Technical Memorandum No. 86-68330-2009-13

2008 Status Report
Paradox Valley Seismic Network
Paradox Valley Project, Colorado

Prepared by

Lisa Block
Chris Wood
Kenneth Mahrer

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

May 2009

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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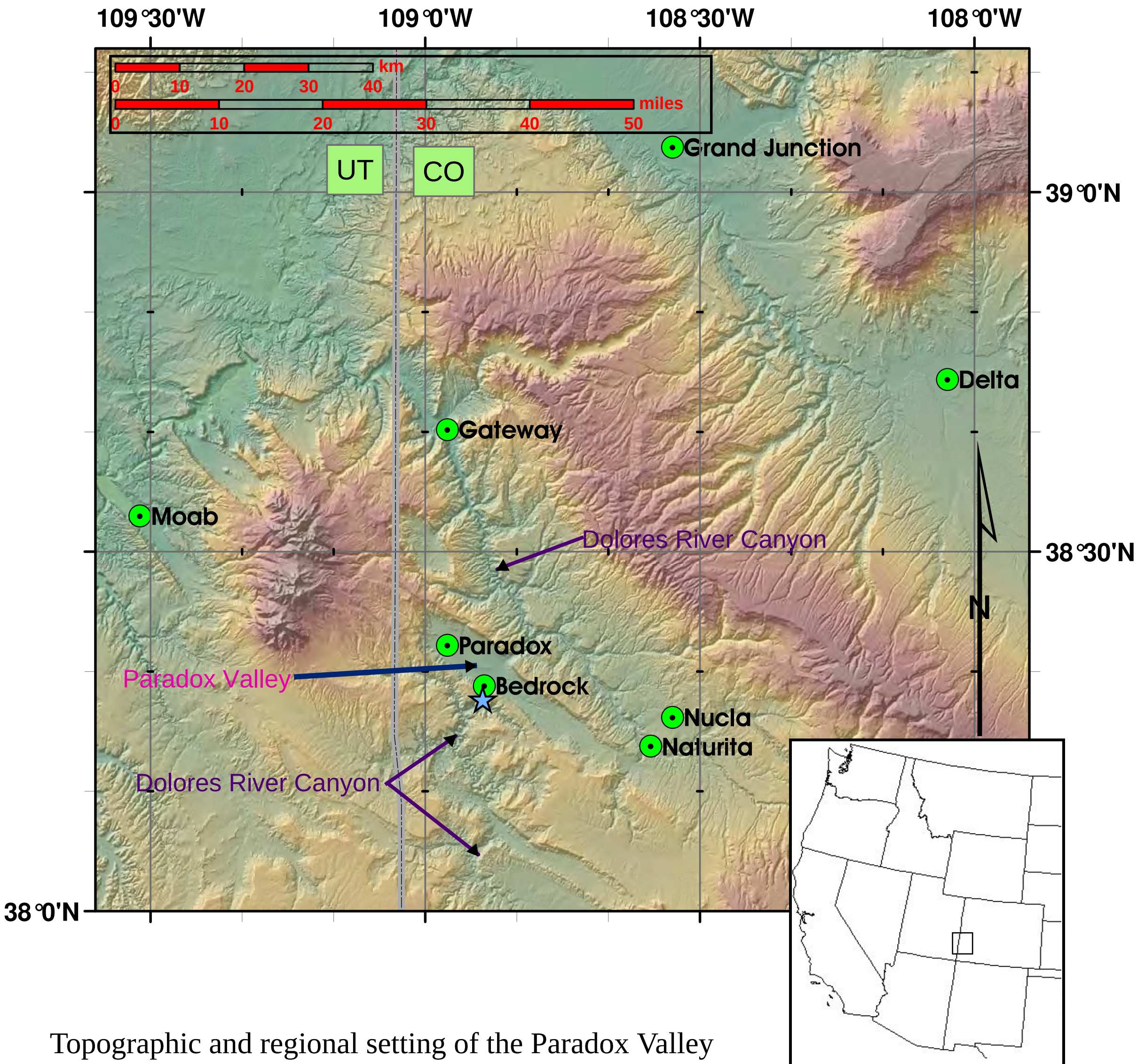
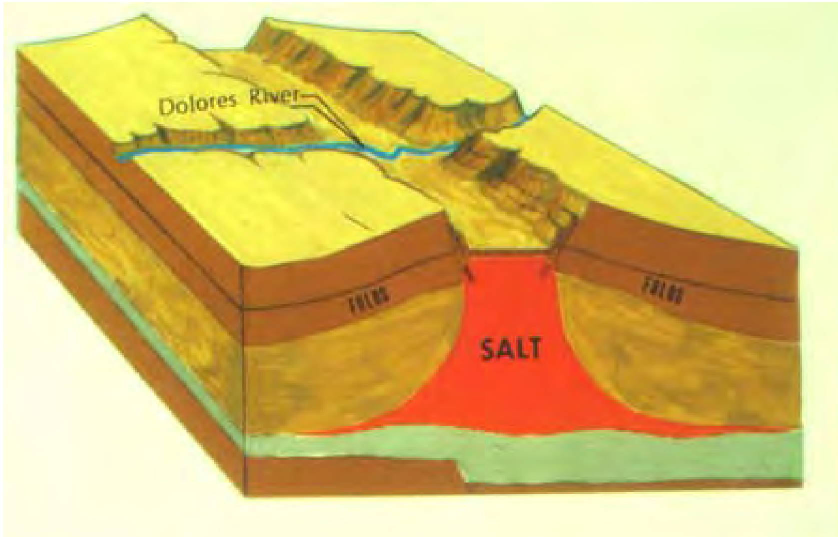


Topographic and regional setting of the Paradox Valley Unit. Shown are the injection well (star), Paradox Valley, Dolores River Canyon, local and regional municipalities (green circles with centered black dot), Colorado-Utah border, and geographic location in the western United States (insert).



Regional cross section showing the Dolores River Canyon and Paradox Valley. View is from the south looking north.

Dolores River Canyon and Paradox Valley, viewed to the northeast. Paradox Valley runs left and right, across the photo near the top.

Floor of Paradox Valley viewed to the northwest along valley axis

1.0 EXECUTIVE SUMMARY

This annual report describes (1) the seismic data from the Bureau of Reclamation's Paradox Valley Unit (PVU) deep-well injection project recorded during calendar year 2008, (2) the operations of the Paradox Valley Seismic Network (PVSN) and its staff in recording, archiving, and analyzing these data, and (3) the conclusions drawn by the staff from the seismic data recorded since the beginning of injection operations at PVU.

1.1 2008 - Highlights

(1) In 2008, PVSN recorded 97 induced microearthquakes located primarily within the two seismogenic zones defined by previous years' induced microearthquake locations (**Figure 1-1**). One zone is the primary seismogenic zone surrounding the injection well (the "near-well" region); the other zone is located ~7.5 km northwest of the injection well (the "NW cluster"). Of the 97 induced events recorded, 59 occurred in or near the primary near-well zone and 38 occurred in or near the secondary NW cluster.

(2) A few events that were recorded in 2008 locate between the primary and secondary zones of induced seismicity. This suggests that the historical aseismic gap between the two zones of induced seismicity may be starting to close.

(3) Five earthquakes that occurred in 2008 locate south and slightly east of the primary zone of induced seismicity, toward station PV03. Five events also occurred in this area in the previous year. This suggests that fluid pressure from the injection well may be migrating farther south.

(4) Nearly all induced seismic events with well-constrained locations recorded since 1991, including most of those recorded in 2008, locate more than 2.5 km below the surface (**Figure 1-2**).

(5) No large (magnitude **M**3.0 or greater) events occurred during 2008; the largest event recorded in 2008 within the two identified zones of induced seismicity was a magnitude **M**2.1.

(6) As in previous years, the spatial patterns of observed seismic sources seem to follow the Wray Mesa fault and fracture system and are consistent with local tectonic stresses.

(7) Injection controls (i.e., reduced injection rate and biannual 20-day shut-downs) were continued during 2008, and the rate of seismic event production remains very low compared to the early years of continuous pumping.

(8) During 2008, PVSN recorded 7 events approximately 12 to 15 km north of the injection well, on the northern edge of Paradox Valley. PVSN has been recording several events in this area every year since 2000. Magnitudes of events recorded in this area in 2008 range from -0.2 to 1.1.

1.2 Cumulative Findings

More than 4,500 induced earthquakes have been recorded by PVSN since injection began in 1991.

Only 22 earthquakes, about 0.5% of the induced events, have magnitudes greater than or equal to **M**2.5. In general, these events, with **M** >= 2.5, are the ones that have been reported felt

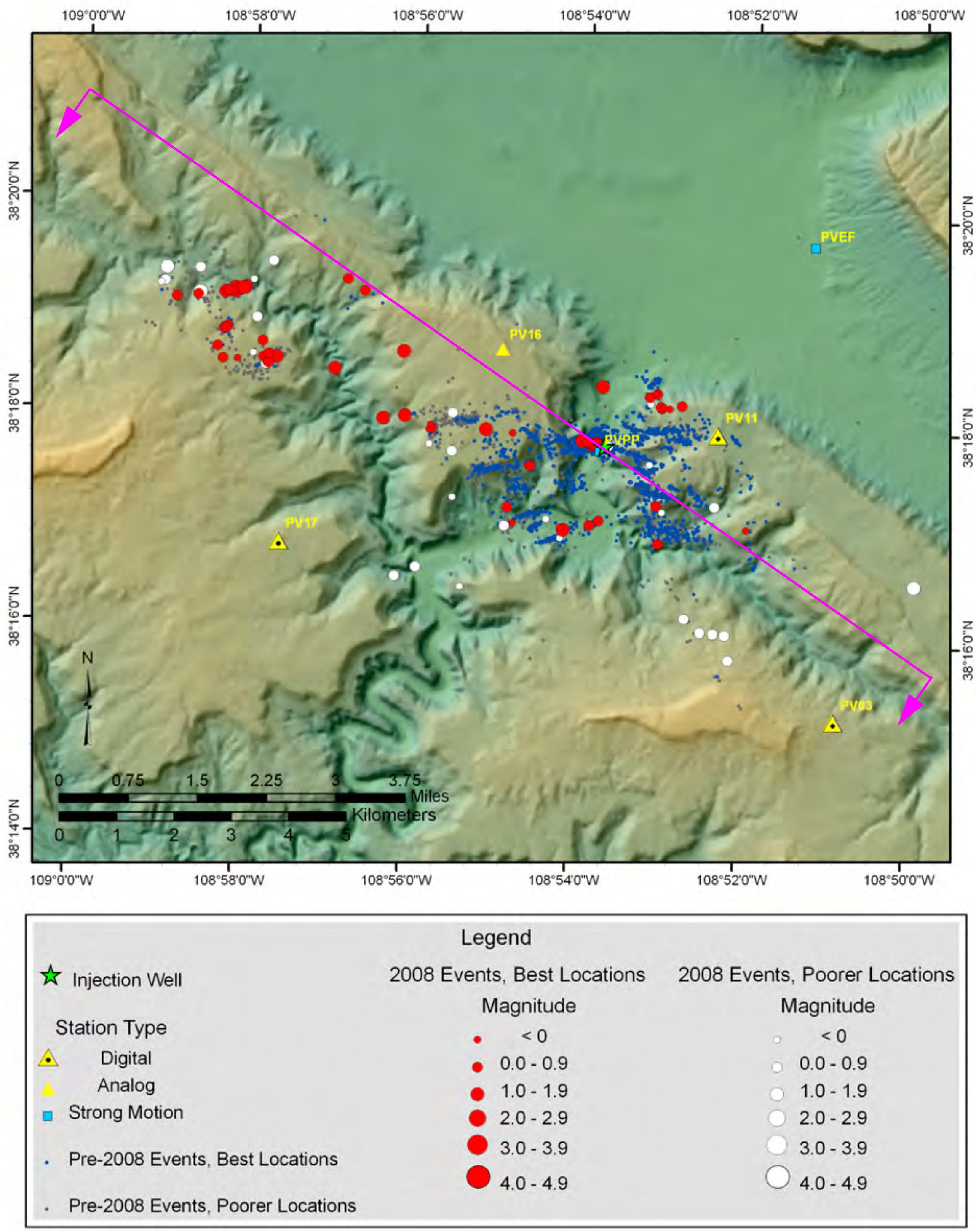


Figure 1-1 Map showing the locations of induced earthquakes recorded in 2008 (red and white circles), compared to the locations of previously-induced events (small gray and blue dots). The magenta line indicates the orientation of the cross section presented in Figure 1-2.

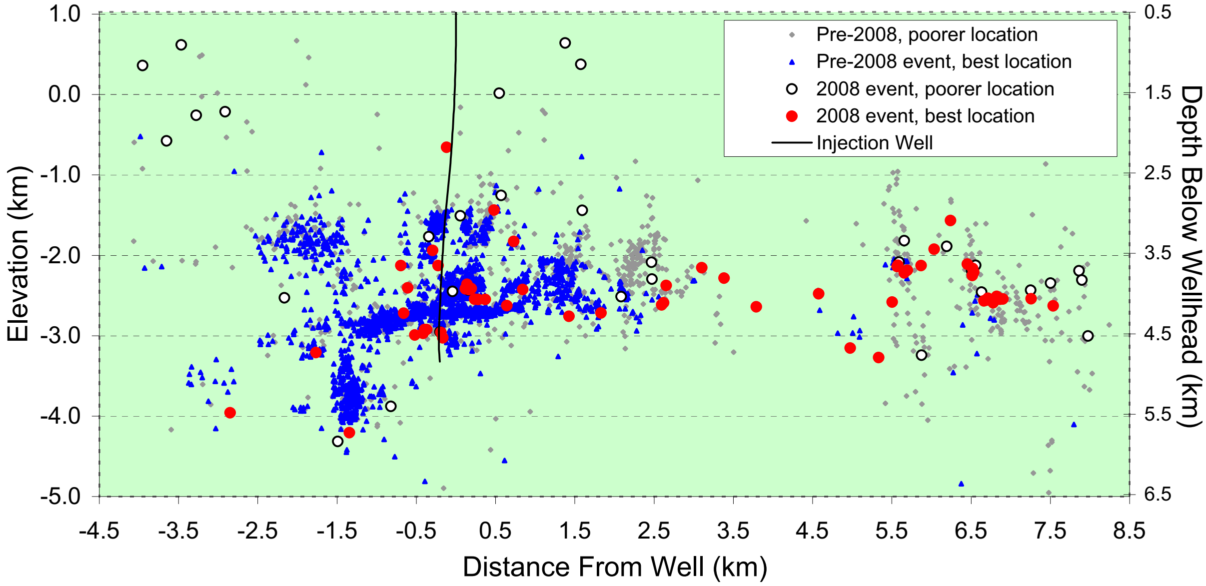


Figure 1-2 Vertical cross section parallel to Paradox Valley (looking to the southwest) showing the locations of induced earthquakes recorded in 2008 (red and white circles), compared to the locations of previously-induced events (small gray and blue dots). (The orientation of the cross section is indicated by the magenta line in Figure 1-1. Note that the depths of events locating shallower than approximately 2 km are poorly constrained.)

by local residents. Of these 22 events with **M** >= 2.5, only 5 have occurred since the injection rate was reduced by 33% in June, 2000.

Only 4 induced earthquakes with magnitude greater than or equal to **M**3.0 have occurred in the history of PVU operations. All but one of these occurred prior to the mid-2000 decrease in injection rate, including the largest induced event - an **M**4.3 event which occurred on May, 2000 (after ~4 years of continuous injection). The single event with magnitude larger than **M**3.0 that has occurred since the injection rate was decreased was an **M**3.9 event, which occurred in November, 2004.

Injection has induced two distinct seismic event zones: a primary zone, asymmetrically surrounding the well to a maximum radial distance of ~3+ km and a secondary zone, centered ~8 km to the northwest of the injection well. The primary seismogenic zone covers a reservoir volume of between 20 and 30 cubic kilometers.

Since about mid-1999, the seismicity has occurred within the interior and on the border of the existing seismogenic zones; the expansion of the seismogenic zones since then is negligible.

The vast majority of the recorded induced seismic events are vertically contained between ~2.5 km and ~6 km depth below the wellhead.

The induced seismicity at Paradox illuminates an extensive, non-symmetric, connected network of fractures, faults, joints, etc. The epicenters group into linear features that appear to coincide with the secondary fracture and fault network of the Wray Mesa fault system.

The spatial distribution of the epicenter lineations imply the locations of the major, through-going faults of the Wray Mesa system. The secondary seismogenic zone lies along the trend of the local fault system, the Wray Mesa system, from the primary seismogenic zone.

The rate of seismicity is not uniform; there are single, multi-day, and multi-week quiet periods and multi-hour to multi-week active periods.

Spatially, the seismicity occurs as isolated events and as occasional swarms; swarms can occur over hours, days, multiple weeks, or months for those swarm events associated with a large main event.

The swarms at Paradox associated with one large event sometimes show foreshocks and aftershocks or just aftershocks.

One seismic zone/swarm region has shown a weak correlation with large-scale pressure changes and is possibly triggered only after the injection pressure exceeds a threshold. It is also possible that this threshold may be increasing with time (i.e., with increased injection volume).

The major faults of the Wray Mesa fault system align with the current principal stress direction, showing only minor, if any, surface-recordable seismicity. However, these faults align with the local (predicted) hydraulic gradient and, most likely, act as fluid conduits. The location and activation of the secondary seismic zone northwest of the injection well confirms the fault-fluid-conduit model.

The fault-planes defined by focal mechanism solutions (i.e., moment tensors) align with the predicted shear directions and with the secondary faults and fractures of the Wray Mesa fault system.

Since 1996, the initiation of continuous pumping at PVU, the nominal injection pressure has exceeded fracture pressure of the injection reservoir.

The initial induced seismicity was probably due to injectate or connate fluids reducing the friction across faults, releasing the pre-existing shear stress across these faults.

The storage of injectate must be facilitated by existing pore space and by the injection pressure creating new (pore or fracture) volume, since injection can hydraulically fracture the rock matrix; the identified primary and secondary faults and fractures of the Wray Mesa system can only accommodate a few percent of the injectate volume.

Surface-recorded seismic events are radiated from shear slip on the pre-existing faults, joints, or other planes of weakness, not tensile or “new-fracture” openings.

The bi-annual 20-day shut-down periods implemented in mid-1999 and reduced injection rate beginning in mid-2000 have greatly reduced the rate of induced seismicity.

In 2002, PVU increased the percentage of Paradox Valley Brine in the injectate from 70% (with 30% fresh water) to 100% brine (no fresh water). This increase has not affected seismicity. However, the increased brine percentage has increased the bottom-hole pressure (due to increased specific gravity of the injectate) which has at times exceeded the maximum bottom-hole pressure prior to 2002.

By the end of 2008, PVU had injected 1561 Mgal of injectate. Since the injectate invasion increases the connate fluid pressure, the volumetric extent of the injectate is probably less than the volumetric extent defined by the seismicity.

2.0 PVSN - PROJECT OVERVIEW

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. The brine is pumped from 9 extraction wells located near the Dolores River, within Paradox Valley. The diverted brine is injected at high pressure into a deep, steel-cased disposal well, designated as PVU Salinity Control Well No. 1. At a depth of 4.3 km below the Earth's surface, perforations in the casing allow for the brine to be permanently stored in the surrounding Mississippian-aged Leadville Limestone and other formations. Operation of the well began in 1991 with a series of 7 separate 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, following the granting of an operations permit by EPA. Disposal of brine has continued round-the-clock since then, with injection occasionally interrupted for remedial maintenance and, beginning in 2000, for 20-day shut-downs every 6 months. Since 1991, the project has disposed of more than 1,400 Mgal of highly saline injectate (nearly 1300 kton of salts).

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. The network has been upgraded and expanded to 16 stations.

Numerous induced earthquakes have been observed since PVU began continuous injection in 1996, a few of which have been felt by nearby communities and reported in the media. To limit the production of felt events, detailed seismic monitoring became central to injection operations. Injection rates and pressures have been carefully managed to limit the production of induced earthquakes to acceptable levels, both in number and in magnitude.

Current 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, analyzing, and cataloging local seismic events within these data; (4) determining the location and origin time of each seismic event; (5) determining the cumulative and individual characteristics of the events; (6) identifying and evaluating relationships between seismicity, geology, tectonics, subsurface brine and connate water/pressure movements and locations, and injection parameters; (7) maintaining a database of both events and injection parameters; and (8) reporting findings both internally and to the scientific community.

To date, PVSN has recorded over 4,500 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 are located in two spatially-separated seismic source zones: a principal zone - asymmetric and E-W elongated surrounding the injection well and containing more than 90% of the recorded events - and a secondary zone - also asymmetric but centered about 7.5 km northwest of the injection well. From the western boundary of the principal zone, the secondary zone lies along the direction of the local major fault trend, the Wray Mesa Fault system.

Throughout most of PVU's injection history, the downhole injection pressure has been in the range of 80±2 MPa (~11,600 psi). This corresponds to surface pressures between 29 and 35 MPa (4,200 and 5,100 psi) and is about 10 MPa (~1,500 psi) above the (rock) fracture pressure at the injection depth. Although the injection pressure presumably causes the injectate and/or connate fluids to fracture (i.e., wedge open) the local rock mass, the data at the PVSN stations do not show the signature of tensile (i.e., fracture-opening) events. We believe to emplace the injectate, tensile events (i.e., opening new fractures and widening existing planes of weakness) are occurring, but these tensile events are too small to radiate sufficient energy (i.e., ground motion) to be detected by PVSN, since the closest PVSN station is 3 to 4 km from a seismogenic zone and is located at the ground surface. Instead, the recorded events are shear failures along pre-existing planes of weakness (e.g., faults, old fractures, etc.). These shear sources are not uniformly or randomly distributed within the two seismogenic zones, but define linear groups. These groups delineate secondary networks of fractures and faults of the Wray Mesa system. The shear planes of slip (i.e., fault-planes of the induced seismicity) align with the linear directions or strikes of these fractures and faults or with the anticipated principal shear stress directions. One very significant finding from these seismically-mapped fractures and faults is the substantial distance the pressure perturbations (either by injectate or connate fluids) have migrated through the Wray Mesa network of faults and fractures; the distance is at least the 7.5 kilometers from the injection well to the second seismogenic region.

The estimated maximum volume of the injectate held by the seismically-identified fractures and faults is nominally only a few percent of the total injectate volume; the remaining injectate has diffused into the local porosity: either into new microfractures or the poorly-developed system of pre-existing pores and microfractures - based on core samples recovered during drilling. This is not surprising, since the injection pressure exceeds the fracture pressure giving the injectate excessive energy to create new or widen existing pores, fractures, and joints.

Over its history, PVU has instituted strategies to mitigate risk of inducing larger (i.e., "felt") seismic events while maintaining the economic viability of injection. These strategies have included reducing injection rate and instituting the biannual 20-day shut-downs. The reduced injection rate presumably allows the injectate time to diffuse from the main fractures into the reservoir rock matrix. This reduces the fracture aperture and thereby reduces it perturbation to the local *in situ* stress. Similarly, the shut-downs allow the formation stresses time to relax as the injectate leaks from main fractures into pores and small fractures of the reservoir rock matrix. Since mid-2000, these changes have substantially reduced the rate of seismic event production.

3.0 PVSN OPERATIONS IN 2008

3.1 Network Maintenance and Upgrades

Upgrades to the Paradox Valley seismic network performed during 2008 included installing and bringing online four new 3-component digital seismic stations, and installing a new equipment rack and data acquisition servers at the Hopkins Field Airport in Nucla. The new equipment rack was installed at Hopkins Field in March, in order to improve network reliability, make the equipment more serviceable, reduce analog telemetry noise, prepare for digital seismic station upgrades, and to accommodate a data acquisition server. New digital stations were installed at existing sites PV02, PV03, PV10, and PV11. The digital seismometers, enclosures, towers, radios, antennas, and other necessary equipment were installed at the individual sites in August. In October, digital radios were added at relay stations PV04 and PV12 to relay signals from the new stations, necessary data acquisition servers were installed at Hopkins Field, and the four new digital stations were brought online. The old analog seismic stations have been temporarily left in-place and online in order to provide data to compare the performance of both systems during a transition period that is expected to last for several years.

