measured antenna and feedline performance. Replaced back-haul antenna cable (used) with new cable. |
| 3 | PV12 | Found design problem with new GPS BOB that causes possible ground loop between clean and dirty power grounds, inducing 1-PPS noise on seismic data. At this site only, the 1-PPS LED from the GPS antenna also glows continuously, indicating a potential ground loop. Replacement circuit board behaves the same. Per discussions via sat-phone with Matrix-5, surface-mount diodes and other components were clipped on the GPS BOB circuit board as a temporary work-around. Obvious 1-PPS noise on seismic data no longer clearly visible, but may show up if data is stacked. Alignment of back-haul antenna to Hopkins Field fine tuned to optimize RSSI. Measured antenna and feedline performance. Bad RF surge suppressor found - moved feedline to backup. |
| 4 | PV14 | Measured antenna and feedline performance. |
| 5 | PV17 | Installed new solar batteries. Measured antenna and feedline performance. |

| | | |
|---|---|---|
| 6 | BR-1 | Found potential new site on the north flank of Ray Mesa, about 1 mile north of the old Morning Glory mine, for monitoring induced events in northwest cluster . Access road has several washouts that would need repair, and becomes completely impassible to the most optimal site. However, a good site was found about 3/4-mile south of the optimal site. GPS coordinates and access track were obtained, and the site was photographed and staked. Because the optimal site was not reasonably accessible, should also look at site about 1-1/2 mile west, near the old Yellow Bird mine. |
| 7 | BR-2 | Found potential replacement site for PV09 on a ridge about 1 mile north of Buckeye Reservoir. Tree cover and radio coverage severely limit possible sites. Found workable site, however an antenna mast might be visible from the access road, possibly making the site too susceptible to vandalism. Also, radio coverage is only possible from PV02, so the site would have no back-up radio link. GPS coordinates and access track were obtained, and the site was photographed and staked. Since this site is not optimal, alternatives to PV09 should continue to be explored. |

# Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2010-2 **Departure Date:** 10/24/2009 **Return Date:** 10/31/2009

**Purpose:** Install digital seismic station equipment at the five sites where new vaults, tower bases, and other site prep work was completed during the April, 2009 field trip. All equipment necessary to bring the stations online was installed, with the exception of the digital seismometers, which are expected to be delivered in December, 2009.

**Work Summary:** Five stations (PV01, PV05, PV07, PV13, and PV16) were upgraded from analog to digital (with the exception of installing the digital broadband seismometers, which are still on backorder). Antenna masts, solar panels, antennas, cabling, station enclosures, batteries, radios, etc., were installed and tested. The radio link from each station to one or more access points was verified.

**Action Items:**

| | |
|---|---|
| 1 | Complete Phase-2 digital radio upgrade work, including replacement of remaining old antennas at PV02, PV12 and Hopkins Field. |
| 2 | Replace initial GPS BOB and DM24 BOB with redesigned version (PV04, PV12, PV14 and PV17). |
| 3 | Complete reconnaissance of new sites ASAP in order to have time to receive permits before scheduled site prep work next May. |
| 4 | Plan to quickly deploy seismometers once they have been delivered (vendor estimates December 4th), as weather and schedules permit. |
| 5 | Prepare a final security plan and formally bring the new communications network into production mode. |

**Personnel:**

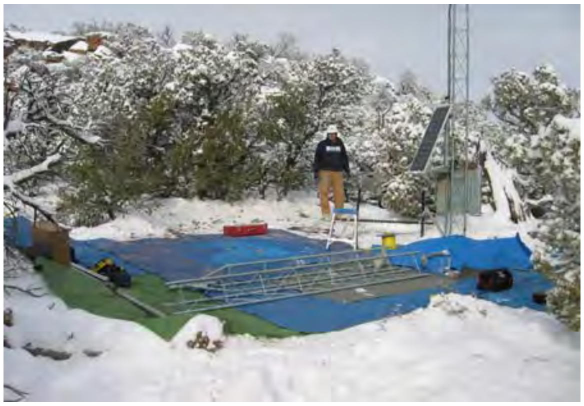
| | Name | Organization |
|---|---|---|
| 1 | Chris Wood | Reclamation, Seismotectonics & Geophysics, 86-68330 |
| 2 | Mark Meremonte | USGS, Golden |
| 4 | Zeb Maharrey | USGS, Golden |