Because of the extensive maintenance work performed at all existing seismic stations during 2007, little maintenance was required during 2008. All seismic stations remained functioning and online throughout 2008 with the exception of station PV08, which is a low-priority site whose original purpose was as a radio repeater site (it no longer serves that purpose). This 3-component station experienced partial/intermittent problems for about 42 days and was then completely down for another 47 days before being repaired and brought back online during the next regularly scheduled maintenance trip. Station PV08 is located far to the northeast of Paradox Valley, and it's main value is in locating non-injection-related local earthquakes and explosions. PVSN's ability to detect and accurately locate induced earthquakes occurring near the injection well was not diminished during the time that PV08 was offline.

3.2 Network Performance

PVSN performed extremely well throughout most of 2008. We've characterized the annual network performance for 2008 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 2008. 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. Solid blue lines in **Figure 3-1** indicate that the data channel was installed and functioning normally. Note that most PVSN seismic data channels were functioning normally throughout 2008, or in the case of the four new digital stations installed in October, 2008, since their date of installation. Dashed red lines in **Figure 3-1** indicate that the data channel was offline and therefore no data from that channel were being recorded. During 2008, only station PV08 went offline, as discussed above. Solid green lines indicate times when the data chan-

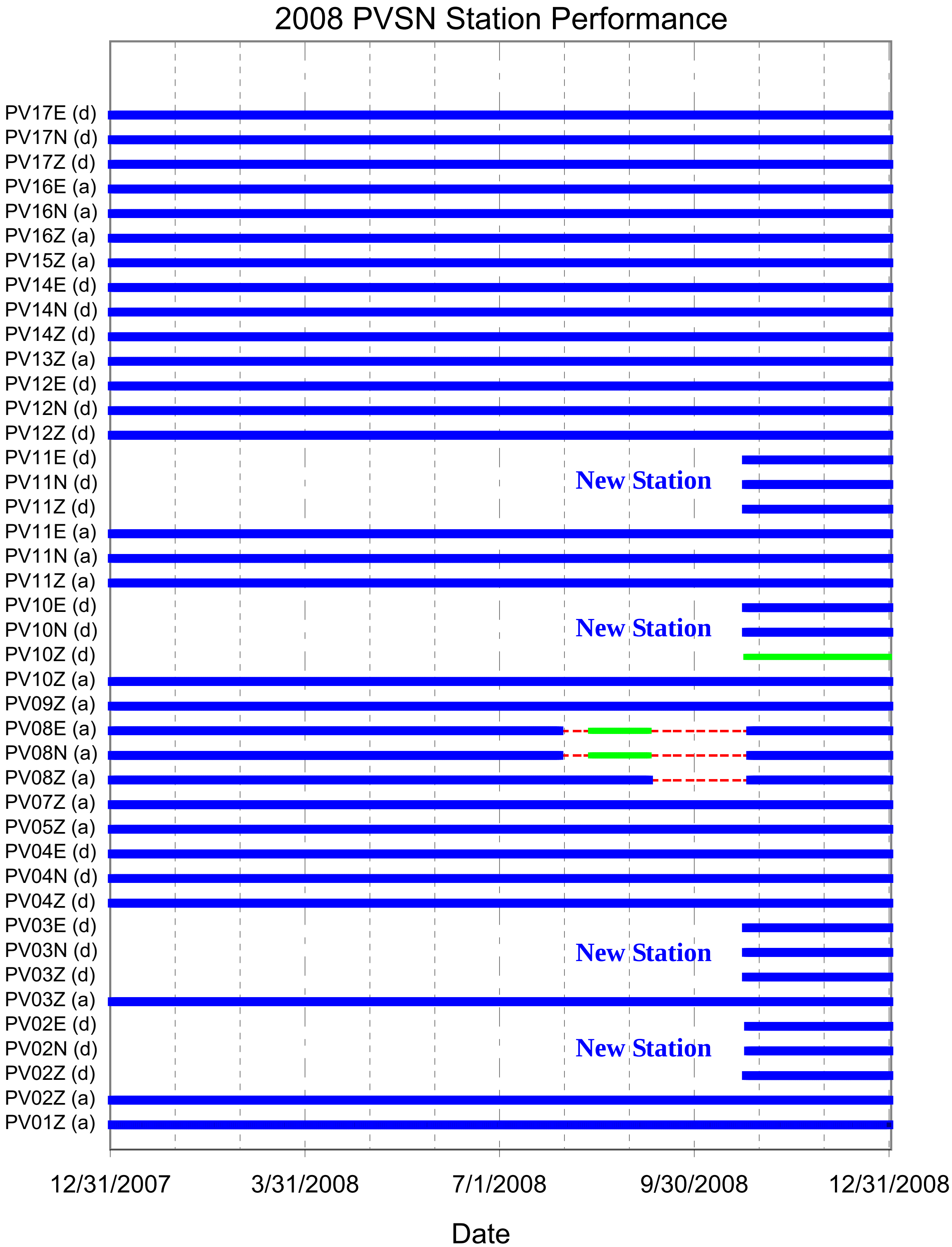


Figure 3-1 Performance of PVSN seismic data channels during 2008. The letter in parentheses indicates whether the data channel is analog (a) or digital (d). Blue lines indicate that the channel was installed and functioning well. Red dashed lines indicate that the channel was offline. Green lines indicate that the channel was online but experiencing some type of problem; see text for explanations. Note that digital stations PV02, PV03, PV10, and PV11 were installed in October, 2008.

nel was either offline intermittently, as was the case for the horizontal components at station PV08 during August-September, 2008, or that there was some other problem with the data that should be addressed. The new digital vertical component at station PV10 is given a partial (green) performance rating because that channel is extremely noisy and the seismometer should be replaced. Note, however, that the analog vertical component at PV10 is still functioning normally and hence good-quality vertical-component data is still being recorded at that site. 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 performance of PVSN data acquisition during 2008 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

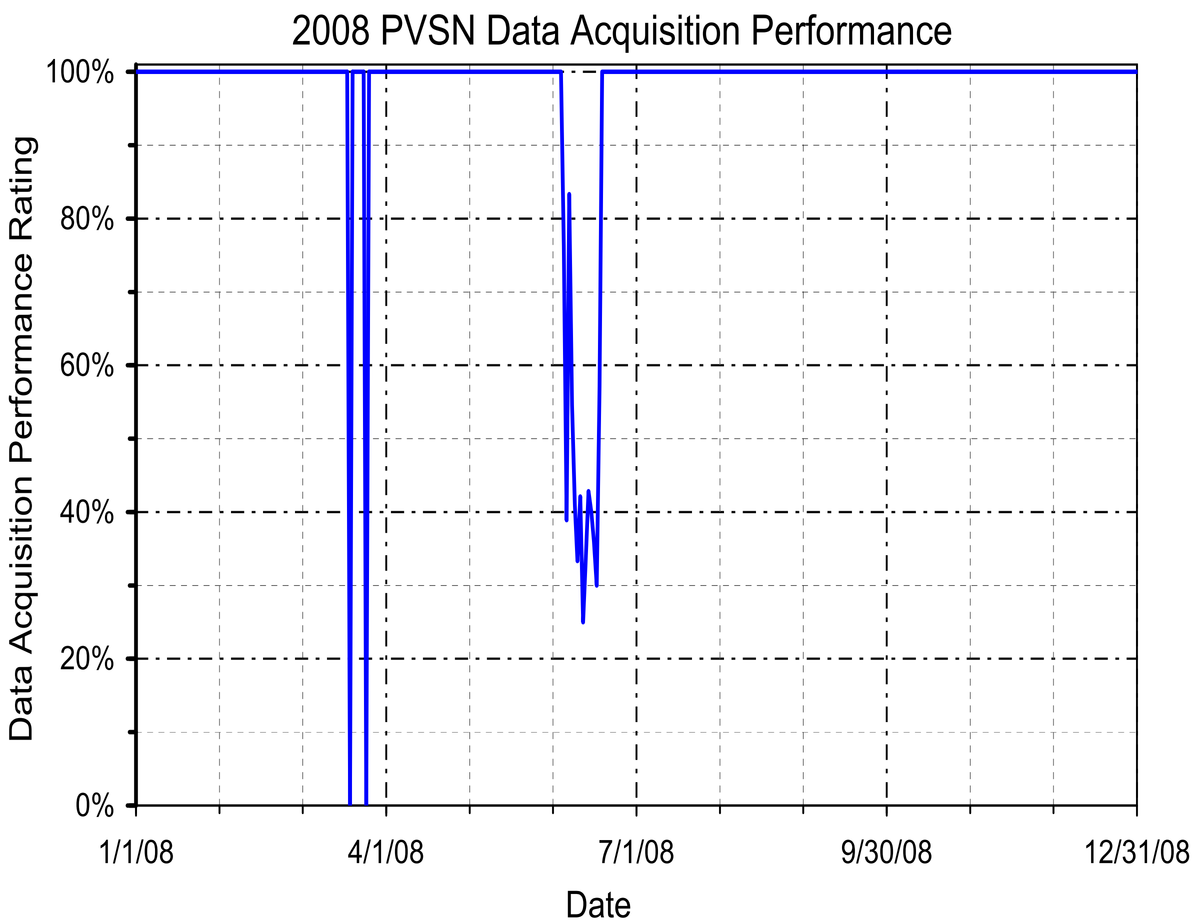


Figure 3-2 Performance of PVSN data acquisition during 2008. A rating of 100% indicates that PVSN was continuously triggering on seismic events above the desired detection threshold and properly recording the seismic datafiles. A rating of 0% indicates that some part of the data acquisition, transmission, or recording system was down and no data were recorded. An intermediate rating indicates that the data acquisition system was functioning abnormally; the rating value indicates the estimated percentage of events that were properly recorded during that time period. See text for further explanations.

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 2008, PVSN data acquisition was completely shut down for only two brief time periods, both of which occurred during March. The first shut-down lasted about 28 hours and was caused by a Denver office security scan which inadvertently brought down routers. The second network shut-down lasted approximately 30 hours and was planned in order to install a new electronics rack at Hopkins Field. The partial data acquisition performance rating shown for June represents a period of 14 days (6/5/2008 - 6/18/2008) when the computer in Denver running the data acquisition system was experiencing internal memory problems. These problems caused a portion of the triggered seismic event data to be lost on each of those 14 days. The percent of seismic event data lost on each day ranges from 17% to 75%. (The computer which experienced these problems is scheduled to be replaced in 2009, when the data acquisition software is ported from the Unix operating system to Linux.) Accounting for the periods when the network was offline and the interval of partial data acquisition, PVSN acquired approximately 356 days' worth of seismic data, out of a 366-day calendar leap year, which is equivalent to 97.2% uptime.

PVSN performance, both in terms of the performance of individual seismic stations and the performance of the data acquisition system, was much improved in 2008 compared to the previous year. The percentage of the seismic data channels (installed at any given time) which were operating properly and being recorded is plotted as a function of time for 2007 and 2008 in **Figure 3-3**. This graph represents the total network performance and includes the affects of both individual seismic station performance and performance of the network data acquisition system. As can be seen, individual station performance began improving in mid-2007 as extensive field maintenance was performed. This greatly improved station performance has been maintained throughout 2008, with 90% or more of the data channels remaining operational at all times. The graph also shows that the number of network shut-downs has been greatly reduced in 2008 compared to the previous year.

3.3 Data Processing Improvements

Several steps were completed in 2008 to improve routine processing of PVSN seismic data. Procedures for routine processing and datafile management of the PVSN seismic event data were formalized in a written document. This document is intended for internal use and is maintained in Reclamation's Denver Office. The written procedures should help provide consistency in PVSN data processing and datafile management through future years, and will be updated periodically as needed. Another improvement was the training of two additional personnel to perform PVSN routine data processing. This has improved our ability to keep up-to-date with incoming seismic data, which is especially important since the event triggering was made more sensitive in November, 2007, and as a result the amount of data to be processed has increased. Also in 2008, the PVSN datafiles and computer codes used for routine data processing were migrated from obsolete computers operating under Unix to new Linux-based computers. In addition to having the seis-

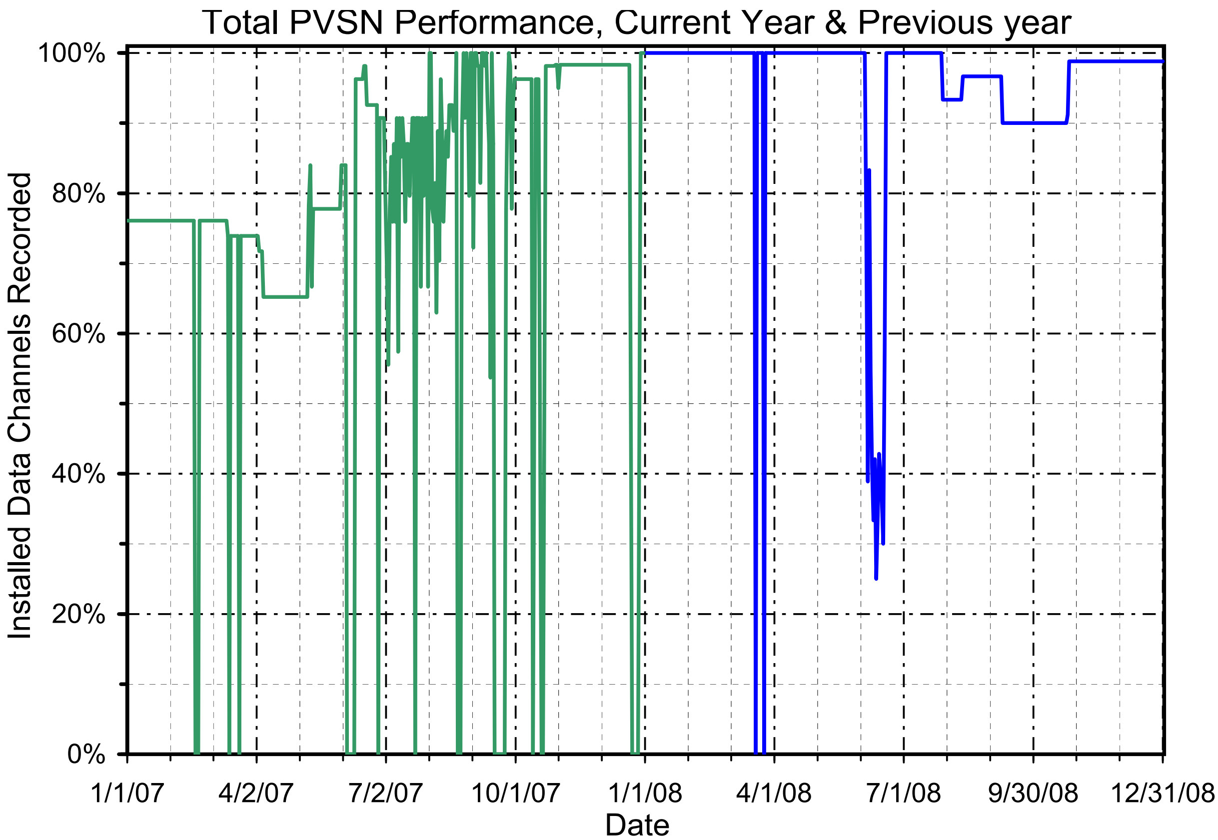


Figure 3-3 Total PVSN performance for the current year (blue line) and previous year (green line). The total performance rating reflects both the performance of individual seismic stations and the performance of the PVSN data acquisition system. It is computed as the percent of installed seismic data channels that are both functioning properly in the field and being recorded correctly by the acquisition system at any given time.

mic data and computer codes residing on more reliable computer systems meeting higher IT security requirements, this migration has improved the ability to have multiple staff members perform routine data processing, since the data and computer codes can be accessed from multiple Linux-based or Windows-based Reclamation computers.

4.0 SEISMIC DATA RECORDED IN 2008

4.1 Annual Summary

114 earthquakes were recorded within the perimeter of PVSN during 2008. 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 2008 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 4-4**. The earthquake locations are plotted on the map in **Figure 4-1.**

Table 4-1 Local earthquakes recorded by the PVSN during 2008

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
1/1/2008	13:40:37	38.2990	-108.9298	-2.38	3.90	-0.5	near-well
1/1/2008	13:40:56	38.2983	-108.9300	-2.59	4.12	-0.1	near-well
1/1/2008	13:41:14	38.2985	-108.9295	-2.62	4.14	0.6	near-well
1/10/2008	1:12:02	38.2875	-108.8843	-4.21	5.73	0.3	near-well
1/11/2008	6:18:47	38.2849	-108.9062	-1.51	3.03	-0.2	near-well
Injection resumed on January 11.							
1/12/2008	22:43:02	38.3028	-108.8839	-2.92	4.45	0.6	near-well
1/12/2008	22:43:54	38.3030	-108.8835	-2.97	4.50	-0.3	near-well
1/12/2008	22:45:04	38.3031	-108.8840	-2.93	4.45	0.1	near-well
1/12/2008	22:50:07	38.3045	-108.8863	-0.66	2.18	0.2	near-well
1/16/2008	21:23:19	38.2841	-108.8976	-2.41	3.93	0.3	near-well
1/19/2008	16:36:48	38.3202	-108.9837	-2.19	3.72	0.1	NW cluster
1/20/2008	7:43:21	38.3199	-108.9845	-2.31	3.83	-0.1	NW cluster
2/4/2008	6:04:11	38.3223	-108.9834	-3.00	4.53	1.2	NW cluster
2/7/2008	9:56:48	38.2865	-108.8832	-4.32	5.84	-0.1	near-well
2/7/2008	19:26:27	38.3186	-108.9766	-2.43	3.96	1.1	NW cluster
2/11/2008	13:50:36	38.2841	-108.8663	-3.96	5.48	-0.4	near-well
2/22/2008	0:10:30	38.3182	-108.9770	-2.54	4.06	0.2	NW cluster
2/25/2008	5:36:13	38.4950	-109.2170	-22.60	24.12	0.6	other
2/27/2008	1:09:01	38.3171	-108.8071	-2.61	4.14	-0.5	NW cluster
2/27/2008	14:00:43	38.3103	-108.9728	-2.11	3.64	0.3	other
3/6/2008	7:19:50	38.3188	-108.9715	-2.54	4.07	1.0	NW cluster

Table 4-1 Local earthquakes recorded by the PVSN during 2008

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
3/6/2008	7:21:03	38.3189	-108.9711	-2.54	4.07	0.8	NW cluster
3/6/2008	7:21:16	38.3190	-108.9709	-2.55	4.07	0.0	NW cluster
3/6/2008	18:59:20	38.2738	-108.9229	0.02	1.51	-0.6	near-well
3/7/2008	12:43:20	38.3178	-108.9813	-2.63	4.15	0.9	NW cluster
3/11/2008	17:03:08	38.3093	-108.9626	-2.22	3.74	0.0	NW cluster
3/13/2008	4:16:18	38.3093	-108.9656	-3.24	4.77	-1.0	NW cluster
3/28/2008	20:14:38	38.3034	-108.8861	-2.96	4.48	-0.1	near-well
3/29/2008	16:32:20	38.2972	-108.8984	-2.55	4.07	0.0	near-well
4/3/2008	2:22:34	38.2970	-108.8979	-2.55	4.07	0.6	near-well
4/3/2008	9:20:33	38.3136	-108.9707	-2.19	3.72	-0.9	NW cluster
4/3/2008	9:20:34	38.3134	-108.9709	-2.25	3.78	0.3	NW cluster
4/3/2008	15:22:35	38.3080	-108.9626	-2.13	3.65	0.7	NW cluster
4/3/2008	15:23:09	38.3087	-108.9632	-1.82	3.34	-0.2	NW cluster
4/3/2008	21:22:34	38.3130	-108.9715	-2.21	3.73	0.4	NW cluster
4/3/2008	22:52:10	38.4041	-108.9276	-3.19	4.72	0.7	northern valley
4/10/2008	6:09:22	38.2679	-108.8748	-0.26	1.78	0.9	near-well
4/20/2008	9:45:16	38.3149	-108.9651	-1.89	3.41	0.1	NW cluster
5/3/2008	16:00:27	38.3074	-108.9493	-2.48	4.00	1.0	NW cluster
5/17/2008	7:43:12	38.3954	-108.9796	-5.47	6.99	1.1	northern valley
5/17/2008	15:11:14	38.3088	-108.9636	-2.19	3.71	0.8	NW cluster
5/18/2008	13:10:38	38.3088	-108.9609	-2.58	4.11	1.3	NW cluster
5/19/2008	4:12:10	38.2761	-108.8324	-2.21	3.73	1.0	near-well
5/21/2008	7:20:59	38.2836	-108.9144	-1.26	2.78	0.0	near-well
5/26/2008	3:48:03	38.2931	-108.9098	-2.43	3.95	0.7	NW cluster
5/26/2008	15:17:48	38.3077	-108.9631	-2.08	3.61	0.3	NW cluster
5/26/2008	18:19:40	38.3079	-108.9626	-2.14	3.66	0.5	near-well
5/28/2008	2:02:41	38.2865	-108.9141	-1.83	3.35	0.2	NW cluster
5/28/2008	4:15:32	38.3113	-108.9638	-2.13	3.65	0.2	NW cluster
6/15/2008	19:24:42	38.2966	-108.8943	-2.45	3.97	0.0	near-well
6/18/2008	19:06:01	38.3083	-108.9687	-1.93	3.45	-0.1	NW cluster
Injection well was shut in on June 19. (wellhead pressure: 4819 psi)							
7/3/2008	17:21:49	38.2849	-108.8957	-2.13	3.65	0.1	near-well
Injection resumed on July 8. (wellhead pressure: 1263 psi)							
7/9/2008	8:25:04	38.3190	-108.9703	-2.51	4.03	0.9	NW cluster
7/9/2008	9:35:33	38.3192	-108.9695	-2.59	4.12	2.1	NW cluster
7/9/2008	9:56:15	38.3194	-108.9684	-2.54	4.06	1.4	NW cluster
7/9/2008	10:06:29	38.3195	-108.9680	-2.56	4.08	1.0	NW cluster
7/9/2008	19:13:45	38.3239	-108.9622	-2.12	3.65	0.0	NW cluster
7/10/2008	18:16:12	38.2767	-108.9319	0.64	0.88	0.4	near-well
7/12/2008	18:16:15	38.3033	-108.8798	-2.72	4.24	0.0	near-well
7/12/2008	18:17:05	38.2596	-108.8024	-5.96	7.49	-0.2	near-well
7/12/2008	18:16:53	38.3028	-108.8822	-2.99	4.52	-0.3	near-well
7/19/2008	21:52:12	38.3934	-108.8676	-2.79	4.32	-0.2	northern valley
7/20/2008	5:48:19	38.3925	-108.8676	-2.78	4.30	0.4	northern valley
7/20/2008	10:16:12	38.3919	-108.8668	-2.70	4.22	0.1	northern valley

Table 4-1 Local earthquakes recorded by the PVSN during 2008

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
7/20/2008	22:03:04	38.3923	-108.8672	-2.74	4.26	0.2	northern valley
7/21/2008	10:06:39	38.3932	-108.8682	-2.81	4.33	0.3	northern valley
8/9/2008	11:14:01	38.3224	-108.9767	-2.35	3.87	0.5	NW cluster
8/15/2008	17:22:49	38.2969	-108.8966	-2.36	3.89	0.1	near-well
8/23/2008	4:19:29	38.3051	-108.8848	-2.96	4.48	0.6	near-well
8/23/2008	4:20:09	38.3051	-108.8850	-3.03	4.55	-0.2	near-well
8/29/2008	14:17:13	38.2960	-108.9300	-2.30	3.82	-0.1	near-well
9/2/2008	9:44:22	38.2950	-108.9254	-2.52	4.04	0.3	near-well
9/2/2008	22:26:41	38.2878	-108.9250	-1.44	2.97	-0.4	near-well
9/9/2008	11:37:54	38.4949	-109.1497	-19.77	21.29	1.5	other
9/9/2008	11:42:50	38.4874	-109.1322	-17.01	18.54	0.4	other
9/9/2008	15:21:11	38.4883	-109.1324	-16.73	18.26	1.1	other
9/16/2008	10:14:24	38.3196	-108.9675	-2.57	4.09	1.2	NW cluster
9/16/2008	10:15:16	38.3209	-108.9659	-2.46	3.98	-0.5	NW cluster
9/18/2008	17:04:19	38.2973	-108.8995	-2.55	4.07	1.0	near-well
9/19/2008	7:13:04	38.2969	-108.8969	-2.43	3.96	0.3	near-well
9/25/2008	18:48:28	38.3104	-108.9356	-2.64	4.16	1.1	near-well
9/30/2008	22:35:37	38.2819	-108.9032	-1.77	3.29	-0.5	near-well
9/30/2008	22:35:37	38.2833	-108.9027	-1.94	3.46	1.2	near-well
10/10/2008	12:29:18	38.2676	-108.8698	-0.58	2.10	0.7	near-well
10/14/2008	18:46:41	38.3010	-108.9254	-2.09	3.61	0.3	near-well
10/16/2008	16:59:51	38.2637	-108.8690	0.36	1.16	0.4	near-well
10/20/2008	20:15:29	38.3131	-108.9712	-2.16	3.69	0.3	near-well
10/20/2008	23:34:31	38.2876	-108.8727	-2.53	4.05	0.3	NW cluster
10/20/2008	23:35:05	38.2939	-108.8859	-3.88	5.40	-0.2	near-well
10/21/2008	0:25:32	38.2699	-108.8780	-0.21	1.74	0.6	near-well
10/28/2008	19:23:18	38.2751	-108.9360	0.38	1.15	0.8	near-well
10/31/2008	12:57:39	38.2969	-108.8967	-2.42	3.94	1.3	near-well
11/1/2008	1:24:54	38.2969	-108.8968	-2.39	3.91	0.2	near-well
11/5/2008	1:34:40	38.2815	-108.8837	-3.21	4.73	0.7	near-well
11/7/2008	19:43:40	38.3004	-108.9349	-2.16	3.68	1.2	near-well
11/10/2008	18:03:54	38.4932	-109.0673	-9.93	11.45	1.9	other
11/11/2008	19:12:27	38.4822	-109.0614	-6.63	8.16	2.0	other
11/11/2008	19:19:25	38.4786	-109.0728	-8.66	10.18	2.0	other
11/12/2008	6:12:19	38.4816	-109.0816	-10.33	11.86	2.1	other
11/12/2008	7:44:40	38.2970	-108.8963	-2.42	3.94	0.6	near-well
11/16/2008	7:14:03	38.3059	-108.8957	-2.63	4.15	1.2	near-well
11/17/2008	9:48:02	38.2968	-108.8975	-2.41	3.94	1.2	near-well
11/17/2008	9:48:24	38.2967	-108.8973	-2.42	3.95	0.8	near-well
11/17/2008	9:49:31	38.2968	-108.8971	-2.43	3.95	0.2	near-well
12/2/2008	21:29:24	38.2678	-108.8722	0.62	0.91	0.6	near-well
12/3/2008	8:14:40	38.2982	-108.9134	-2.76	4.28	-0.8	near-well
12/3/2008	8:14:43	38.2986	-108.9187	-2.72	4.24	1.3	near-well
12/7/2008	0:13:30	38.3083	-108.9716	-1.57	3.09	0.9	NW cluster
12/7/2008	3:17:23	38.3197	-108.9438	-3.15	4.68	0.7	NW cluster

Table 4-1 Local earthquakes recorded by the PVSN during 2008

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
12/10/2008	22:30:55	38.2841	-108.9128	-1.44	2.96	-0.2	near-well
Injection well was shut in on December 17. (wellhead pressure: 4822 psi)							
12/17/2008	16:29:49	38.5301	-108.5752	-19.12	20.64	0.9	other
12/21/2008	15:45:15	38.3215	-108.9473	-3.27	4.80	0.9	NW cluster
12/28/2008	12:18:49	38.2836	-108.9034	-2.13	3.65	-0.5	near-well
12/31/2008	23:46:39	38.2998	-108.9393	-2.29	3.81	1.1	near-well

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

near-well: located within 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 2008 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 not operating properly (green marks across the top of the chart), injection well shut-ins (blue marks at the top of the chart), and site visits (vertical dashed lines). Note that during the 14-day period in June during which time the network was not fully functional (as indicated by the green mark across the top of the chart in **Figure 4-2),** the network was online but the data for approximately 57% of the triggered seismic events were lost due to corrupted memory in the data acquisition computer (as described in section 3). Hence, the seismicity rate for that time interval is under-estimated.

4.2 Injection-Induced Earthquakes

Figure 4-2 shows that there was a distinct change in the nature of the induced seismicity during the later part of 2008, when injection resumed after the July injection well shut-in. During the first half of the year, events were detected in both the main zone of induced seismicity ("near-well" region), and in the zone of induced seismicity located about 7.5 km northwest of the well ("NW cluster"). Between the onset of injection in mid-January and the injection well shut-in in mid-June, typically 2 to 3 times more events occurred in the NW cluster than in the near-well region. Shortly after injection resumed following the July shut-in, several relatively large events occurred in the NW cluster (up to **M**2.1), and a few much smaller events occurred in the near-well region (as well as several small-magnitude northern-valley events). This was followed by a period of nearly a month with no detected induced seismicity. From about mid-August to the end of 2008, PVSN detected a fairly regular number of induced seismic events, with the overwhelming majority of them occurring in the near-well region. Very few NW-cluster events (and no northern-valley events) were detected after mid-August. The seismicity rate of the near-well events substantially increased in mid-August (compared to before the July injection well shut-in)

Table 4-2 Summary of events recorded during 2008 in the four defined location categories

Location Category[1]	Number of Earthquakes	Magnitude Range	Median Magnitude
near-well	59	-0.8 to 1.3	0.30
NW cluster	38	-1.0 to 2.1	0.45
northern valley	7	-0.2 to 1.1	0.30
other	10	-0.5 to 2.1	1.30
TOTAL	114	-1.0 to 2.1	0.35

[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 2008. These rates were computed using the approximate number of days the network was operational, 356, as discussed in section 3.

Earthquake Group	All Magnitudes		Magnitude >= **M**0	
	Number of Events Recorded	Average Daily Rate	Number of Events Recorded	Average Daily Rate
near-well induced events	59	0.166	41	0.115
NW-cluster induced events	38	0.107	32	0.090
all induced events	97	0.273	73	0.205
northern valley events	7	0.020	6	0.017
other (isolated local earthquake)	10	0.028	9	0.025
TOTAL	114	0.320	88	0.247

and the seismicity rate of the NW-cluster events significantly decreased (**Figure 4-3**). This implies that stress conditions changed in both reservoirs during July-August. A possible explanation for this is that the fluid flow to the northwest reservoir was reduced, resulting in locally higher stresses and more seismicity in the main fractured reservoir near the injection well. Past data have not been re-analyzed to determine how often such reversals in the relative amounts of near-well and NW-cluster seismicity occurs.

The magnitudes of the induced events occurring in the near-well and NW-cluster regions during 2008 were of similar magnitude, as can be seen in the event summary in **Table 4-2** and the magni-

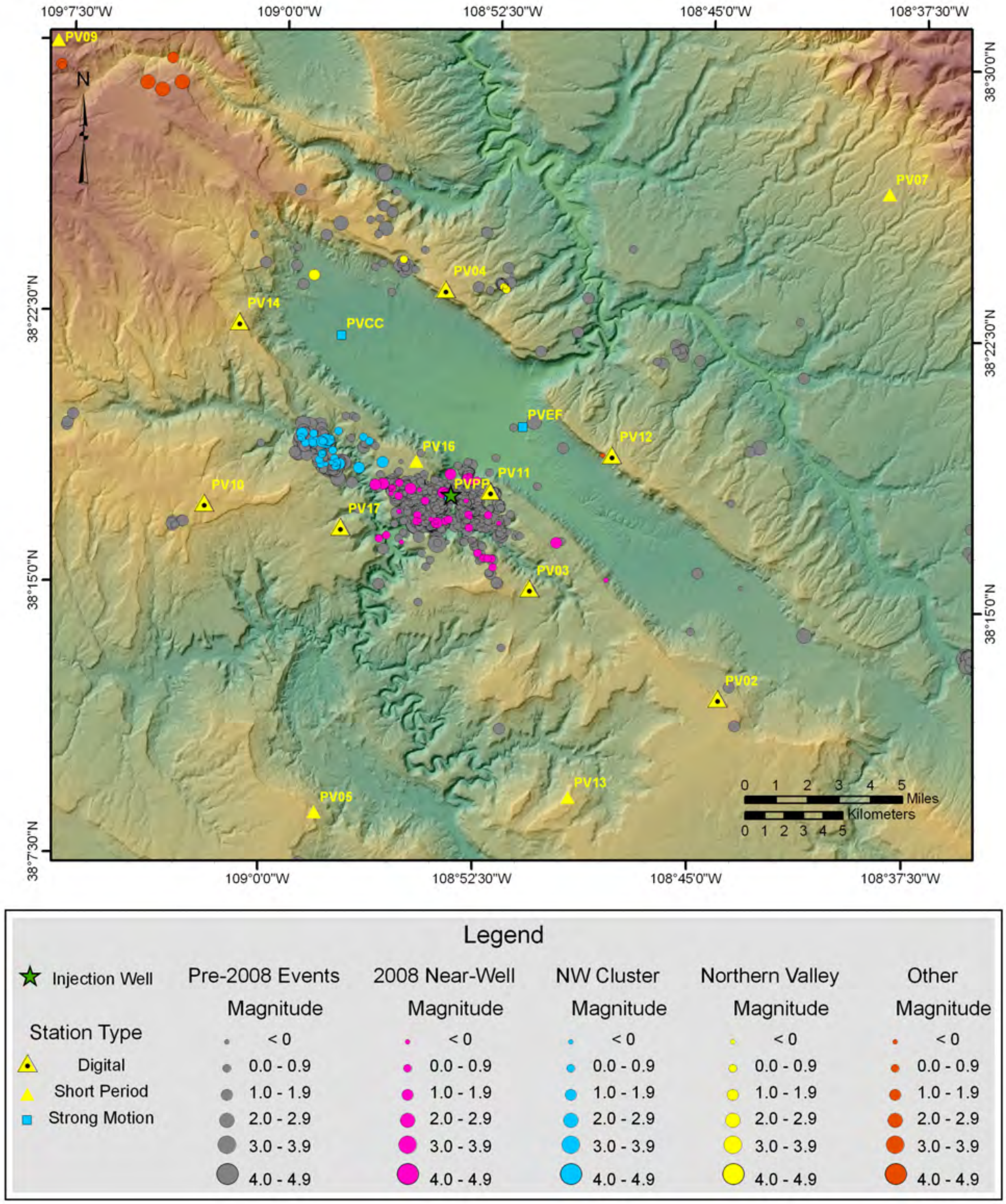


Figure 4-1 Locations of local earthquakes recorded by PVSN during 2008 (colored circles) and previous years (gray circles). Note that some of the pre-2008 local events shown may be explosions that have not been properly classified in the data files.

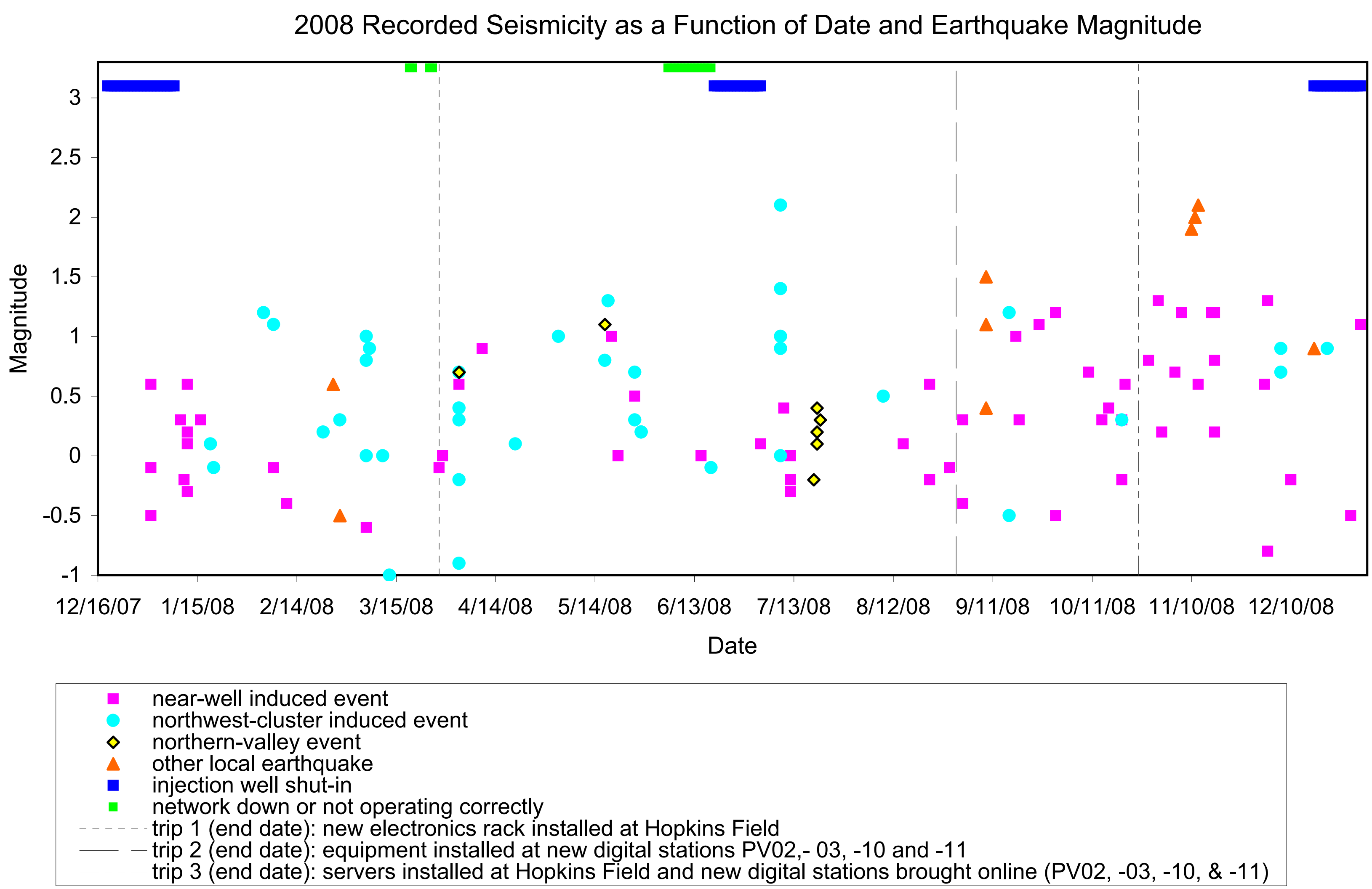


Figure 4-2 Earthquakes recorded by PVSN during 2008, plotted as a function of date, magnitude, and event location category. The dates of network down-times, injection well shut-ins, and other significant activities such as PVSN site visits are included as indicated by the legend.

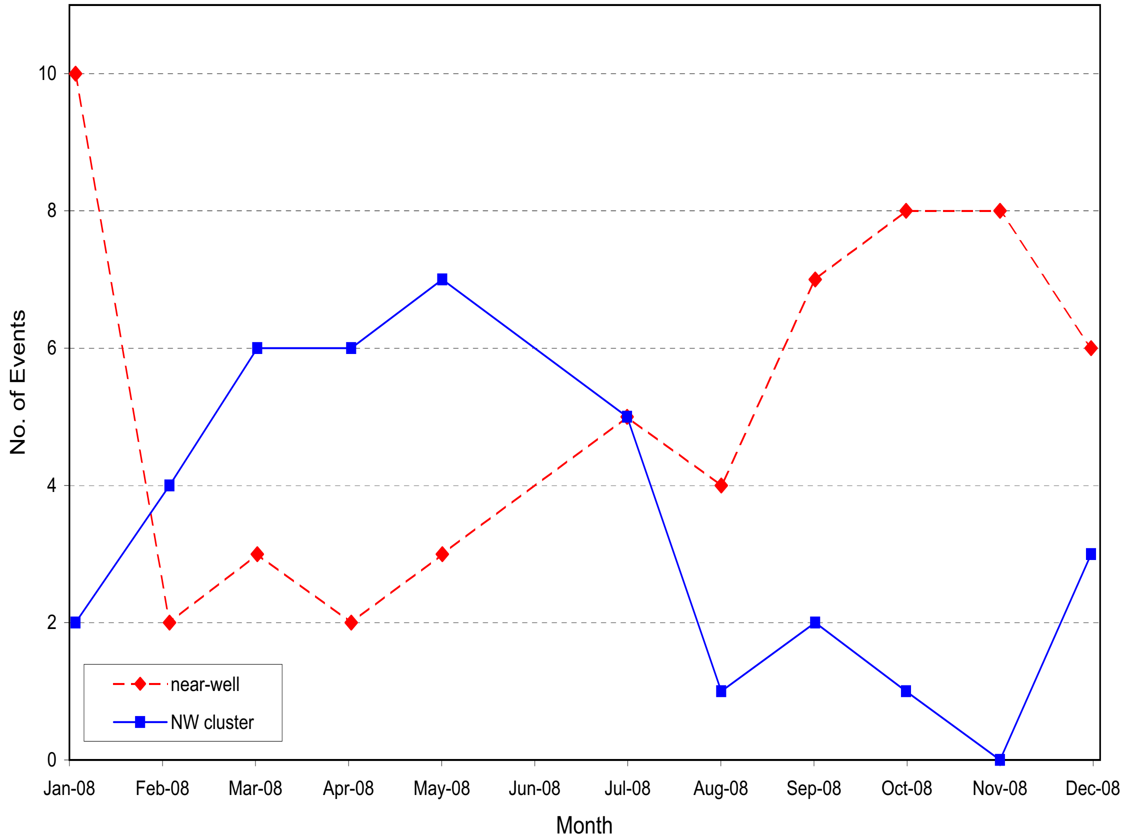


Figure 4-3 Number of earthquakes detected in the near-well (dashed red line) and NW-cluster (solid blue line) regions per month during 2008. Note that data for the month of June is not presented because the seismicity rate for that month is under-estimated due to loss of data. See text for details.

tude histograms presented in **Figure 4-4**. Magnitudes of the near-well events range from -0.8 to 1.3, with a median value of **M**0.30. Magnitudes of the NW-cluster events range from -1.0 to 2.1, with a median value of **M**0.45.

The majority of the induced earthquakes recorded during 2008 locate in areas of previous seismic activity, as seen in the expanded-scale map presented in **Figure 4-5** and the vertical cross section in **Figure 4-6**. In these figures, the earthquakes that occurred during 2008 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 events recorded during 2008 occur on or very near previously-active fractures, especially those that have the best-constrained hypocenters (red circles). With a few exceptions (described below), events that locate farther from previously-active fractures are generally those having less reliable hypocenters (white circles).

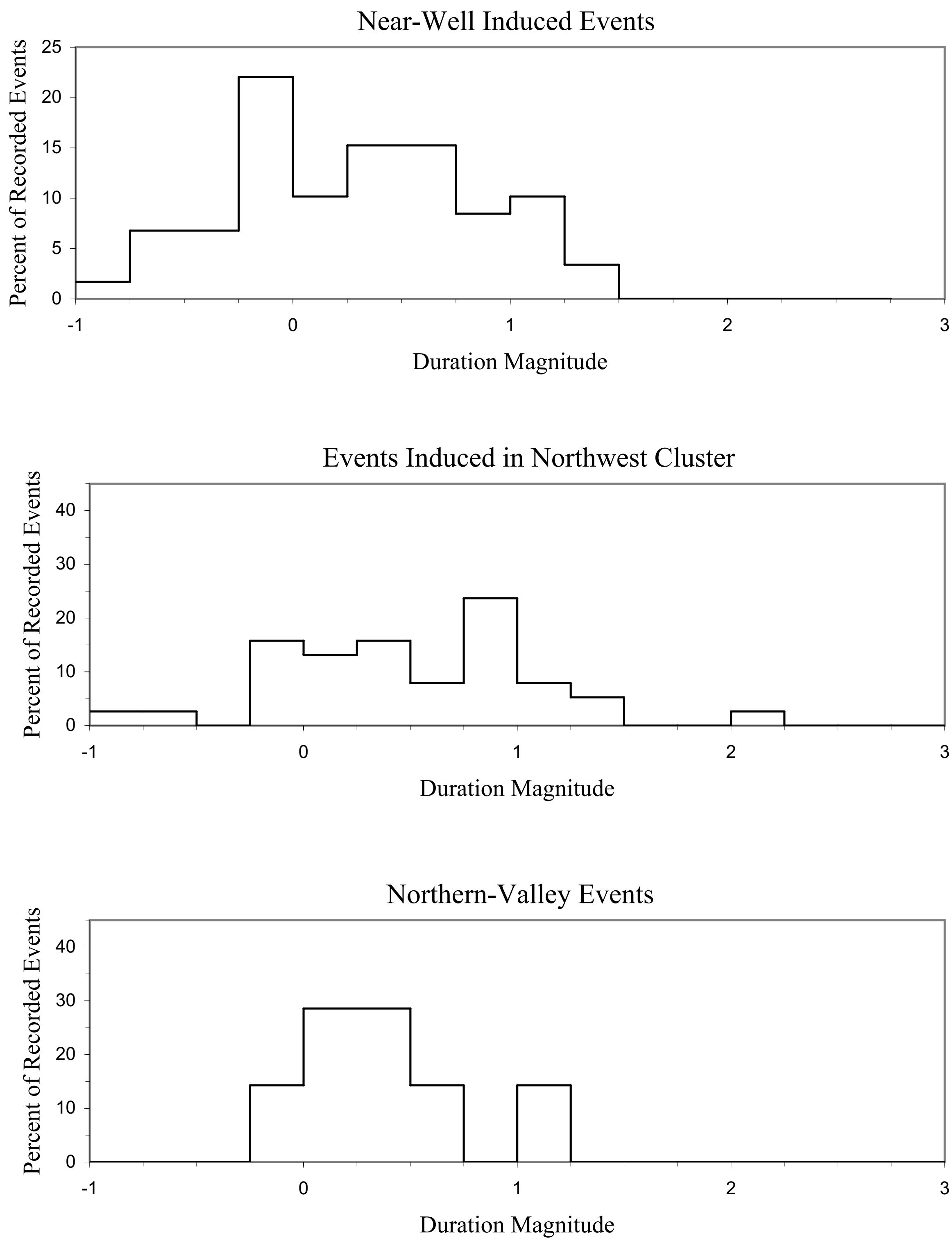


Figure 4-4 Magnitude histograms for events recorded in the near-well region (top), in the northwest zone of induced seismicity (middle), and in or near northern Paradox Valley (bottom) during 2008.