**Work by Site:**

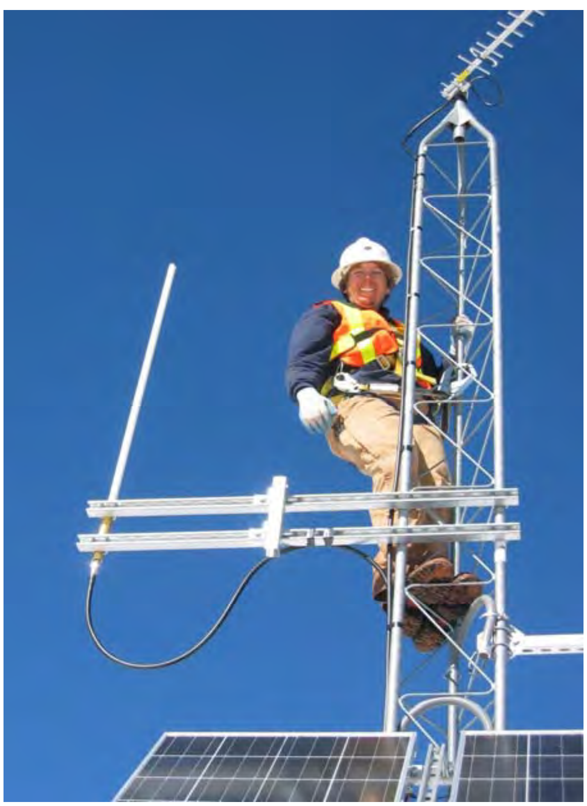
| | Site | Work Accomplished |
|---|---|---|
| 1 | PV01 | Installed tower, solar panel, GPS and communications antennas, enclosure, conduit, batteries, cables, radios, and electronics. Made final preparations for seismometer installation, including terminating and installing Sensor Vault BOB, installing insulation and North indicator, and cleaning vault base. |
| 2 | PV04 | Replaced old back-haul antenna. Replaced Sensor Vault BOB and GPS BOB. Measured radio and antenna performance. |
| 3 | PV05 | Installed tower, solar panel, GPS and communications antennas, enclosure, conduit, batteries, cables, radios, and electronics. Made final preparations for seismometer installation, including terminating and installing Sensor Vault BOB, installing insulation and North indicator, and cleaning vault base. |
| 4 | PV07 | Installed tower, solar panel, GPS and communications antennas, enclosure, conduit, batteries, cables, radios, and electronics. Made final preparations for seismometer installation, including terminating and installing Sensor Vault BOB, installing insulation, and cleaning vault base. |
| 5 | PV13 | Installed tower, solar panel, GPS and communications antennas, enclosure, conduit, batteries, cables, radios, and electronics. Made final preparations for seismometer installation, including terminating and installing Sensor Vault BOB, installing insulation and North indicator, and cleaning vault base. |
| 6 | PV16 | Installed tower, solar panel, GPS and communications antennas, enclosure, conduit, batteries, cables, radios, and electronics. Made final preparations for seismometer installation, including terminating and installing Sensor Vault BOB, installing insulation, and cleaning vault base. |
| 7 | Hopkins Field | Installed replacement Omni antenna. Replaced LAN cabling for new radios. Tested and measured radios, antennas, and feedlines. |


Newly installed tower, solar panel, GPS antenna, and new enclosure at PV01.


Sensor Vault BOB wiring.


Preparing to install new tower at PV05.

Completed PV05 enclosure.


PV04 antenna replacement.

Old and new PV05 seismic stations.


Preparing to sling loads by helicopter to PV16 from STIF.


Slinging load into PV16.

# Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-2010-3 **Departure Date:** 11/18/2009 **Return Date:** 11/23/2009

**Purpose:** Upgrade existing digital stations and radios to a new system that will allow for digital upgrades of the remaining 8 analog stations, eliminate data dropouts, and provide redundant telemetry paths.

**Work Summary:** Replacement break-out boxes were installed at PV04, PV12, PV14, and PV17 to correct problems discovered with the equipment installed during October, 2009, and which had lead to PV04 going offline for several weeks. Several outstanding tasks from the digital radio upgrade were completed, including detailed measurement and validation of transmission lines and antennas. Several old antennas were replaced as a result of these measurements. Maintenance of analog instrumentation at stations PV02, PV11, PV15, and Hopkins Field was performed to bring analog stations PV11 and PV15 back on line. Several potential new new seismograph station sites were visited.