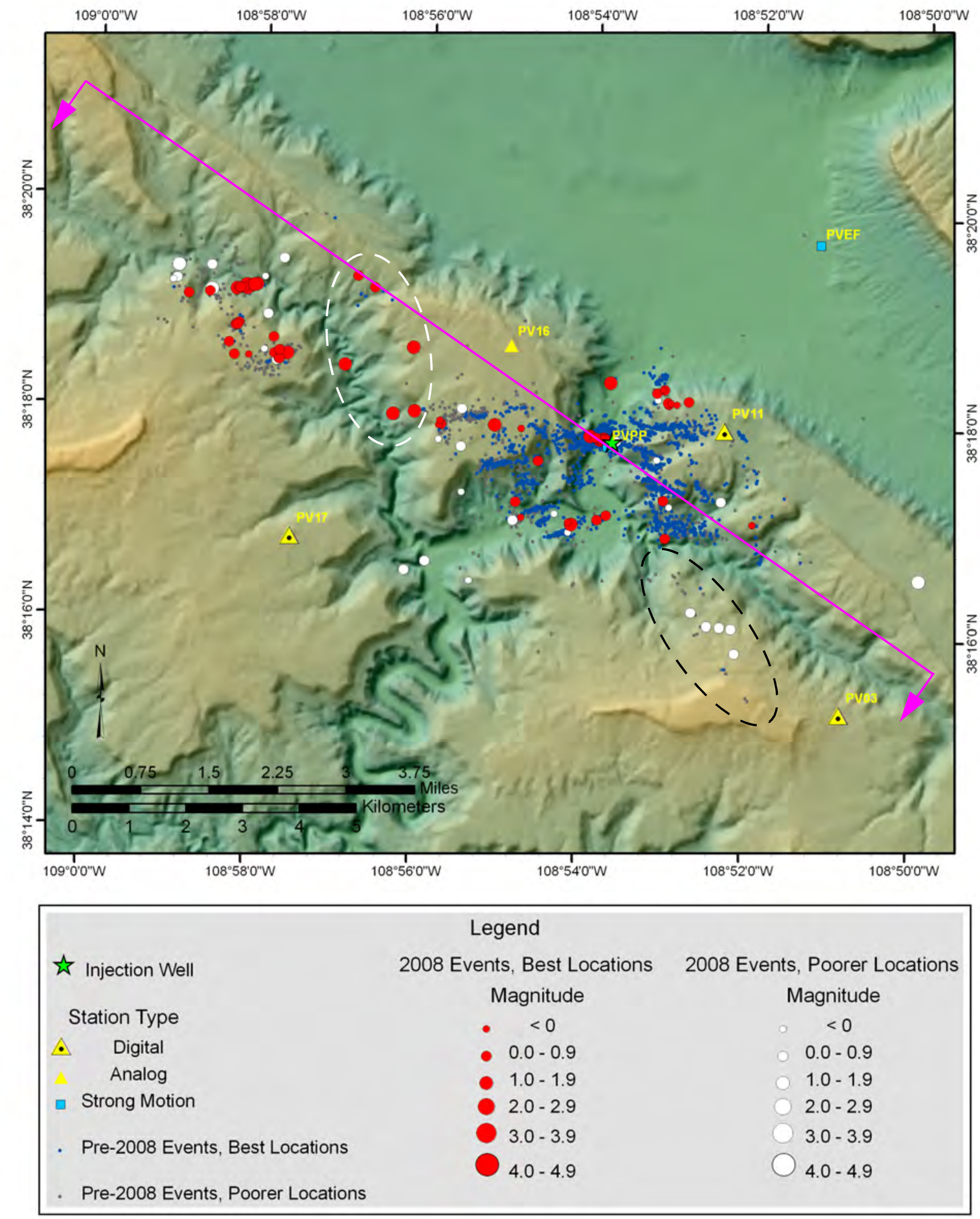


Figure 4-5 Map showing the locations of induced earthquakes recorded in 2008, compared to the locations of previously-induced events. The dashed ellipses indicate areas of recent seismic activity having little historical seismic activity. The magenta line indicates the orientation of the cross section presented in Figure 4-6.

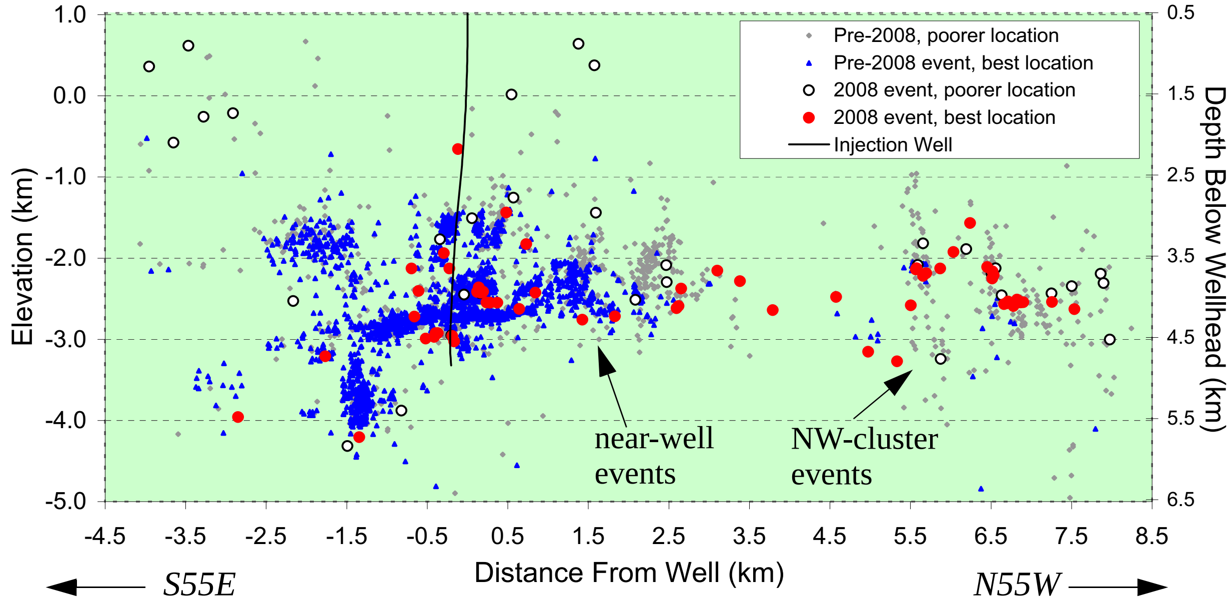


Figure 4-6 Vertical cross section parallel to Paradox Valley (looking to the southwest) showing the locations of induced earthquakes recorded in 2008, compared to the locations of previously-induced events. (The orientation of the cross section is indicated by the magenta line in Figure 4-5. Note that the depths of events locating shallower than approximately 2 km are poorly constrained.)

The geographical distribution of earthquakes appears to be changing in two subtle ways. First, the induced earthquakes have historically occurred in two distinct seismic zones, the primary zone surrounding the injection well (the "near-well" region) and a smaller secondary zone centered about 7.5 km northwest of the injection well ("NW cluster"), with an aseismic gap between these two areas. The historical aseismic gap between the two zones of induced seismicity may be closing, as indicated by a few earthquakes (with well-constrained hypocenters) that occurred during 2008 between the near-well and NW-cluster regions. The events occurring in this gap with little previous seismic activity are indicated by the white dashed ellipse on the map in **Figure 4-5** and are also evident in the cross-sectional view (**Figure 4-6**).

Secondly, several events are occurring to the south, and slightly east, of the primary near-well zone of induced seismicity, as indicated by the dashed black ellipse in **Figure 4-5**. Five events occurred in this area during 2008, ranging in magnitude from **M**0.4 to **M**0.9. Several events have located in this area in previous years, as summarized in **Table 4-4**, including 5 events in 2007. In the past, these events have been dismissed as having unreliable calculated hypocenters. Closer examination of the ray coverage constraints for the events detected in this area in 2008 indicate that they are reasonably constrained. The parameters used in this report to rank a hypocenter as a "best location" or "poorer location" are somewhat arbitrary. All of the events located in this area in 2008 (and roughly half of those located in this area in past years) are reasonably constrained, having ray coverage parameters only slightly outside the ranges that would earn them a rank of "best location". These events are locating shallow, roughly 1 to 2.5 km depth relative to the wellhead (roughly 1.5 to 3.0 km depth relative to local ground surface). At this time, it appears that the constraints on the events that located in this area during 2008 are sufficient to conclude that

Table 4-4 Events detected south of the primary zone of induced seismicity (in the area indicated by dashed black ellipse in Figure 4-5), listed by year of occurrence.

Year	Number of Events	Magnitude Range
1996	0	
1997	0	
1998	2	0.5 - 1.5
1999	1	0.3
2000	3	0.1 - 0.9
2001	2	0.2 - 0.3
2002	3	0.4 - 0.8
2003	6	0.0 - 1.2
2004	0	
2005	0	
2006	0	
2007	5	-0.7 - 0.3
2008	5	0.4 - 0.9

they are occurring at some nontrivial distance away from the primary zone of seismicity (> ~1.5 km). However, the accuracy of their absolute locations, especially their depths, is not known. Ray coverage limitations and inaccuracies in the velocity model used in the event location algorithms can systematically bias computed hypocenters. If seismicity continues in this area and the uncertainty of the computed hypocenters needs to be better understood, further analysis (likely including sensitivity testing with synthetic data) would need to be conducted.

4.3 Northern-Valley Earthquakes

Seven earthquakes were detected in the northern Paradox Valley region during 2008. Magnitudes range from -0.2 to 1.1 (**Table 4-2** and **Figure 4-4**). The earthquakes which have been detected in the northern Paradox Valley region in recent years appear to locate in three groups: (1) events located about 3 km east of station PV04, (2) events located northwest of station PV04, and (3) a smaller group of events located approximately 3 to 4 km northeast of station PV14. Five of the seven northern valley events detected in 2008 occurred in group 1, east of station PV04. They occurred in a swarm over the course of two days during July. Magnitudes of these events range from -0.2 to 0.4. The computed (relative) hypocenters of the three best-constrained events nearly coincide. Their computed elevations are -2.7 to -2.8 km relative to sea level, corresponding to approximately 4.5 to 4.6 km depth relative to the local ground surface. One event, with magnitude 0.7, occurred in group 2, northwest of PV04. It's computed elevation is -3.2 km relative to sea level, corresponding to a depth of 5.2 km below local ground surface. The largest northern valley event detected during 2008, with **M**1.1, occurred in group 3, northeast of PV14 (**Figure 4-1**). It locates beneath the valley floor, at a depth of about 7.2 km below the local ground surface.

However, the location of this event is not as well-constrained as those of the events occurring in the first two groups.

4.4 Other Local Earthquakes

Ten local earthquakes, not associated with the northern valley events discussed above, were recorded by PVSN during 2008. One of these is a very small event, M-0.5, that locates on the northeastern edge of Paradox Valley, almost directly under station PV12, at a depth of approximately 4.5 km. The remaining earthquakes locate near or just outside the perimeter of the Paradox Valley Seismic Network, and because of this their computed locations are very uncertain. Although they are reported here because they locate near the network, they may actually be occurring farther away from Paradox Valley than reported. One event locates about 8 km southeast of station PV08 (beyond the range of the map shown in **Figure 4-1**), and the remaining 8 events locate in the vicinity of station PV09.

5.0 GEOLOGIC SETTING

5.1 Location

The Paradox Valley Unit is located in western Montrose County approximately 90 km southwest of Grand Junction, CO and 16 km east of the Colorado-Utah border. Paradox Valley is about 40 km long on a N55^{o}W axis and from 5 to 10 km wide (**Figure 5-1**, **Figure 5-2**, and **Figure 5-3**). The most prominent local feature is the LaSal Mountains in the Manti-LaSal National Forest, which rise to an elevation of about 3.7 km above mean sea level (msl) and border Paradox Valley on the northwest. Paradox Valley has a relatively flat floor enclosed by steep walls capped by sandstone. Elevations vary from about 1.5 km above msl in the valley to slightly more than 2.0 km above msl along the valley rim.

Paradox Valley is one of five northwest-striking, collapsed diapiric salt anticlines in southwestern Colorado and southeastern Utah. The formation of these anticlines began about 250 mya when the emergence of mountainous uplifts placed intensive lateral stresses on the intervening sedimentary formations, causing faulting and fracturing along weak axial zones. Subsequently the stresses relaxed and, combined with the weight of overlaying strata, forced a deeply buried, salt-rich layer to flow upward into the faulted area creating the anticline. As pressures eased, the crest of the anticline gradually dropped downward into fault blocks. That and subsequent erosion created Paradox Valley. Currently, the Dolores River flows across the strike (i.e., axis) of the valley near Bedrock, CO (**Figure 5-2** and **Figure 5-3**).

The Dolores River originates in the San Juan Mountains south of Paradox Valley in southwest Colorado and flows generally north, northwest for about 300 km to Paradox Valley and another 110 km north, northwest to its confluence with the Colorado River, northeast of Moab, Utah.

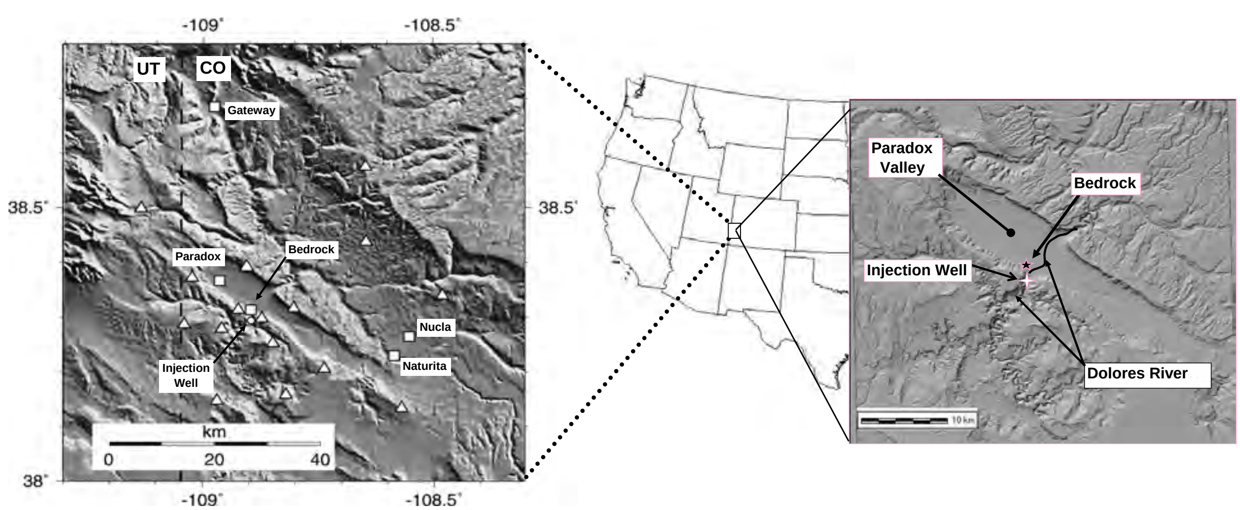


Figure 5-1 Location Map of Paradox Valley Unit, Dolores River, and Local Topography. See Figure 5-2 for expanded version of map.

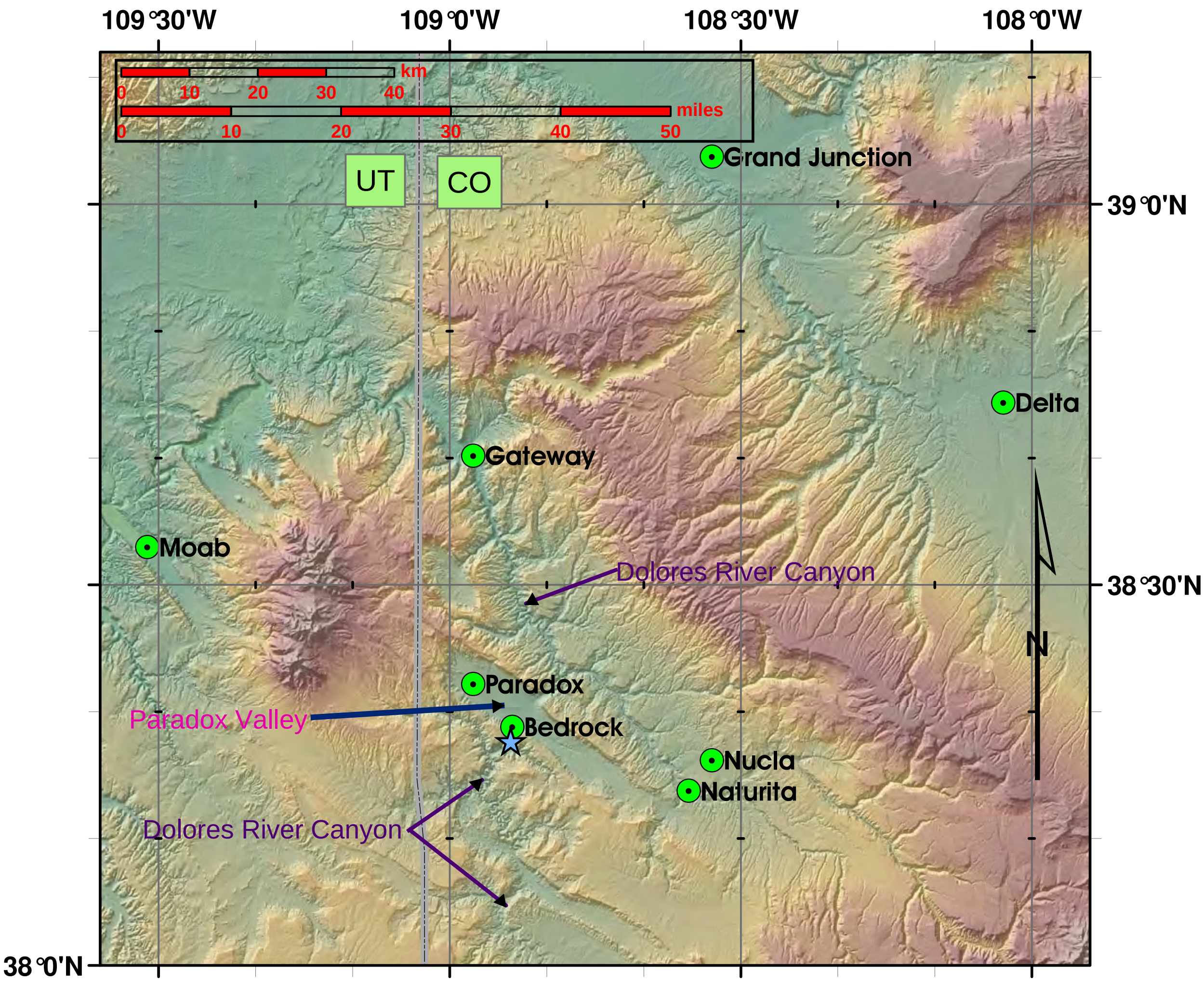


Figure 5-2 Local Topographic Setting of PVU Injection Well, Paradox Valley, Local and Regional Municipalities, and the La Sal Mountains between Paradox and Moab.

Small tributaries in the area include La Sal Creek, which enters from the northwest about 8 km upstream from Paradox Valley, and West and East Paradox Creeks, which enter from the northwest and southeast within the valley. East Paradox Creek is intermittent, however, and has essentially no effect on the river flow. Over its path through Paradox Valley, the Dolores can pick up more than 180,000 metric tonnes (200,000 standard tons) of salts annually, primarily from brine-saturated groundwater, (called Paradox Valley Brine or PVB), percolating through seeps and springs in the salt body and into the Dolores. There are two general types of seeps and springs: brackish water with total dissolved solids (tds) varying from about 1,500 milligrams per liter (mg/l; 1 mg/l = 1 ppm) to 4,000 mg/l and the Paradox Valley Brine with ~260,000 mg/l. (For reference, the EPA defines fresh water as tds less than between 400 mg/l and 500 mg/l.) Water pumped from 9 extraction wells near the river has a salinity of ~260,000 mg/l (260,000 mg/l is saturation, the maximum salt carrying capacity of fresh water). This brine, which is nearly eight times the salinity of ocean water, consists mostly of sodium and chloride, with much smaller amounts of

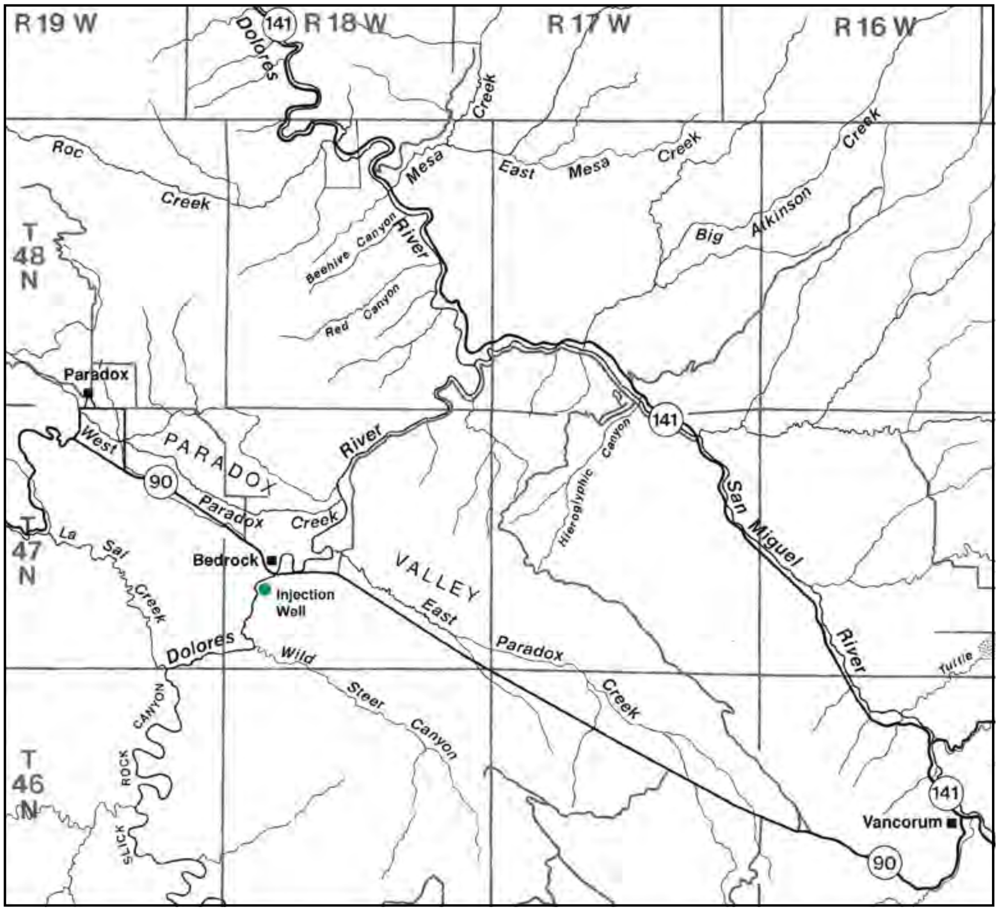


Figure 5-3 Paradox Valley Unit Injection Well and Local Geography. Figure is adapted from Parker (1992). Each square is approximately 10 km by 10 km.

sulfate, potassium, magnesium, calcium, and bicarbonate. Heavy metals, particularly iron and lead, and non-radioactive strontium are also present in small amounts. Noticeable amounts of hydrogen sulfide gas are released as the brine surfaces, creating a noxious odor.

5.2 Wray Mesa Fault and Fracture System

The Wray Mesa fault system has been active in creating an extensive fracture network. PVU Salinity Control Well No. 1 was sited so that injectate would intersect the generally NW-SE trending faults of the Wray Mesa and its fracture system. The main trend of the Wray Mesa fault system (N55^{o}W) parallels the general trend of Paradox Valley (**Figure 5-2**). In their 1988 report, Bremkamp and Harr predicted that PVU injectate would move in the direction of least reservoir resistance and lowest hydrostatic pressure. They predicted this direction to be to the northwest and up dip along the fracture permeability of the Wray Mesa system. Our findings, as discussed below and based on injection-induced, seismic source locations, support their prediction. **Figure 5-4** shows Bremkamp and Harr's (1988) northeast-southwest cross section of Paradox Valley and bordering region. Note the Wray Mesa Fault system. The Bremkamp and Harr (1988) cross section runs through the injection well and shows their original interpretation of the Wray Mesa faults. [A note of caution: the surface topography in **Figure 5-4** west of the salt anticline (i.e., Paradox Valley) appears to be at the same level as the valley. However, the actual surface west of the valley shows a sharp elevation increase to plateaus (**Figure 5-1** and **Figure 5-2**). This discrepancy occurs because the survey used by Bremkamp and Harr did not follow a straight line (i.e., the plateau topography), but instead changed direction and followed the incised canyon of the Dolores River before using the primary surface topography of the plateaus bordering Paradox Valley.]

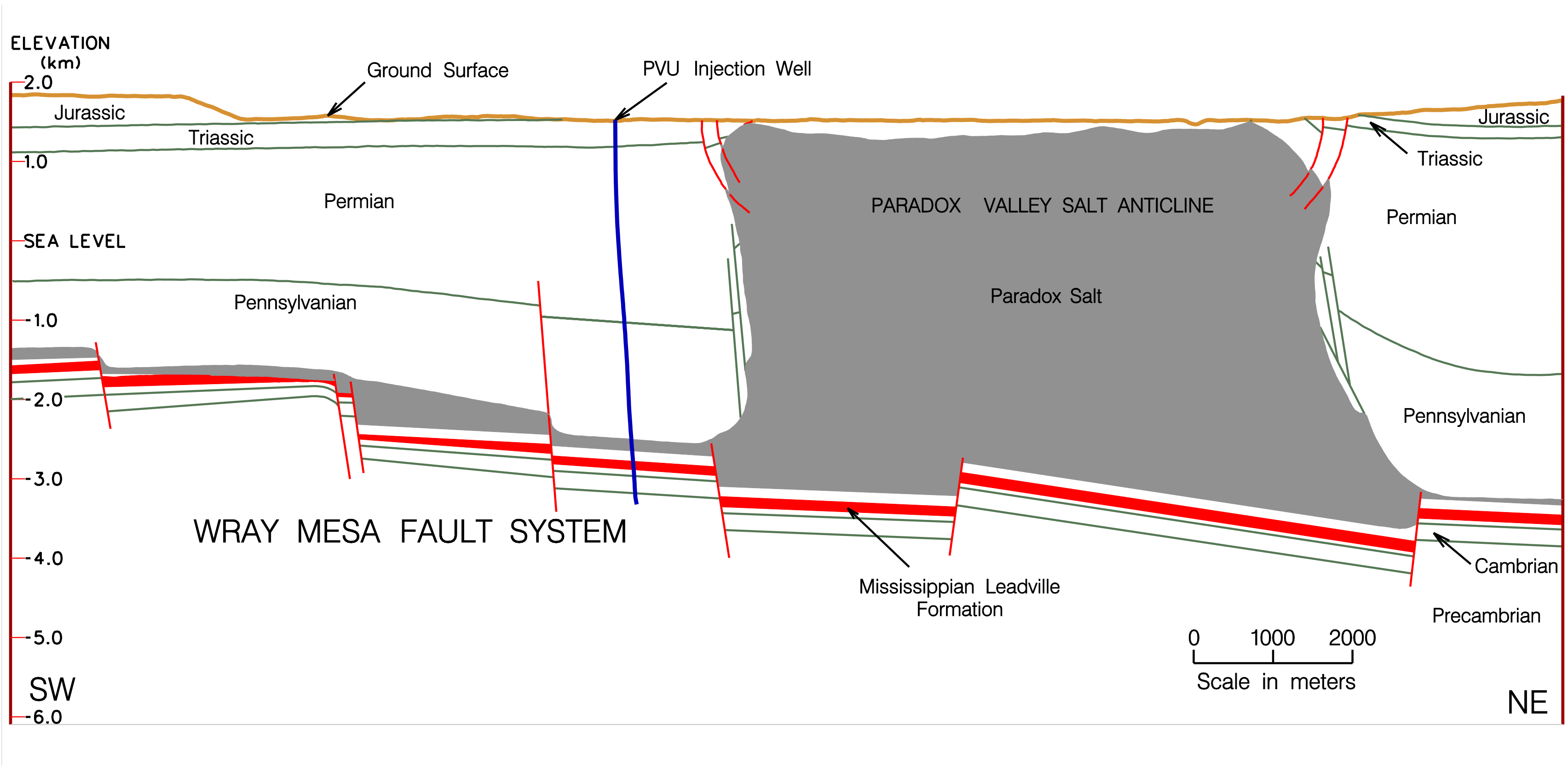


Figure 5-4 Bremkamp and Harr's (1988) Northeast-Southwest Cross Section Through Paradox Valley and its Bordering Region. Cross Section runs through the injection well and surface topography reflects surveyors path up the canyon of the Dolores River and not the local mesa topography.

6.0 PVU INJECTION OPERATIONS

6.1 PVU Salinity Control Well No. 1

PVU operates the Salinity Control Well No. 1, which is located along the western boundary of Paradox Valley, approximately 1.5 km from Paradox Valley, up the canyon formed by the Dolores River (**Figure 5-1**, **Figure 5-2** & **Figure 5-3**). The well is located in SW SE section 30, township 47N, range 18 W Paradox Valley, Montrose County, CO. Its latitude and longitude are 38.2965^{o} N, 108.8950^{o} W, respectively. The wellhead elevation (i.e., ground surface) is 1,524 m (5,000 ft) above mean sea level. The Kelly bushing of the well, the base elevation marker used by drillers and well loggers when listing depths, is listed at 9.8 m (32 ft) above ground surface.

The 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 prime injection zone with the upper Precambrian as a secondary zone (Bremkamp and Harr, 1988). The well casing of PVU No. 1, Inconel (C-276, a nickel-molybdenum-chromium alloy), was perforated at ~20 perforations/m in two major intervals between 4.3 km and 4.8 km depth. Well-log-based, near-wellbore stratigraphy, the perforation intervals, and a plan view of the well are shown in **Figure 6-1**.

6.2 PVU Operations by Injection Phase

From 1991 through 1995 PVU conducted a series of 7 injection tests. These tests were conducted to acquire an EPA permit for continuous brine disposal. Following these tests, the EPA granted the permit, and, in July 1996, PVU began continuous injection. Since continuous injection began, PVU has instituted and maintained three major injection changes. 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*" that could be evaluated. We created this distinction to differentiate and evaluate operational parameters and resulting reservoir response(s), including induced seismicity, during the separate phases. Described below are the four injection phases. **Table 6-1** summarizes the injection phases. In the table the averaging of values includes both active pumping and shutdown days.

6.2.1 Phase I - (22-July 1996 through 25-July 1999)

The initial phase, *Phase I*, followed inception and a few months of building up injection pressure. During this phase, PVU injected at maximum: ~1290 l/min (~345 gpm) at ~33 MPa (~4,900+ psi) surface pressure, which corresponded 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

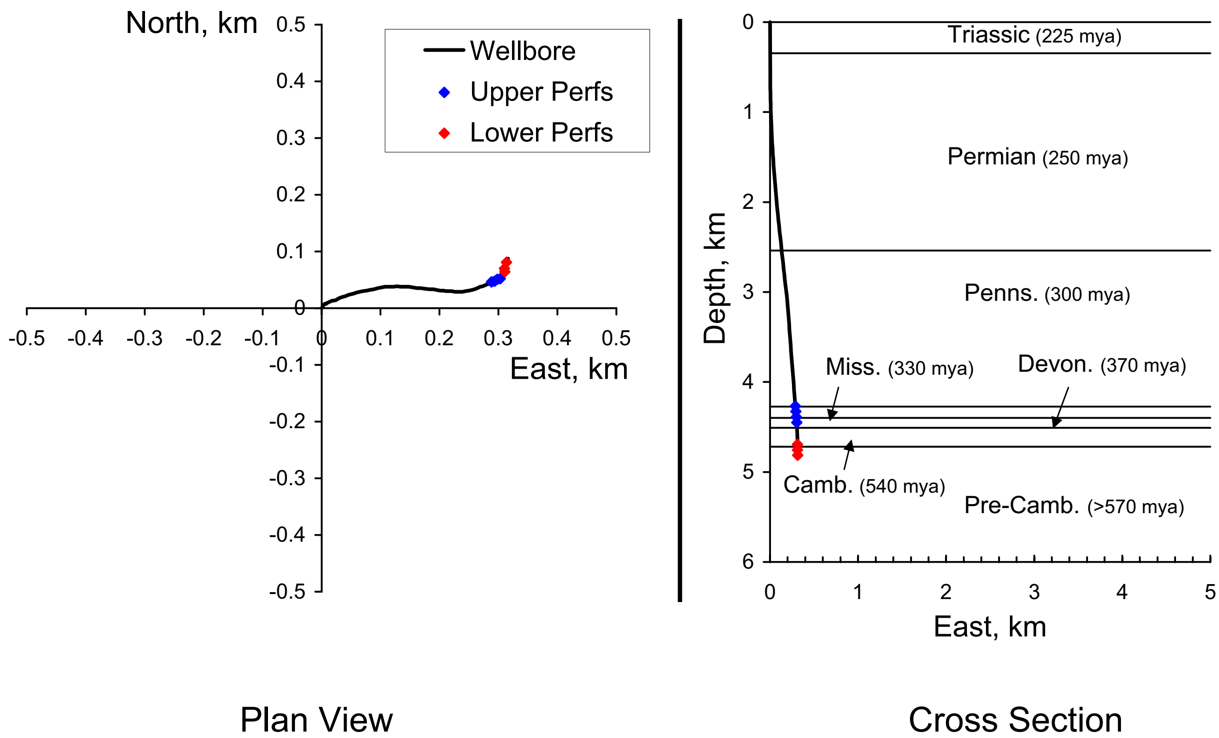


Figure 6-1 PVU injection well: Salinity Control Well No. 1 in plan view (left) and north-viewing vertical cross section (right). Figures include the near-wellbore stratigraphic column, based on well logging of Salinity Control Well No. 1, and locations of the upper and lower casing perforations.

~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 were often and ran for minutes, hours, or a few days. Maintenance shutdowns ran for a few weeks up to a maximum of 71 days in mid-1997; the 71-day shut down was needed to replace injection pumps. 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), 30% fresh water.

6.2.2 Phase II - (26-July 1999 through 22-June 2000)

Following a magnitude **M**3.5-event in June 1999 and a magnitude **M**3.6 event a month later, in July 1999, PVU augmented injection to include a 20-day (pressure-diffusion) shutdown (i.e., a "shut-in") every six months (one in December-January and one in May-June). The scheduled shut downs were included so that the injectate from the pressurized fractures and faults could diffuse into the formation rock matrix (i.e., *in situ* stress relaxation). 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) reduced during and following unscheduled maintenance shutdowns and during the

Table 6-1 Phases of Pumping, Associated Time-Averaged Injection Parameters, and Injection Characteristics since 1996

Phases	Duration	Avg. Wellhead Pressure	Avg. Pressure @ 4,300 m* depth	Avg. Inj. Rate	Injectate *PVB%: H_2O%*	Biannual 20-day Shut -downs	Approx. No. Recorded Seismic Events***
	days	**MPa**	**MPa**	**lpm**		**y/n**	
I	1099	29.7 (4302 psi)	76.9 (11147 psi)	1047 (272 gpm)	70:30	No	2590
II	333	29.3 MPa (4250 psi)	76.5 (11095 psi)	948 (247 gpm)	70:30	Yes	440
III	563	27.7 (4023 psi)	74.8 (10842 psi)	745 (194 gpm)	70:30	Yes	242
IV	2551**	28.2 (4091 psi)	77.5 (11245 psi)	735 (191 gpm)	100:0	Yes	550

*Depth = Top of the casing perforation interval, i.e., the top of the targeted injection horizon, the Leadville Limestone, which well testing indicates has the greatest injectivity
**through 12/31/08
***Includes all recorded induced events, regardless of magnitude.
"**MPa**" = megapascals & 1 MPa = 145 psi; "**lpm**" = liter/minute & 1 lpm = 0.26 gal/minute

shutdowns following the injection tests of 1991 through 1995. As detailed later in this report (section 9), the shutdowns reduced the seismicity, but did not sufficiently reduce the proclivity to produce large seismic events. When injecting during this phase, injection continued at the same pressure and rate as *Phase I*.

6.2.3 Phase III - (23-June 2000 through 6-January 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 effect on seismicity and decided to institute a new strategy to reduce the seismic threat. The new strategy changed operations from 3 injection pumps to 2 pumps. On June 23, 2000, PVU resumed pumping using 2 pumps. This change decreased the injection rate by 33% compared to earlier phases, to ~870 l/min (~230 gpm). The lower injection rate reduced surface pressure by about 10%, to between ~4,400 and 4,500 psi. The 70:30 ratio of brine to fresh water and the bi-annual, 20-day shutdowns were maintained.

6.2.4 Phase IV - (7-January 2002 through the 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 when 100% PVB interacted with connate fluids and the dolomitized Leadville Limestone at downhole (initial) temperatures and pressures, PVB would precipitate calcium sulfate that would restrict 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, and possibly clog, the wellbore perforations. Further discussions indicated that, if precipitation occurs, its maximum expected rate is ~8 tons of calcium sulfate per day. To put this amount into perspective, injecting at ~230 gpm, assuming a density of 8.33 lbs/gal, gives a daily injection tonnage of ~1380 tons/day. The maximum expected precipitate is ~0.6% of the daily injection mass.

After considering this new information, the decision was made to begin injecting 100% PVB, in order to increase the amount of salt disposed of with the reduced injection rate initialized in *phase III*. Injecting 100% PVB began on January 7, 2002, following the December-January 20-day shutdown, and has been maintained since. The same reduced injection rate as in *phase III* (~870 l/min; ~230 gpm) and bi-annual 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.

6.3 PVU Injection History By Year

Table 6-2 summarizes PVU Well No. 1’s annual injection history. The values in **Table 6-2** are in standard units of millions of gallons (Mgal) and thousands of tons (ktons).

Table 6-2 Annualized Summary of PVU Injection

Year	Phase	Injectate (approx.)	Paradox Valley Brine (approx.)	Salt Disposed (approx.)*
		Mgal	**Mgal**	**ktons**
1991	Tests	11.7	3.9	4.3
1992	Tests	9.8	7.8	8.4
1993	Tests	26.2	10.0	10.8
1994	Tests	81.7	58.7	63.7
1995	Tests	34.4	24.1	26.2
1996	*Phase I*	44.6	31.1	33.7
1997	*Phase I*	127.8	89.4	97.0
1998	*Phase I*	166.2	116.1	126.0
1999	*Phases I & II*	150.4	104.5	113.3
2000	*Phases II & III*	112.4	85.4	92.7
2001	*Phase III*	99.6	69.7	75.6
2002	*Phase IV*	103.0	103.0	111.8
2003	*Phase IV*	104.2	104.2	113.0
2004	*Phase IV*	94.8	94.8	102.8
2005	*Phase IV*	93.6	93.6	101.5
2006	*Phase IV*	93.5	93.5	101.4
2007	*Phase IV*	104.6	104.6	112.7
2008	*Phase IV*	102.7	102.7	111.4
TOTAL	**--**	**1,561**	**1,297**	**1,406**

* Assumes a salinity of 1.085 ktons of salt per 1 Mgal of brine.

7.0 PARADOX VALLEY SEISMIC NETWORK

7.1 Overview

The Paradox Valley Seismic Network (PVSN) monitors a 4,000 km^2 area of the Colorado Plateau physiographic province near the Utah-Colorado border, approximately centered on the PVU injection well (**Figure 7-1**). PVSN consists of two independently-recorded seismic monitoring components: (1) a 16-station, continuously telemetered, high-gain seismic array; and, (2) a 3-station event-triggered strong motion array. The two components are complimentary. The high-gain telemetered array provides detailed coverage of injection-related seismicity, as well as a regional seismicity baseline; 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 7-1**. More detailed information about the stations is provided in **Table 7-1,** including installation date, station type, and number of components. **Table 7-2** lists descriptive information about the telemetered stations, including a legal descriptions of the station locations.

7.2 Network History

Local seismic monitoring of Paradox Valley began in mid 1983 with the installation of a 10-station telemetered array (stations PV01-PV10, see **Figure 7-1**). The initial array was designed to gather a multi-year, pre-injection seismicity baseline of the region surrounding the proposed injection well. 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, and was reinstalled in October, 2007.

The first strong motion instrument (station name PVPP), was installed near the injection wellhead in 1997. A second strong-motion instrument was installed near the extraction facilities (PVEF) in 2003, and the third was installed in the nearby community of Bedrock, Colorado (PVCC) in 2005.

Once the first 10 stations were installed in 1983, data from the high-gain array was recorded and analyzed by the USGS at their facilities in Golden, Colorado. The USGS used a data acquisition system tailored after the CEDAR system invented by Carl Johnson at Caltech (Johnson, 1979).

On January 1, 1990, Reclamation assumed responsibility from the USGS for recording and analyzing data from PVSN, and the data terminus for the network was moved from the USGS facilities in Golden to Reclamation’s seismic processing facilities located in Lakewood, Colorado. Reclamation used an in-house data acquisition system (TROLL) that employed essentially the same event detection algorithm as the CEDAR system, and which had successfully been used since 1987 to collect data from other Reclamation seismic networks.

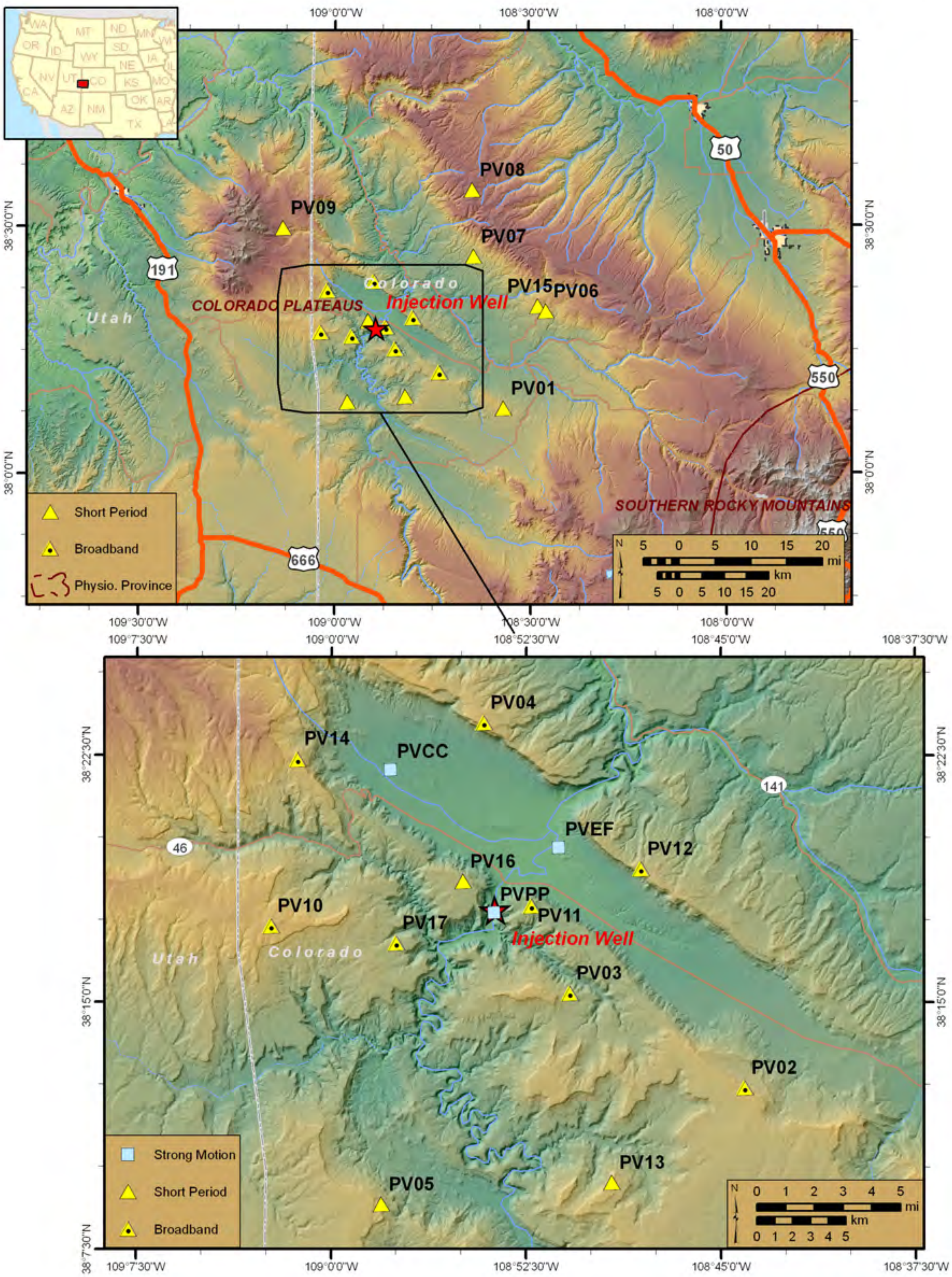


Figure 7-1 Locations of the Paradox Valley Seismic Network stations and the Paradox Valley Unit injection well. PVCC, PVEF & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Physiographic provinces from Fenneman and Johnson (1946).

Table 7-1 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	5/83-10/08 10/08-present	short-period broad-band	vertical triaxial
PV03	38.25	108.85	1972	5/83-present 10/08-present	short-period broad-band	vertical triaxial
PV04	38.39	108.90	2176	5/83-6/06 5/07-present	short-period broad-band	vertical triaxial
PV05	38.15	108.97	2142	5/83-present	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 9/89-10/03 10/07-present	short-period short-period short-period	triaxial vertical triaxial
PV09	38.50	109.13	2662	6/83-present	short-period	vertical
PV10	38.29	109.04	2266	6/83-10/08 10/08-present	short-period broad-band	vertical triaxial
PV11	38.30	108.87	1882	12/89-10/08 10/08-present	short-period broad-band	triaxial triaxial
PV12	38.32	108.80	2092	12/89-7/05 11/05-present	short-period broad-band	vertical triaxial
PV13	38.16	108.82	2158	12/89-present	short-period	vertical
PV14	38.37	109.02	2234	12/89-4/02 6/07-present	short-period broad-band	vertical triaxial
PV15	38.34	108.48	2234	6/95-present	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: Elevations are relative to mean sea level (msl), the surface elevation of the injection well is 1540 m above msl. See text for a description of the station types. Stations with vertical sensor direction are single-component; triaxial are 3-component (vertical, north, and east).

Table 7-2 Current PVSN Telemetered Sites - Legal Description

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 S12 C,NM
PV16	Nyswonger Mesa	T47N R19W S24 C,NM
PV17	Wray Mesa East	T47N R19W S34 C,NM

Data from the high-gain array always has been continuously telemetered in either analog or digital form from the remote seismic stations located in western Colorado to the USGS (and later Reclamation) seismic processing facilities located near Denver, Colorado. From 1983 through October of 2000, data telemetry (purely analog) was done using a combination of FM radio links, microwave data channels, and private-line telephone circuits. The telemetered signals remained in analog form until reaching their ultimate destination near Denver, where they were finally digitized (using 12-bit analog-to-digital converters) for event detection and analysis.

Before October, 2000, the path the analog data took from the remote seismic stations in Paradox Valley to reach the processing facilities near Denver (initially in Golden, and later Lakewood) was somewhat circuitous. Data was first telemetered from each station to a main repeater site high on the Uncompaghre Butte (also the location of seismic station PV08). From there, the signals were transmitted by FM radio to a Reclamation facility in Montrose, Colorado. From Montrose, signals were carried on microwave links owned by the Western Area Power Administration (WAPA), to WAPA facilities located in Loveland, Colorado. The final link was from Loveland, via private-line telephone circuits, to the seismic processing facilities located near Denver, Colorado. This multitude of telemetry links required considerable maintenance and coordination, and the inherent noise of the system limited the dynamic range of seismic signals that could be obtained.

In October, 2000, the high-gain array was re-configured to eliminate the long-distance analog telemetry links (i.e., the microwave and private-line links) and thereby improve the quality of the data. Instead of transmitting analog data directly from the stations to Lakewood for digitization and processing, a local data collection facility was established at Hopkins Field in Nucla, Colorado. The network was then re-configured so that analog data from all 16 stations were transmitted by FM radio links to Nucla, where it was digitized using new 16-bit analog-to-digital converters. A wide-area network (WAN) link was established at Hopkins Field in order to bring the digitized data back to Lakewood. This change substantially reduced the number of single points-of-failure, improved signal-to-noise levels, and greatly reduced telemetry costs. In addition to the telemetry changes, the TROLL data acquisition system was replaced by the USGS-developed Earthworm system. Earthworm uses essentially the same event detection algorithm as was used by the previous TROLL data acquisition systems; it remains the current data acquisition system for PVSN.

Recent changes have focused on upgrading the existing high-gain telemetered array. 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.

7.3 Coverage and Site Conditions

Eleven of the current 16 high-gain, telemetered stations are concentrated within 20 km of the injection well, and provide detailed coverage of induced earthquakes. The remaining stations extend coverage to a distance of about 40 km from the injection well, and provide a baseline of naturally-occurring tectonic earthquakes in the surrounding region. Station spacing for the original 10 stations (PV01-PV10) was about 15 km. With the 6 additional stations installed after 1989, the spacing decreased to about 5-8 km for those stations nearest the injection well. Most stations in the high-gain array are founded on bedrock (typically shale and sandstone), although a few are on shallow soils. All of the strong motion sites are founded on soil.