**Action Items:**

| | |
|---|---|
| 1 | Visit all remaining potential new seismograph sites. |
| 2 | Install seismometers at the 5 upgraded sites as soon as possible after the vendor delivers the instrumentation. |
| 3 | Configure additional security measures (RADIUS authentication) once basic operation and reliability have been established |
| 4 | Prepare a final security plan and formally bring the new communications network into production mode. |
| 5 | Optimize hub antenna position at PV02 once there are remote sites transmitting through PV02. |

**Personnel:**

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

**Work by Site:**

| | Site | Work Accomplished |
|---|---|---|
| 1 | PV02 | Tested transmission lines and antennas for digital radios; replaced used Omni antenna with new. Rewired solar panel fuses per current Matrix-5 recommendation. Tested analog receivers, and measured/set analog signal levels from PV15. |
| 3 | PV04 | Diagnosed why station was offline (both fusable links were tripped on the output stage of the dual linear power supplies within the DM-24 BOB). Measured current draw from installed seismometer, and found it to be within specifications. Opened seismometer vault and replaced sensor vault break-out-box (SV-BOB). Replaced GPS-BOB circuit board, and DM24-BOB. Ran cable tester to validate rewiring. Measured and validated transmission lines and antennas; replaced used Omni antenna with new unit. Rewired solar panel fuses per current Matrix-5 recommendation. Station back on line. |
| 5 | PV11 | Analog maintenance: Replaced DC/DC converter. Tested and adjusted analog instrumentation and radio. Analog station back on line. (Digital station already on line - no change). |
| 6 | PV12 | Replaced GPS-BOB circuit board, and DM-24-BOB. Measured and validated transmission lines and antennas; replaced defective PolyPhaser. Rewired solar panel fuses per current Matrix-5 recommendation. |
| 7 | PV14 | Replaced GPS-BOB circuit board, and DM-24-BOB. Measured and validated transmission lines and antennas; replaced used Yagi antenna with new unit. Rewired solar panel fuses per current Matrix-5 recommendation. |
| 8 | PV15 | Analog maintenance. Tested and adjusted analog instrumentation and radio. |
| 9 | PV17 | Replaced GPS-BOB circuit board, and DM-24-BOB. Measured and validated transmission lines and antennas; replaced used Yagi antenna with new unit. Rewired solar panel fuses per current Matrix-5 recommendation. |
| 10 | Hopkins Field | Analog maintenance: tested and adjusted signals from analog receivers. Tested PV11 and PV15 discriminators (were OK). |

# Paradox Valley Seismic Network - Site Visit Summary

**Site Visit Number:** PVSN-20010-4 **Departure Date:** 12/5/2009 **Return Date:** 12/7/2009

**Purpose:** Reconnaissance of new sites for seismograph stations

**Work Summary:** Final locations for four potential seismograph stations were determined, and the sites were staked, photographed, and documented. GPS coordinates and access tracks were recorded.

**Action Items:**

| | |
|---|---|
| 1 | Prepare an evaluation of options for upgrading the remaining set of stations to be completed in calendar year 2010, including likely decommissioning and replacement of PV08 and PV09, and adding new stations. |
| 2 | Reach a decision on which sites to add, if any, and decide on the final set of stations to upgrade to digital. |
| 3 | Prepare documentation needed for permit applications. |
| 4 | Submit permit applications and obtain permits (by April 15th, if possible). |
| 5 | Plan for late April or May trip with USGS to perform site preparations for this final set of stations. |

**Personnel:**

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

**Work by Site:**

| | Site | Work Accomplished |
|---|---|---|
| 1 | BR-5 | Cone Mountain (north of Sinbad Valley): revisited this area to better determine the indefinite contact between Quaternary landslide deposits and Morrison formation, and find suitable station site located on Morrison. Site was staked and documented. |
| 2 | BR-7 & BR-9 | Carpenter Ridge (northwest end of Paradox Valley, north side): found two suitable sites providing coverage of the northern valley events area. Sites are on Morrison (BR-7) or Dakota (BR-9) formation, have good radio coverage, and acceptable access. Sites were staked and documented. Also visited BR-2 again (upper northwest end of Carpenter Ridge) for comparison. |
| 3 | BR-8 | West end of Paradox Valley, south side of valley on bench formed by Glen Canyon group sandstones: found two suitable sites providing good coverage of the northwest cluster of induced events. Best site was staked and documented. |