7.4 High-gain Array - Analog, Short-period Instrumentation

Instrumentation for 8 of the 16 stations of the current telemetered high-gain array remains entirely analog, and ground motions are measured using short-period seismometers. Instrumentation for this type of station consists of the following components: (1) short-period velocity seismometers having a natural period of 1 Hz and damping of 0.65 critical (Teledyne Geotech model S-13-102); (2) high-gain amplifiers with 2-pole butterworth high- and low-pass filters with corner frequencies of 0.2 and 25 Hz, respectively (Teledyne Geotech model 42.50-1); (3) voltage controlled oscillators (VCO) to modulate the low-frequency seismic signal onto a voice-band carrier tone, allowing telemetry over voice-band channels (Teledyne Geotech model 46.22); (4) analog, voice-band telemetry over VHF radios, microwave links, and private-line telephone circuits, and (5) discriminators with a 3-pole butterworth low-pass filter to demodulate the original amplified seismic signals. The overall amplitude response of the analog instrumentation has been measured using end-to-end calibration tests. The amplitude response is approximately flat to ground motion velocity for frequencies between 1 and 17 Hz (**Figure 7-2**).

Of the 8 analog, short-period stations, 6 record ground motion in the vertical direction only. The remaining two stations have three seismometers each: one vertical, and two horizontal (these are called 3-component sites). In general, vertical-component seismometers installed at the earth’s surface are best for recording P-wave first arrivals, while horizontal-component seismometers are needed to reliably record S-wave first-arrivals. The three 3-component stations therefore provide more information than the single-component stations, but have a greater installation and equipment cost.

The remote analog stations are powered by 40-watt solar panels and 12-Volt solar-recharged batteries. In 2007, all batteries were replaced, new solar panels were installed at many sites, pulse-width modulated (PWM) solar-panel regulators were installed at every site, and voltage regulators for the analog signal-conditioning electronics were installed at every site to reduce noise and improve reliability.

Signals from the analog sites are continuously transmitted by low-power (< 1 Watt ERP) narrow-band FM transmitters (both VHF and UHF) to receivers located at Hopkins Field. Each seismic component is then digitized using Guralp model RM-16 analog-to-digital converters at a sampling rate of 100 samples per second, and with 16-bit resolution. The RM-16 digitizers use an attached GPS receiver to provide absolute time (estimated accuracy <10 microseconds). The sampled data from each channel is time-stamped, packetized into 1-, 5-, or 10-second packets, serially multiplexed with packets from other stations or components, and the entire data stream is transmitted to Earthworm servers located at Reclamation’s processing facilities in Denver.

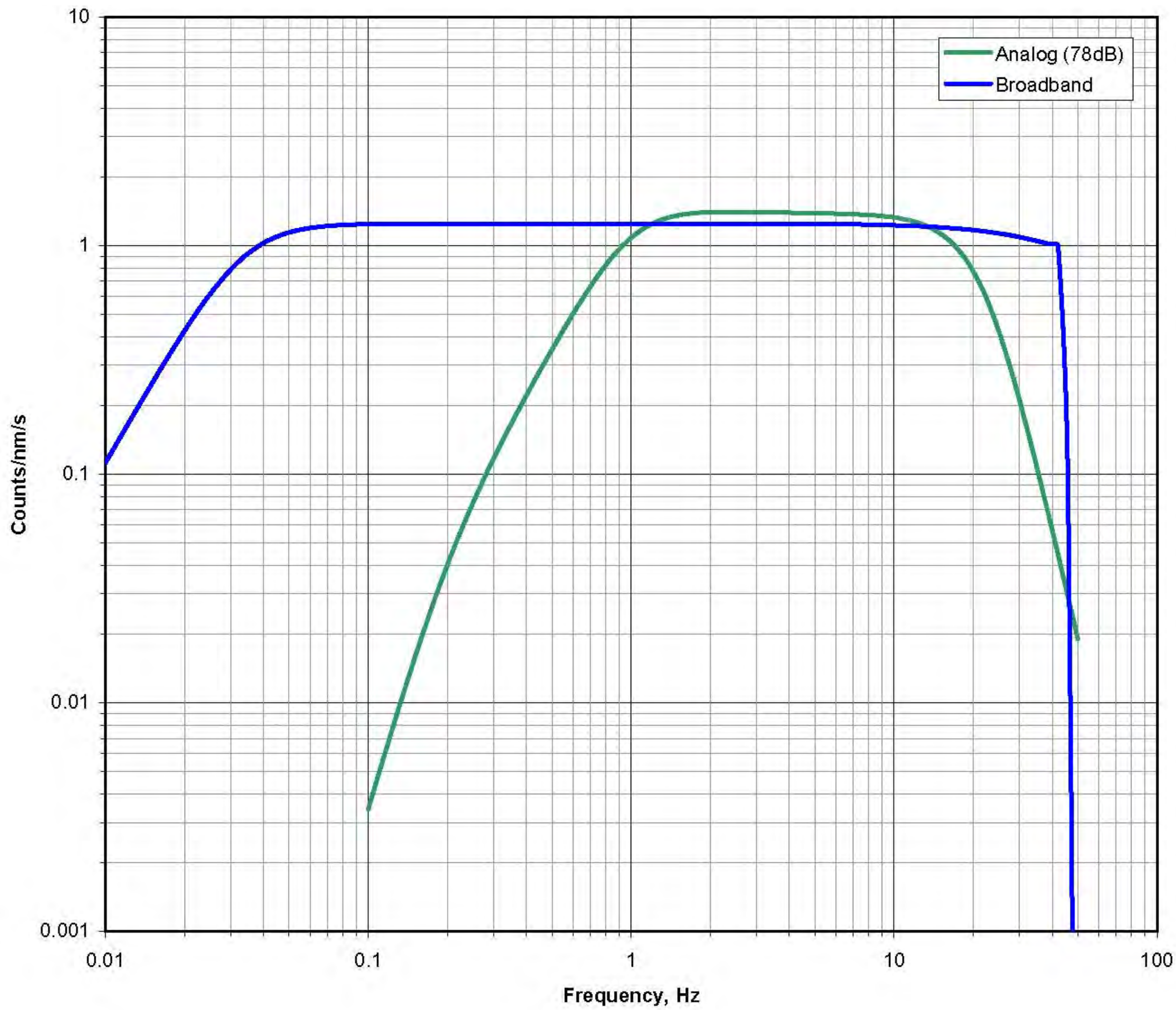


Figure 7-2 Typical velocity response as a function of frequency for an analog short-period PVSN station (Teledyne Geotech S-13 seismometer and external electronics) and a digital broadband station (Guralp CMG-40TD seismometer with integrated electronics).

7.5 High-gain Array - Digital Broad-band Instrumentation

Beginning in 2005, 7 of the analog short-period stations were upgraded to digital broad-band (PV02, PV03, PV04, PV10, PV11, PV12, and PV14), and an entirely new broad-band station (PV17) was also installed. These upgrades are planned to continue. Instrumentation for the present digital stations consists of : (1) Guralp model CMG-40TD 3-component, broad-band seismometer with integrated Guralp model DM-24 24-bit digitizers set at a sampling rate of 100 samples per second; (2) GPS receiver to provide absolute time (accuracy < 10 microseconds); (3) Matrix-5 low-noise voltage regulator and break-out-boxes; and, (4) FreeWave model DGR-115 digital spread-spectrum serial radios. Two stations (PV04 and PV12) were re-configured in 2007 to serve as digital repeaters; a Guralp model CRM-6 combiner-repeater module was added to each station to serially multiplex all incoming packet data streams into a single output stream.

The bandwidth and dynamic range of the digital instrumentation is shown in **Figure 7-2**; the broad-band seismometers have a response that is flat to velocity from about 30 seconds (0.03 Hz) to more than 30 Hz (over 10 octaves). The 24-bit digitizer is directly attached to the seismometer, providing a nominal dynamic range of 138 dB. In contrast, the short-period instrumentation provides a bandwidth of 1 to 17 Hz (just over 4 octaves), with a dynamic range of about 66 dB (although the 16-bit digitizer provides a nominal dynamic range of 90 dB, the VCO and analog telemetry further limit the actual dynamic range). Both types of instrumentation have approximately the same amplification at 1 Hz. In practical terms, the digital broad-band instrumentation is capable of recording, without saturation, much larger earthquakes than is possible using the analog instruments. The advantages of replacing the short-period analog systems with the broad-band digital systems also include simpler operations and maintenance requirements.

7.6 Strong Motion Instrumentation

The strong motion instruments installed at PVSN differ from the high-gain telemetered instrumentation in two important ways. First, they are designed to record very large ground motions that would otherwise saturate even the digital broad-band instruments. Second, the instruments are configured to autonomously record data using an event-detection mode of operation. In contrast, the high-gain stations continuously telemeter data back to a central site, which then performs data acquisition and event detection based on signals from the entire array. The strong-motion instruments continuously monitor ground motions, but only record data when a pre-set level (typically 0.001 g) is exceeded. A pre-event memory allows a complete time-history of the ground motions to be captured, and the instruments have sufficient memory to store multiple events.

The strong-motion instruments use a dial-up modem and standard POTS (“plain old telephone system”) line for communications. When a strong-motion instrument detects an event, an attached triggered modem controller (TMC) causes the modem to dial out and connect to Reclamation’s strong-motion data acquisition servers. These servers then automatically download and process the strong-motion data, with the entire process including data transfer typically requiring less than 5 minutes. The servers are also configured to automatically poll the strong motion instruments at least once each day to monitor state of health.

The strong motion instruments consist of a data logger with a 24-bit digitizer, GPS clock for timing, and either an external or internal sensor. The current installed instruments are Kinemetrics model K2 data loggers using either an external Kinemetrics model FBA-23 triaxial accelerometer, or an internal Kinemetrics model EpiSensor triaxial accelerometer. The accelerometers have a full scale range of +/-1 g, and are sampled at 100 samples per second. Data from the strong motion instruments is eventually merged with data obtained from the high-gain telemetered array. An earlier generation strong-motion instrument was installed at PVPP through 2003 and did not have absolute timing; that data could not be merged since it lacked an accurate time base. Over 110 events have been recorded by the strong-motion instruments.

7.7 Historical Event Detection Capabilities

Although a rigorous analysis of PVSN's event detection magnitude threshold (i.e., magnitude above which virtually all seismic events are detected) as a function of time through it's operational history has not been performed, some information about how PVSN's detection capabilities have changed over time is known. Specifically, there are two known points in time when PVSN's detection sensitivity markedly increased. The first occurred in October, 2000, when the data telemetry, digitizing, and acquisition system were upgraded. The second occurred in November, 2007, when the triggering parameters in the data acquisition software were carefully tuned. In both instances, the improvement in network operations resulted in PVSN triggering more consistently on lower-magnitude seismic events, as described below.

As explained in some detail in section 7.2, in October 2000, a data collection facility was established in Nucla to directly receive analog data via radio telemetry from the seismic stations, digitize that data, and then send the real-time stream of digitized data to Lakewood via a wide-area network (WAN) connection for subsequent event detection and recording. A new data acquisition system - Earthworm - was installed to detect and record events. Previously, the seismic data had been telemetered to Lakewood in purely analog form via a combination of FM radio signals, microwave links, and telephone lines, and the TROLL data acquisition system was used to digitize, detect and record events.

There was a transition period between the new and old data acquisition systems lasting just over a month (between October 3 and November 14, 2000). During that time, data was acquired on both systems in order to compare performance and to calibrate triggering parameters on the new system. Analysis of events triggered during the transition period shows that the new telemetry and digitization system detected and recorded more than twice as many local seismic events as did the old system (**Table 7-3**). Between Oct. 3 and Nov. 14, 2000, there were 22 local seismic events recorded by the old system. The new system recorded all 22 of those events, plus an additional 27 local seismic events that the older system did not record. More events were detected in every geographical location throughout the network using the new system compared to the old system: in the primary, near-well region of induced seismicity, there were 42 events recorded with the new system, compared to 19 events with the old system; in the northwest zone of induced seismicity, 4 events were recorded with the new system, compared to 3 events with the old system; and 3 events in the northern Paradox Valley area were recorded with the new system, compared to 0 events with the old system (**Table 7-3**).

The increased sensitivity of the newer system for detecting seismic events is primarily due to improved signal-to-noise levels of the incoming seismic data stream, which in turn is the result of both the transition from 12-bit to 16-bit digitizers and the elimination of the analog telemetry links between Nucla and Lakewood. The event detection algorithms of the new (Earthworm) and old (TROLL) data acquisition systems were essentially the same (and used similar parameters); however, the improved signal-to-noise ratio of the data allows Earthworm to better detect events with magnitudes less than **M**1.0. During the transition period (Oct. to Nov., 2000), both systems recorded the same 7 events with magnitudes greater than **M**1.0. However, for events with **M** <= 1.0, the new system recorded 42 local earthquakes, whereas the older system only recorded 15

Table 7-3 Number of local seismic events detected by the old and new data telemetry and acquisition systems, from October 3 to November 14, 2000.

Location Category	Number of Local Events Detected	
	Old: Analog Telemetry to Lakewood; 12-Bit Digitization at Lakewood; TROLL Data Acquisition System	New: Analog Telemetry to Nucla; 16-Bit Digitization at Nucla; WAN to Lakewood; Earthworm Data Acquisition System
near-well	19	42
NW cluster	3	4
northern valley	0	3
total	22	49

local events. The largest improvement in detection capabilities was in the magnitude range of **M**0.0 to **M**0.5, which saw a 317% increase in the detection rate (**Figure 7-3**). The improvement in detection of events with magnitudes between **M**0.5 and **M**1.0 was also significant, showing a 67% increase.

Another significant improvement in PVSN's detection capabilities occurred in November, 2007. At that time, the triggering parameters in the data acquisition software were retuned to optimally trigger on very small-magnitude events, especially those occurring near the injection well. Seismic events are detected using a two-step process in both the TROLL and Earthworm systems. The first step requires maintaining running averages of the long-term and short-term signal levels for each station. A station trigger is activated (and remains on) whenever the ratio of short-term to long-term signal levels exceeds a pre-set threshold. An activated station trigger turns off a short time after the ratio decreases below the threshold. The second step in event detection is to continuously track the number of simultaneously active station triggers for groups of adjacent stations. If the number of triggered stations exceeds a pre-set threshold, than an event is declared and the seismic data from all stations in the network are recorded. The basis for this method is the observation that the largest-amplitude seismic phases typically arrive at stations in approximately the same order and proportion as their distance from the epicenter (i.e., they show move-out), whereas noise tends to produce station triggers having a more random distribution among geographically distant stations.

In order to minimize the number of noise triggers - a key concern with the older TROLL data acquisition system, which had limited memory and storage - data acquisition parameters were set so that at least five stations needed to be triggered before an event was declared. In addition, the threshold ratio of short-term to long-term signal averages was set at 2.0 for station triggering.

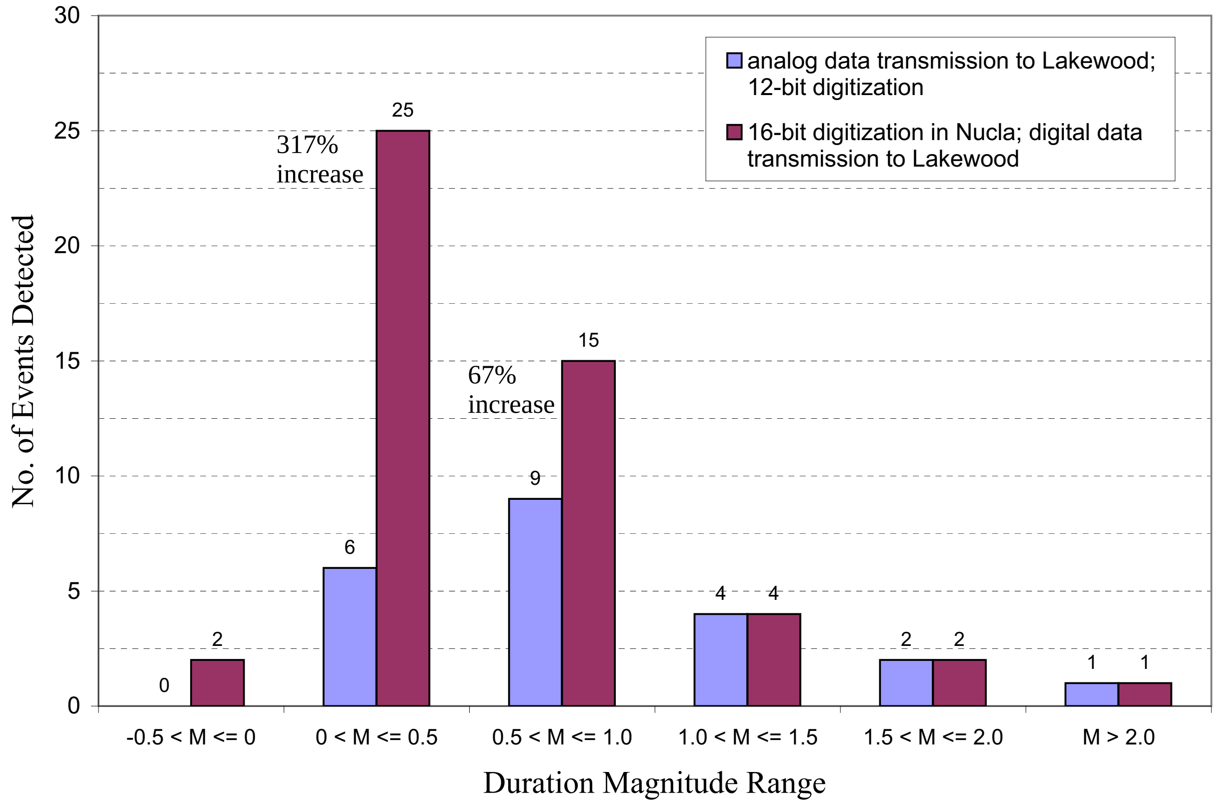


Figure 7-3 The number of seismic events detected as a function of magnitude when transmitting seismic data to Lakewood in analog form and using 12-bit digitizers in Lakewood (blue), compared to the number of events detected when using 16-bit digitizers in Nucla and then transmitting the digital data to Lakewood (red). The data were acquired using both telemetry and digitization systems from Oct. 3 to Nov. 14, 2000.

With the advent of inexpensive disks and memory, data storage costs are no longer a significant factor in network operations costs. With faster computers and automated processing, noise triggers tend to have a smaller impact on operations, and can usually be processed and deleted with little expense. In 2007, there was a concern that the triggering parameters were overly conservative and had not kept pace with advances in technology, which could result in an unnecessary loss of data in the event that several stations were down and thus unable to provide for the minimum number of triggered stations.

In November, 2007, the triggering parameters were changed so that only three stations are now required for an event trigger (and only two, if they are the two stations nearest the injection well, PV11 and PV16). In addition, the ratio of short term to long term signal averages required to activate a station trigger was reduced from 2.0 to 1.6. As a result of these changes in the triggering parameters, there was an abrupt marked increase in the number of events with magnitudes less than **M**0.5 detected, beginning on about Nov. 14, 2007 (**Figure 7-4**). Hence, PVSN's detection threshold was approximately **M**0.5 or slightly larger prior to November, 2007, and then abruptly decreased. Based on the seismicity detected since November, 2007, it appears that PVSN's current detection threshold is about **M**0.0 or slightly lower (**Figure 7-4**).

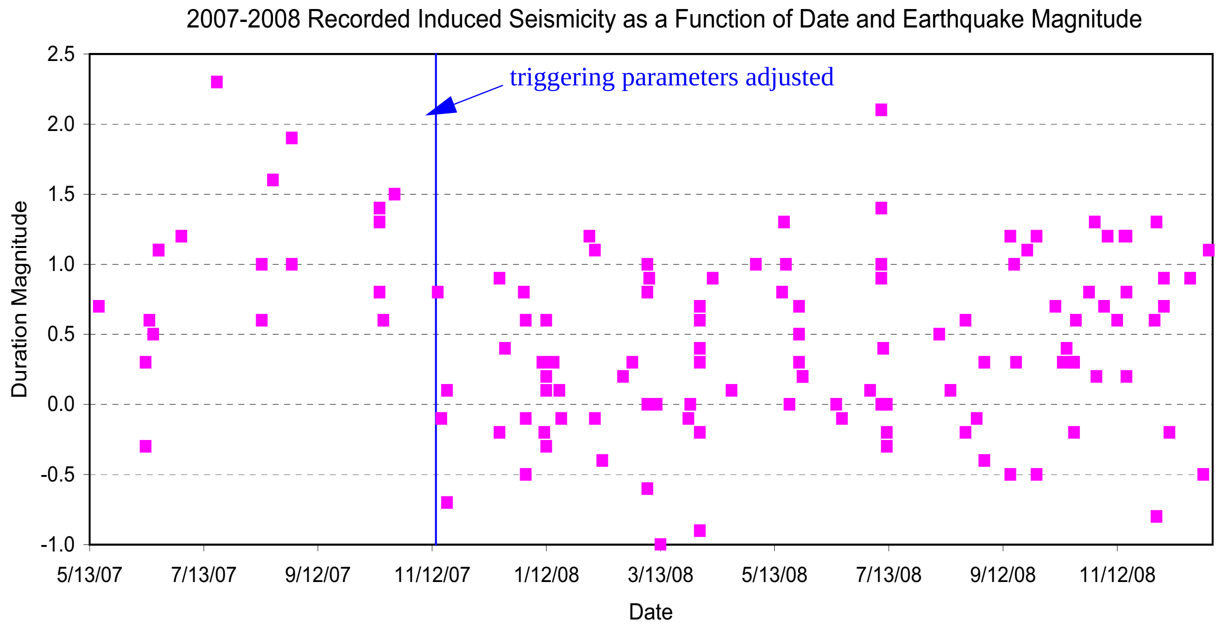


Figure 7-4 Induced seismicity detected from mid-2007 through 2008, plotted as a function of date and event magnitude. The vertical blue line indicates the date when PVSN's triggering parameters were adjusted to increase the network's sensitivity to detecting small-magnitude events.

7.8 PVSN Performance

Automated methods of monitoring PVSN performance have not yet been implemented. In recent years, annual variations in network performance have been evaluated by tracking the number of days of total network downtime. This is the most basic form of network performance monitoring; with improvements in operations and maintenance that began in 2007 resulting in few periods with the network totally down, more detailed methods of tracking performance are needed. The annual numbers of days of total network downtime, for years beginning in 2000, are listed in **Table 7-4.** Prior to 2005, the annual number of days of total network downtime ranged from 5 to 24 (corresponding to network uptimes of 93.4% to 98.6%). The annual number of days of total network downtime increased in 2005 to 2007, ranging from 34 to 47 days (corresponding to 87.1% to 90.7% uptime). Because of extensive station maintenance and other upgrades performed during 2007, the number of days of total network downtime in 2008 decreased to 10 (corresponding to 97.2% uptime). Further details of PVSN performance during 2008 are given in section 3.

Table 7-4 Annual PVSN Total Network Uptime

Year	Total No. 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%

*sum of all network down days, including partial days
**not tabulated in 2001

8.0 SEISMIC ANALYSIS METHODS

8.1 Local Seismic Magnitude Scale

Earthquake magnitudes for PVSN are computed from the duration of the recorded signal. This scale, called the duration or coda magnitude, is denoted **M** in this report. The particular duration magnitude scale used by PVSN was developed for the western Colorado region and has not been calibrated specifically for the Paradox Valley area.

8.2 Typical Seismograms from PVU

The following figure, **Figure 8-1**, shows typical seismic signals (i.e., seismograms) recorded by PVSN and induced by PVU injection. **Figure 8-1(a)** is an **M**0.9 event recorded on January 29, 1994; **Figure 8-1(b)** is also an **M**0.9 event but was located about 3 meters (m) from **(a)** and was recorded in February 7, 1994; **Figure 8-1(c)** is also an **M**0.9 event located about 9 m from **(a)** but was recorded on February 11, 1997; and **Figure 8-1(d)** is an **M**0.2 event located about 90 m from **(a)** and recorded on October 33, 1999. Each seismogram has been 0.5-20 Hz bandpass filtered using a 4-pole, zero-phase Bessel filter.

8.3 Event Location Methods

Locating earthquakes requires (1) appropriate array geometry, (2) identification of a minimum of 4 arrival times of specific phases (P and S) in the recorded signals, and (3) a velocity model of the region through which the signals travel. For local earthquakes detected by PVSN, arrival times are initially determined automatically by processing software, but then are manually checked and re-picked as necessary. Compressional-wave (P-wave) arrival times are determined primarily from the vertical-component seismograms, at all stations with acceptable signal-to-noise ratios. Shear-wave (S-wave) arrival times are only determined from the horizontal seismogram components. The number of PVSN stations with horizontal components has increased over the years from the initial 2 (PV08 and PV11) to the current 8 (PV02, PV03, PV04, PV08, PV10, PV11, PV12, and PV14).

Preliminary earthquake locations for all events occurring within the perimeter of PVSN are computed using the manual arrival time picks and a local three-dimensional (3-D) P-wave velocity model (**Figure 8-2**). The S-wave velocity model used is calculated from the 3-D P-wave velocity model and a 1-D model of the ratio of P-wave to S-wave velocity (Vp/Vs, **Figure 8-3**). The 3-D P-wave velocity model and 1-D Vp/Vs model were developed for the Paradox Valley area from an iterative hypocenter-velocity inversion of a subset of the earthquake arrival time data. (For a mathematical description of the inversion technique, see Block, 1991.) In this inversion, arrival times were used from 1256 injection-induced events meeting the following criteria: magnitude >= **M**0.7, total number of arrival times >= 10, number of S-wave arrival times >= 1 (at either station PV11 or PV16), maximum gap in the azimuthal ray coverage <= 100^{o}, and distance from epicenter to nearest recording station divided by the focal depth <= 1.0. In addition, arrival times from 19 regional earthquakes and 51 identified mine blasts were included. Note that at the time that

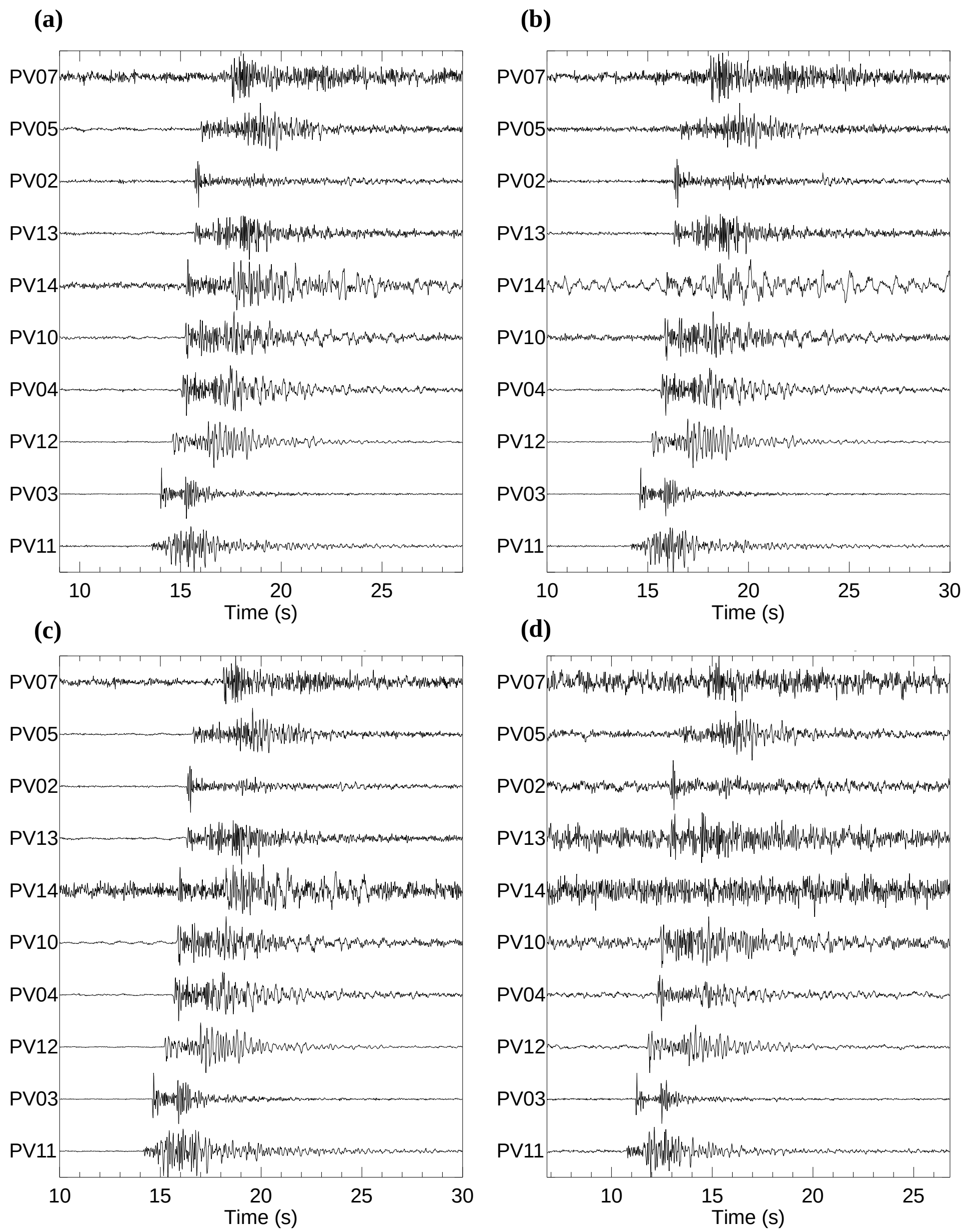


Figure 8-1 Examples of vertical-component seismograms from four closely-spaced events recorded by the indicated PVSN stations.

this data set was constructed, the overwhelming majority of available S-wave arrival times were from stations PV11 and PV16. Only a handful of S-wave arrival times were available from a newly-installed 3-component station at PV12; the other 3-component stations were not yet online. Since stations PV11 and PV16 are very close to the injection well, the 1-D Vp/Vs model developed from the hypocenter-velocity inversion, and the corresponding S-wave velocity model, are only accurate in the vicinity of the injection well. However, because we have no better S-wave velocity model for the Paradox Valley area, we currently use this S-wave velocity model when

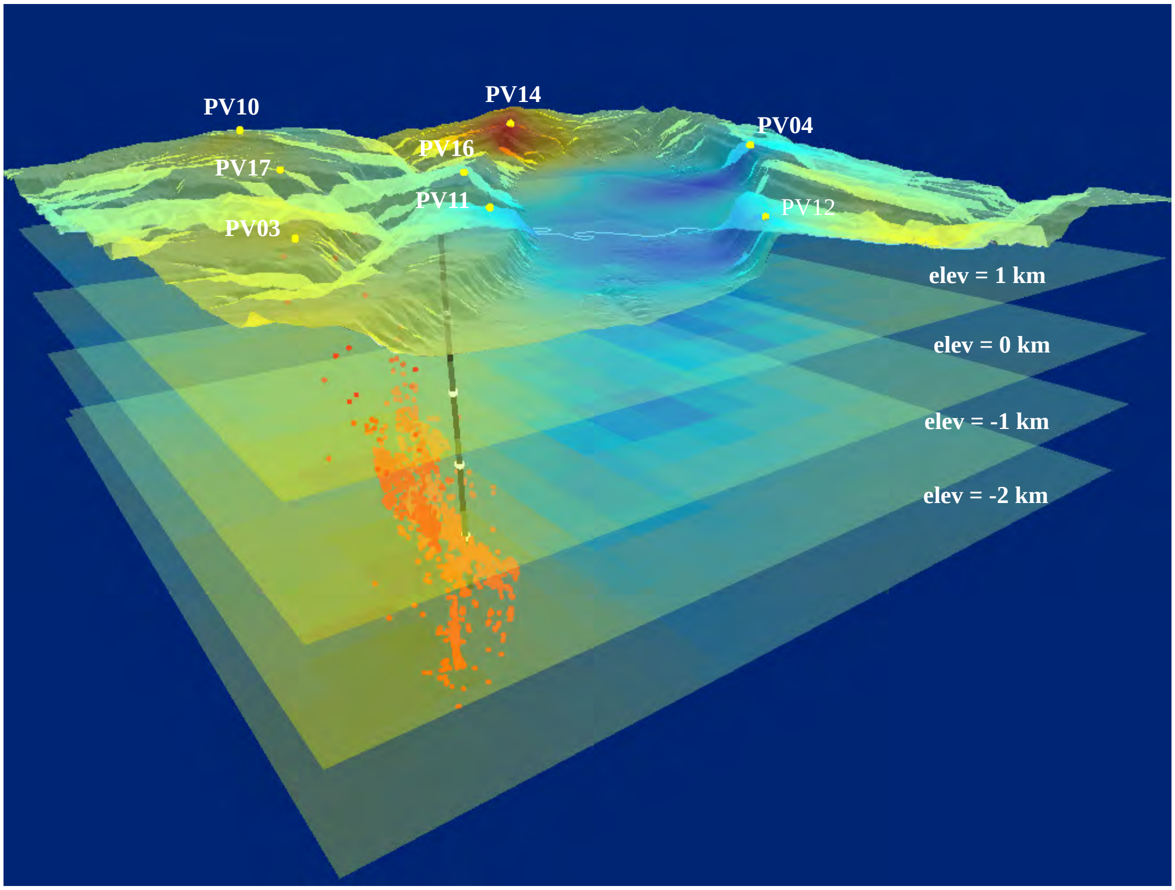


Figure 8-2 Three-dimensional P-wave velocity model used to locate local PVSN seismic events. View is looking toward the northwest. Vertical exaggeration = 2. Velocities between 4.2 km/s and 6.2 km/s are color-coded, with the cooler colors (blue) representing the slower velocities and the warmer colors (orange, red) representing the higher velocities. The black line is the injection wellbore, with white depth markers shown at 1-km increments. The labeled yellow squares are seismic stations. The orange dots are the hypocenters of induced earthquakes.

processing the S-wave arrival time data from all the current 3-component stations, including those located at considerable distances from the injection well.

For the induced earthquakes in the vicinity of the injection well, the preliminary earthquake locations are refined by performing a relative event relocation (similar to Waldhauser and others, 1999). The relative relocation procedure uses arrival time differences between pairs of waveforms recorded at the same station from two nearby events. The arrival time differences are computed by time-domain waveform cross-correlation and are about an order of magnitude more accurate than the differences in the manually-picked arrival times. More than 14 million arrival time differences were used simultaneously to compute accurate relative locations of the induced events recorded between July, 1991 (when the first injection test was performed) and the end of 2008. Nearly 97% of the induced events had sufficient signal-to-noise ratios and azimuthal ray coverage

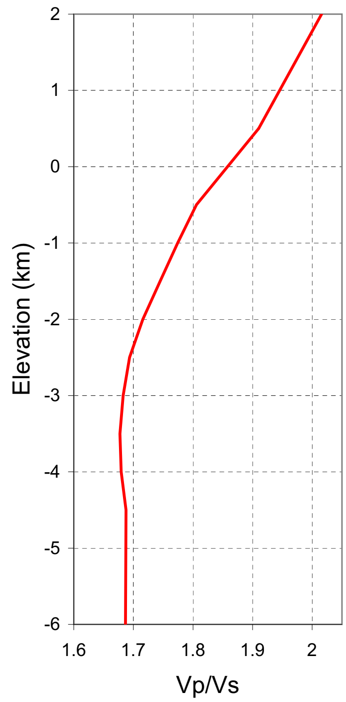


Figure 8-3 One-dimensional Vp/Vs model used to locate local PVSN seismic events. The S-wave velocity model is computed from the 3-D P-wave velocity model shown in Figure 8-2 and this 1-D Vp/Vs model.

to be included in the relative relocation. In 2008, a separate relative relocation of earthquakes occurring at the northern end of Paradox Valley was also performed. Approximately 70% of the events occurring in that region were tied into that relative relocation. For the remaining induced events, local earthquakes, and explosions, the locations computed from the manual arrival time picks are used.

9.0 LONG-TERM OBSERVATIONS AND ANALYSES

9.1 Local Pre-Injection Seismicity

Figure 9-1 shows the epicenters of the pre-injection data, recorded between 1985 and June, 1991. In the six years prior to injection at PVU, PVSN recorded only four local earthquakes (Enviro-Corp, 1995; Ake and others, 1996) and none within 15 km of the injection well site.

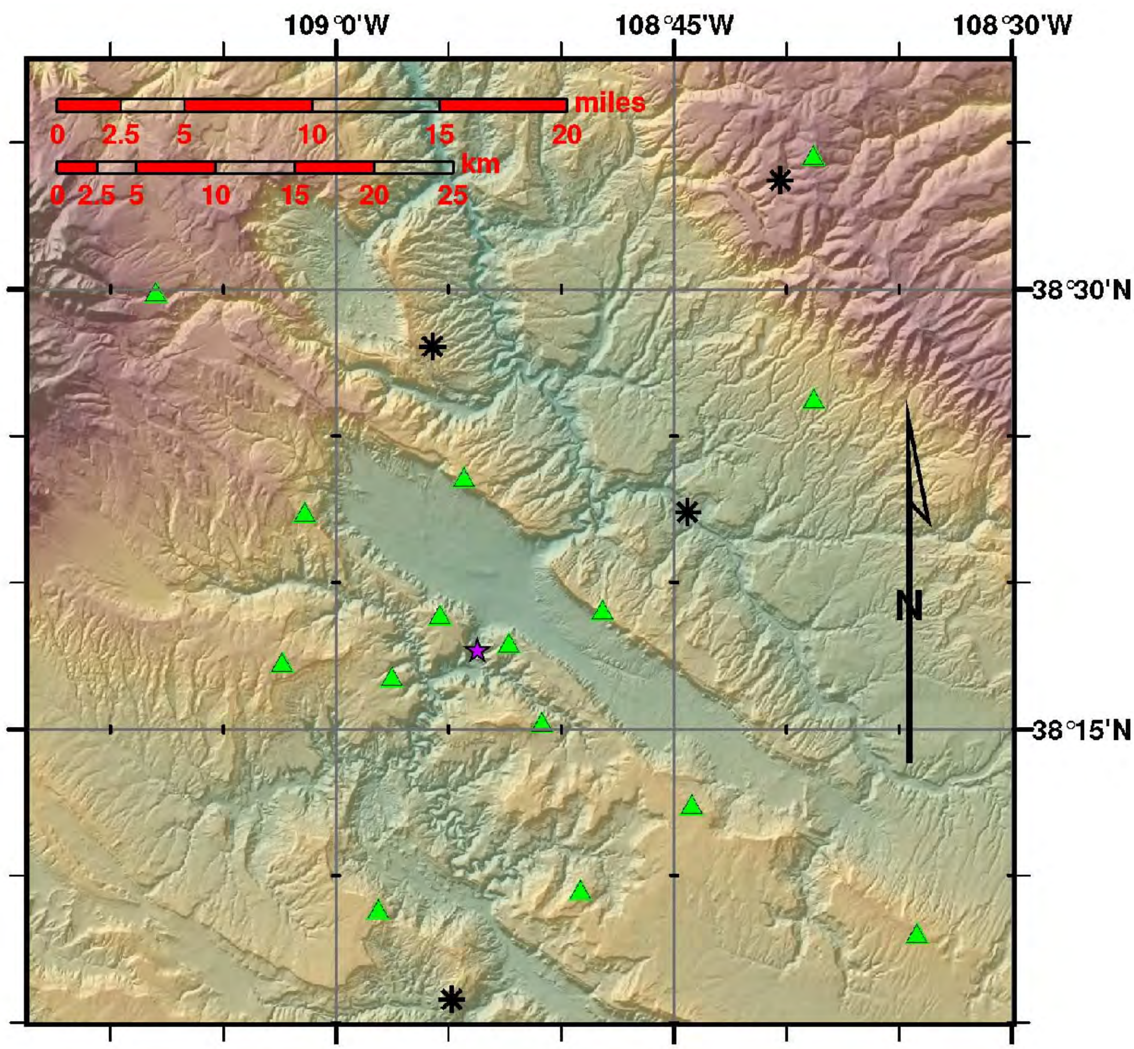


Figure 9-1 Paradox region natural seismicity recorded in 1985-1991. Asterisks are the epicenters of the natural seismicity, triangles show PVSN seismic stations, and the star is the injection well.

9.2 Induced Seismic Events and Well Testing (1991-1995)

Between July, 1991 and April, 1995, PVU ran 7 injection tests. Each test consisted of a continuous pumping period followed by a wellhead shut-in to monitor downhole pressure fall off with time. **Table 9-1** summarizes the injection tests including injected volume, pumping duration, and number of induced seismic events recorded. In conjunction with **Table 9-1**, **Figure 9-2** shows the injection rate and number of induced seismic events per day. Also noted in the figure is the 1993 acid stimulation. The stimulation was performed to increase the imbibition of the well (Envirocorp, 1995). **Figure 9-3** shows the cumulative epicenters induced by the injection tests.

Table 9-1 Injection tests, 1991-1995

Test No.	Injected Volume	Initial Pumping Date and Duration	Injectate	Hydrostatic Pressure @ 4,300 m[a] depth	No. Induced Seismic Events
	m^3	***(date) days***	***%PVB[b]:%FreshWater***	**(MPa)**	
1	11,000	(11Jul91) 14	0%:100%	42	20
2	16,000	(15Aug91) 12	33%:67%	44	9
3	54,000	(5Nov91) 54	67%:33%	47	16
4	42,000	(6Jul93) 47	0%:100%	42	0
--	38	(20Sep93) 14	28% HCl acid injection	--	--
--	34		100% fresh water flush following acid injection[c]		
5	54,000	(3Oct93) 28	70%:30%	47	81
6	89,000	(18Jan94) 41	70%:30%	47	170
7	354,000	(14Aug94) 242	70%:30%	47	370
Total	**620,000**	**438 days**	**---**	**--**	**666**

[a]Depth = Top of the casing perforation interval; i.e., the top of the injection target horizon, the Leadville Limestone formation

[b]PVB = Paradox Valley Brine (260,000 mg/l total dissolved solids)

[c]Injection well surface pressure became negative (i.e., below hydrostatic) following water flush of acid injection;

To convert ***m^3*** (volume) to gallons multiply by 264.2.

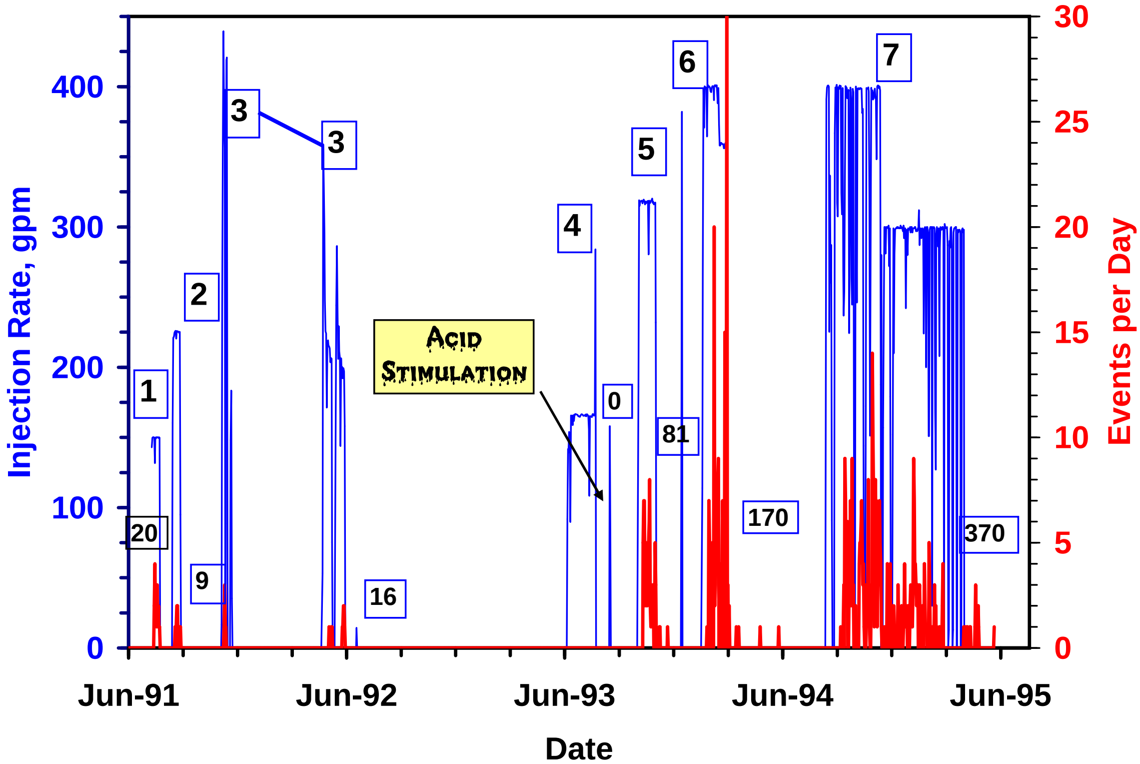


Figure 9-2 Injection rate (blue lines) and daily number of injection-induced seismic events (red lines) for tests. The boxed numbers at the top of the figure identify the tests; the boxed numbers at the bottom of the figure are the number of seismic events recorded during and immediately following the specific tests.

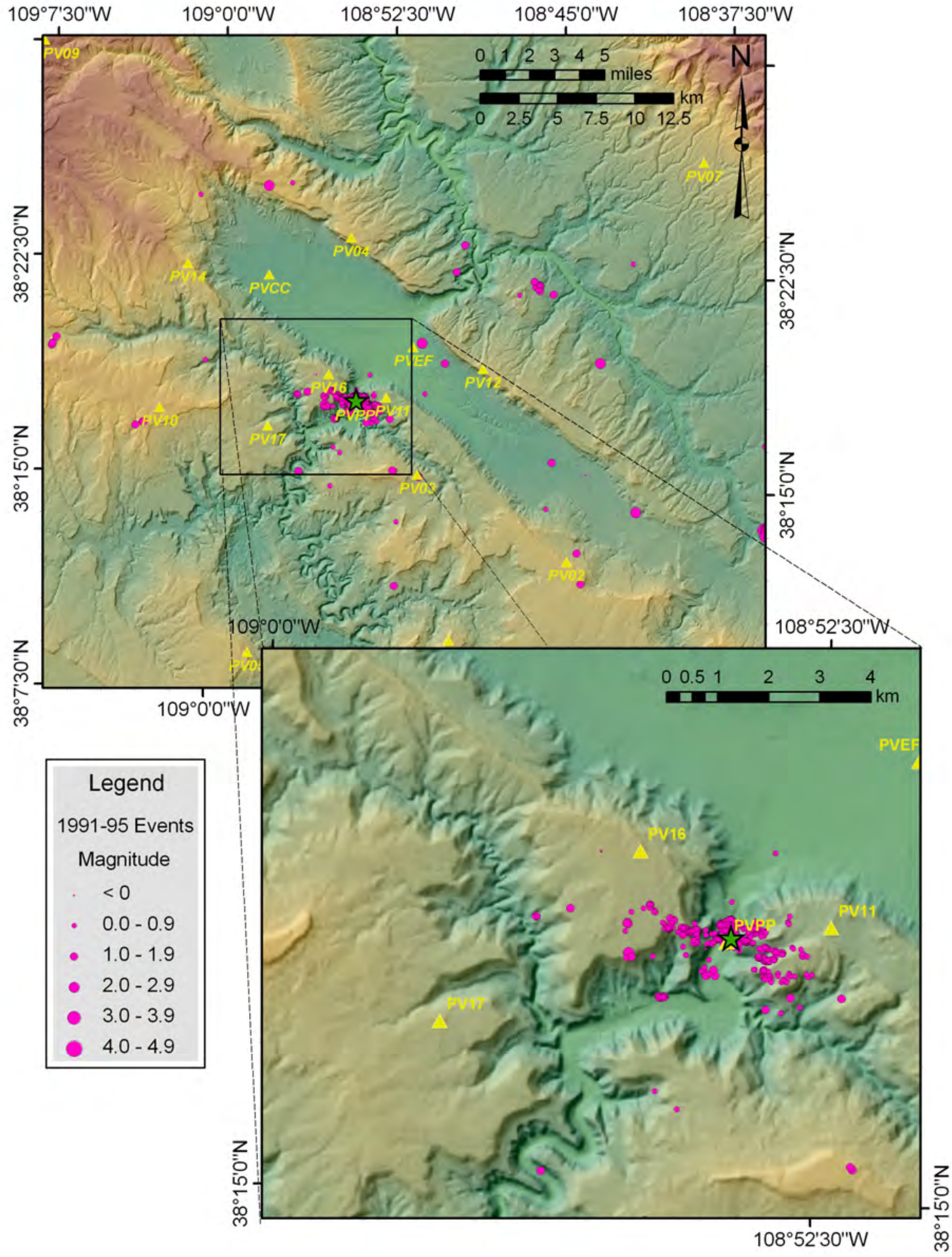


Figure 9-3 Epicenters of seismic events recorded during injection tests, 1991-1995. Triangles show the current local stations of PVSN and star is the injection well. Note that many of the events occurring at large distances from the injection well are likely explosions that have not been properly flagged in the datafiles.

9.3 Induced Seismic Events and Continuous Injection (1996-Present)

The event detection capability for PVSN has varied during it's operational history due to changes in network operations, as discussed in section 7.7. The detection threshold, the magnitude above which seismic events are consistently detected, has generally decreased over time as improvements have been made. In order to compare cumulative seismicity rates (i.e., the number of recorded events per year of a given magnitude or greater) over the history of the network, these changes in the detection threshold must be accounted for. While quantitative methods exist to adjust observed seismicity rates to account for such changes, the simplest and most direct method of comparison is to consider only those events with magnitude greater than or equal to the maximum historical detection threshold. In previous annual reports, cumulative seismicity rates were computed using an implied detection threshold of **M**0.0; year-to-year comparisons were made of the cumulative number of recorded events with **M**0.0 or greater per year. However, it is now clear that for much of PVSN's history, the detection threshold was somewhat larger than **M**0.0. Analysis of historical data indicates that PVSN's sensitivity to detecting events less than **M**1.0 increased substantially in October, 2000, when improvements were made to the data telemetry and digitization components of the network (see section 7.7 for details). PVSN's ability to consistently detect events with **M** < ~0.5 again improved significantly in November, 2007, when the data acquisition triggering parameters were tuned to optimally trigger on low-magnitude events (**Figure 7-4**), especially for the area near the injection well. Hence, variations in observed seismicity rates over time for events with magnitudes less than **M**1.0 are partially due to changes in the event detection capability of the network. In contrast, seismicity rates for earthquakes with magnitude >= **~M**1.0 do not appear to have been affected by documented changes in historical detection capabilities. Seismic events of this magnitude are likely to produce ground motions sufficient to trigger most, of not all, of PVSN's seismic stations, thereby making the detection of events with **M** >= 1.0 fairly insensitive to times when several stations may have been offline or marginally operational because of maintenance issues. For these reasons, a detection threshold of **M**1.0 is considered to be more reliable for comparing cumulative seismicity rates over the history of the network than the previously-used value of **M**0.0.

Table 9-2 gives an annual listing of computed rates of induced seismicity since the start of continuous injection (in July, 1996). Rates are shown for earthquakes with magnitude >= **M**0.0, for consistency with past annual reports, and for earthquakes with magnitude >= **M**1.0, a more reliable indicator of changes in actual seismicity rates since 1996. Events occurring in the primary zone of induced seismicity surrounding the injection well and in the secondary induced seismicity zone northwest of the well are included. The numbers of days of seismic monitoring listed in **Table 9-2** have been corrected for the numbers of days of total network downtime for those years for which this information is available. Ignoring the initial low seismicity rate for 1996 when continuous injection began (since it took nearly 4 months for the reservoir to re-pressurize and start inducing seismicity), the seismicity rates for earthquakes with **M** >= 1.0 for the previous three years are the lowest rates observed to date during continuous injection operations at PVU.

Table 9-3 and **Figure 9-4** demonstrate that regular injection well shut-downs and reduced injection rate have dramatically reduced event production. **Table 9-3** presents the seismicity rates for events with magnitude >= **M**1.0 by PVU injection phase (see section 6 for a description of the

Table 9-2 Computed induced seismicity rates since the start of continuous injection operations at PVU.

Year	No. of Days of Seismic Monitoring[5]	M >= 0.0		M >= 1.0	
		No. of Induced Events Detected	Average Seismicity Rate (no. events per day)	No. of Induced Events Detected	Average Seismicity Rate (no. events per day
1996[1]	163	9	0.06	2	0.01
1997[2]	365	508	1.39	121	0.33
1998	365	1108	3.04	247	0.68
1999	365	1070	2.93	263	0.72
2000	342	282	0.82	71	0.21
2001	365	81	0.22	31	0.08
2002	360	58	0.16	29	0.08
2003	350.5	134	0.38	80	0.23
2004	350	106	0.30	52	0.15
2005	331	101	0.31	54	0.16
2006	318	25	0.08[3]	15	0.05
2007[4]	178	22	0.12	11	0.06
2008	356	73	0.21	19	0.05

[1] The rate for 1996 was computed for a partial year, starting on July 22 when continuous injection began. Because of the time between the last injection test in 1995 and the start of continuous injection more than a year later, induced seismic events were not detected in 1996 until 111 days after the start of continuous injection.

[2] The number of events and seismicity rate for 1997 may be biased low because of possible missing datafiles.

[3] The seismicity rate for 2006 for M >= 0 is believed to be biased low, because of probable poor network performance during part of the year. (See 2007 Annual Report, section 4, for discussion)

[4] The number of events and seismicity rate for 2007 is reported only for that portion of the year for which the network was sufficiently operational (6/11-12/31) (see 2007 Annual Report, section 4, for discussion).

[5] The numbers of days of seismic monitoring used to compute the seismicity rates have been corrected for the number of days which the network was offline for the years 2000 and 2002-present (as listed in Table 7-4). The network downtime is not available for the other years, and therefore the rates for those years have been computed assuming that the network was operational for the entire year.

Table 9-3 Induced events by injection phase for M >=1

Phase	Dates	Duration	No. of Days of Seismic Monitoring[1]	No. of Induced Events, M >= 1	Avg. Events per Day, M >= 1	Injected Volume
		Days				Mgal
I	7/22/96 - 7/25/99	1099	1099	581	0.53	427
II	7/26/99 - 6/22/00	333	321	86	0.26	118
III	6/23/00 - 1/6/02	563	551	72	0.13	156
IV	1/7/02 - 12/31/08	2551	2387.5	262	0.10	697

[1] The numbers of days of seismic monitoring used to compute the seismicity rates have been corrected for the number of days which the network was offline for the years 2000 and 2002-present (as listed in Table 7-4), as well as for the five months of poor network performance during 2007 (see 2007 Annual Report, section 4, for details). Network downtime is not available for the other years, and therefore the seismicity rates have been computed assuming that the network was operational for the entire year.

injection phases). The number of induced events per day decreased substantially from *phase I* to *phase II*, when the bi-annual 20-day shut-downs were implemented, and again from *phase II* to *phase III*, when the injection rate was decreased by 33%. **Figure 9-4** shows histograms of monthly injection volume and monthly event detection (for **M** >= 1) since the beginning of continuous pumping in 1996. The figure shows the injection phases and emphasizes how dramatically event production has declined since mid-2000 when PVU reduced the injection rate by one third from ~345 gpm to ~230 gpm (i.e., from 3-pump injection to 2-pump injection). The correlation between the decrease in injection rate and the decrease in seismicity rate is also demonstrated in **Figure 9-5**, which presents the daily injection rates and daily seismicity rates (for **M** >= 1) for continuous injection operations.

Figure 9-6 shows the ratio of the cumulative number of induced seismic events with **M** >= 1 to cumulative injection volume (red line), since continuous injection operations began. (A histogram of the seismicity rate (gray) and a plot of the average daily downhole injection pressure (blue) are included for reference.) From late 1996 through mid-1999, the ratio generally increases. (The decrease in the ratio for the later half of 1997 is questionable because of possible missing data files.) The ratio peaks in mid-1999 and then generally decreases through the present. Note that the time the ratio peaks correlates with the onset of the bi-annual 20-day injection well shut-downs. Hence, not only have these shut-downs decreased the absolute seismicity rate, but they have also significantly decreased the rate of seismicity as a fraction of injection volume.

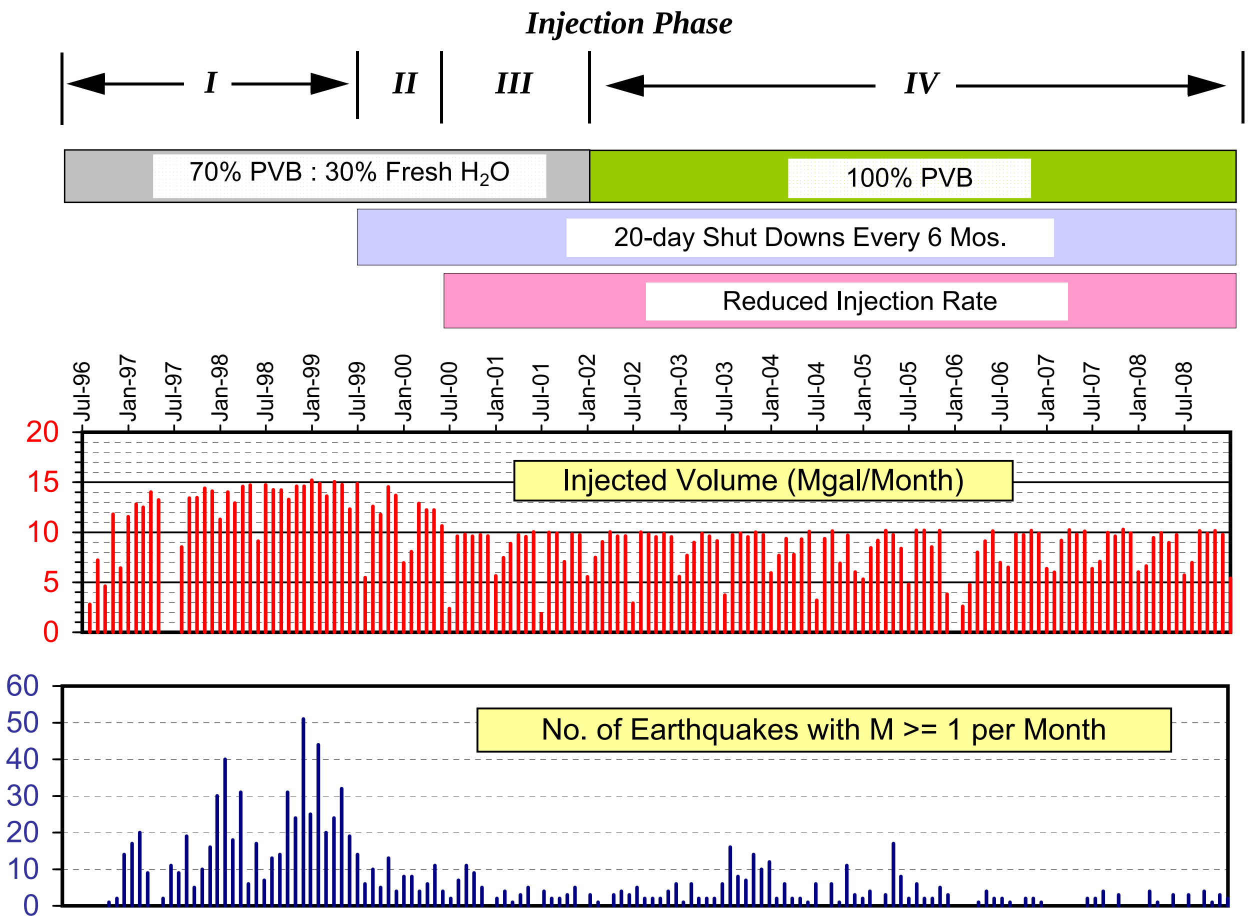


*Figure 9-4 Injection volume and monthly earthquake production for **M** >= 1 at PVU since continuous injection began in 1996. At the top note the injection phases and corresponding time bars. From top down the time bars are (1) the change in injectate ratio, (2) the implementation of bi-annual, 20-day shut-downs and, (3) the reduced injection rate.*

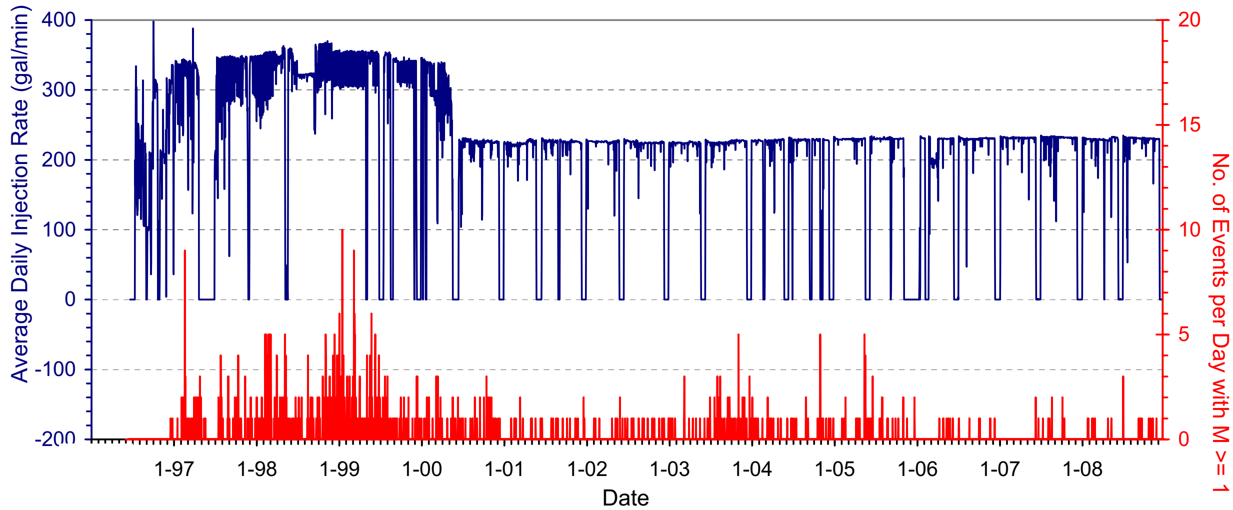


*Figure 9-5 Number of events per day with **M** >= 1 (red) and average daily injection rate (blue) vs. time, for continuous injection operations at PVU.*

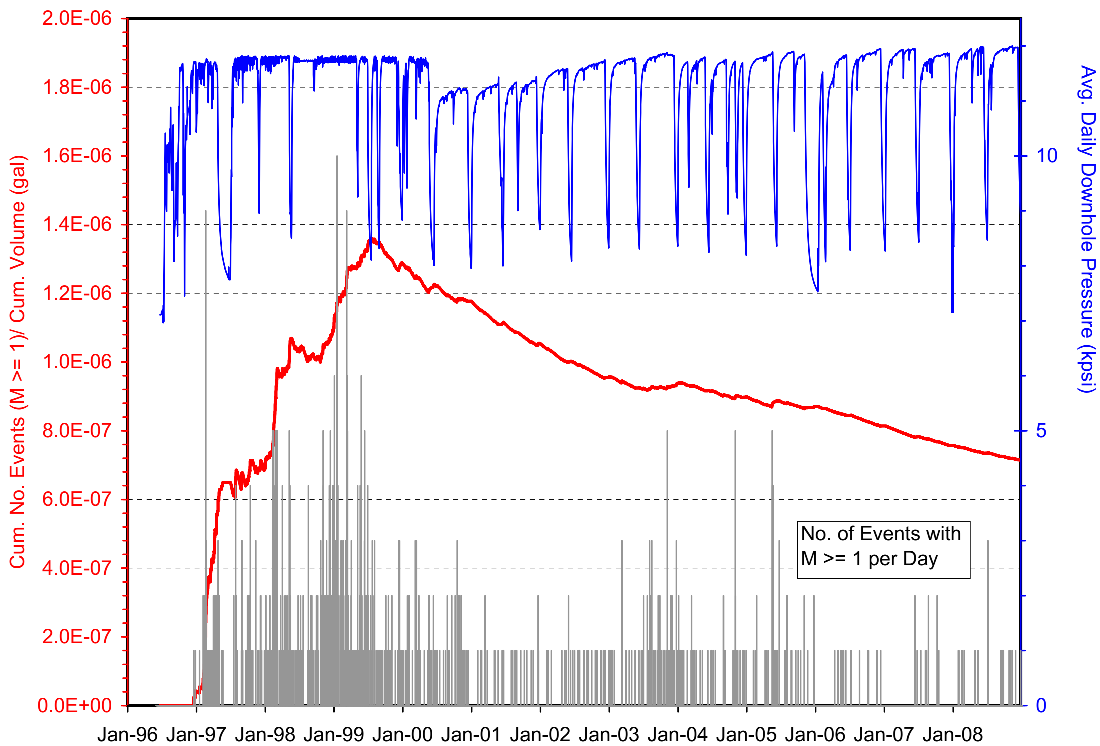


*Figure 9-6 Ratio of cumulative number of seismic events with **M** >= 1 to cumulative injection volume vs. time (red line), for continuous injection operations at PVU. Additional curves are events/day (for **M** >= 1, gray histogram) and average daily downhole pressure (blue).*

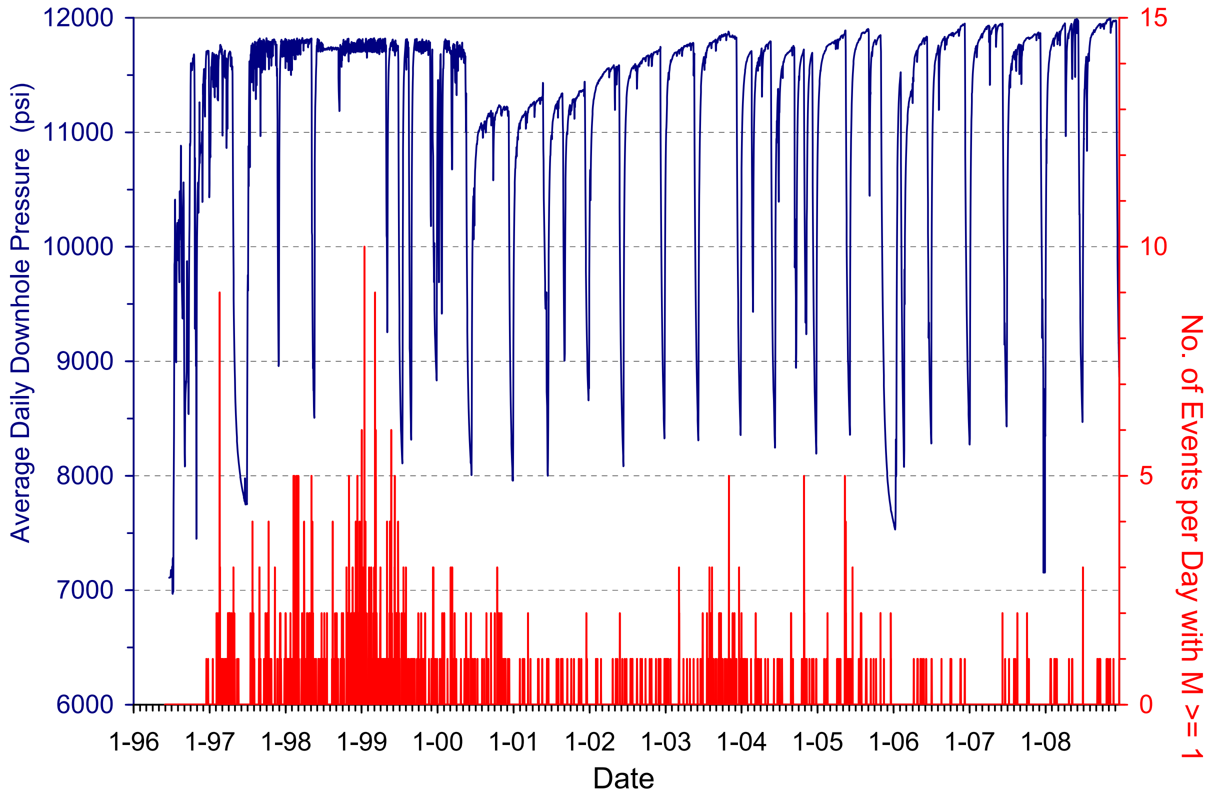


Figure 9-7 Number of events per day (with ***M*** *>= 1; red) and downhole injection pressure (blue) vs. time, for continuous injection operations at PVU. Downhole pressure is calculated for the depth 4.3 km (14,080 ft) below the wellhead.*

When the injection rate was decreased in mid-2000, the downhole pressure immediately fell (**Figure 9-7**). The pressure then gradually increased, more or less linearly (ignoring the injection well shut-in periods), until mid-2003, when it reached about the same pressure as before the 2000 injection rate decrease. Hence, it took about 3 years for the reservoir to re-pressurize at the lower injection rate. Note that the seismicity rate did not immediately decrease after the injection rate was reduced in mid-2000. The seismicity rate decreased in late 2000 - early 2001, and then stabilized at a much lower rate (**Figure 9-7**). Hence, it took the reservoir roughly 6 months to come to equilibrium after the pressure was decreased at the wellhead. The seismicity maintained this low rate while the reservoir was re-pressurizing. In mid-2003, as the downhole pressure in the well approached it's previous maximum, the seismicity rates increased somewhat. (Note that the apparent lack of seismicity in the winter months of 2006 and 2007 shown in **Figure 9-7** may be due to critically low batteries at many of the seismic stations, limiting PVSN's ability to trigger on seismic events during non-daylight hours.)

9.4 Spatial Distribution of Induced Seismic Events

The induced earthquakes occur within two seismogenic groups: a primary zone, asymmetrically surrounding the well to a maximum radial distance of about 3.5 km and a smaller secondary zone, located 6 to 8 km northwest of the injection well (**Figure 9-8**). Events were first induced in the primary zone during injection test no. 1 in July, 1991, while the secondary zone first became active in mid-1997, about a year after the start of continuous injection. Both zones have shown seismic activity every year since then. The vast majority of recorded events occurred within the primary zone in the early years of continuous injection, especially prior to the decrease in injection rate in 2000. In more recent years, the percentage of induced events that occur in the secondary zone to the northwest has increased. This change over time can be seen in the maps of epicenter locations plotted by years of occurrence shown in **Figures 9-9** to **9-20**. This time sequence also shows the growth of the near-wellbore seismic zone, indicating that by 1999 the expansion of the seismic zone surrounding the well had reached maturity and any subsequent expansion is negligible.

The alignments of the epicenters (**Figure 9-8**) are consistent with the interpretation that most of the tectonic stress release takes place along (existing) linear features with orientations consistent with either the primary set of focal mechanisms (N86^{O}E) or the two sets of fractures observed in the oriented core samples (primary: N69^{o}W and N74^{o}W; secondary: N38^{o}W and N42W; Ake and Mahrer, 1999). Relatively little seismicity appears to be occurring along planes with strike consistent with the Wray Mesa fault system, as defined by Bremkamp and Harr (1988). (A small subset of the earthquakes with identified strike-slip focal mechanisms does have a nodal plane orientation very close to the strike of the major Wray Mesa faults; see section 9.5). Bremkamp and Harr (1988) estimated the strike of the Wray Mesa fault system to be ~N55^{o}W. It is likely that these features are the most through-going structures in the area. The spatial distribution of the linear features defined by the epicenters in **Figure 9-8** suggests communication through conduits in ~N35^{O}W to ~N55^{o}W directions. We believe this behavior suggests that fluid is being preferentially carried along steep planes of the Wray Mesa fault system. Opening of these planes will require the least energy and is less likely to induce surface-measurable events, since these planes are oriented normal to the least principal stress direction. The lack of seismic events located between the primary seismic zone near the injection well and the secondary zone to the northwest indicates that these two zones communicate hydrologically by a conduit(s) of fluid, probably through one or more principal faults of the Wray Mesa system, aligned with a principal stress direction.

At least within the primary zone of induced seismicity, the earthquakes also appear to generally follow the stratigraphic layering. The earthquakes within the primary seismicity zone shallow toward the southwest, as shown in **Figure 9-21**. In this plan view, the epicenters are color-coded by depth relative to the wellhead. The shallowing of events toward the southwest is consistent with the local dip of the geologic layering, including the primary injection target horizon, the Leadville Formation.

Figure 9-22 shows a NE-SW geological cross section normal to the strike of the valley and passing through the injection well. The geology, fault structures, etc. are based on Bremkamp and

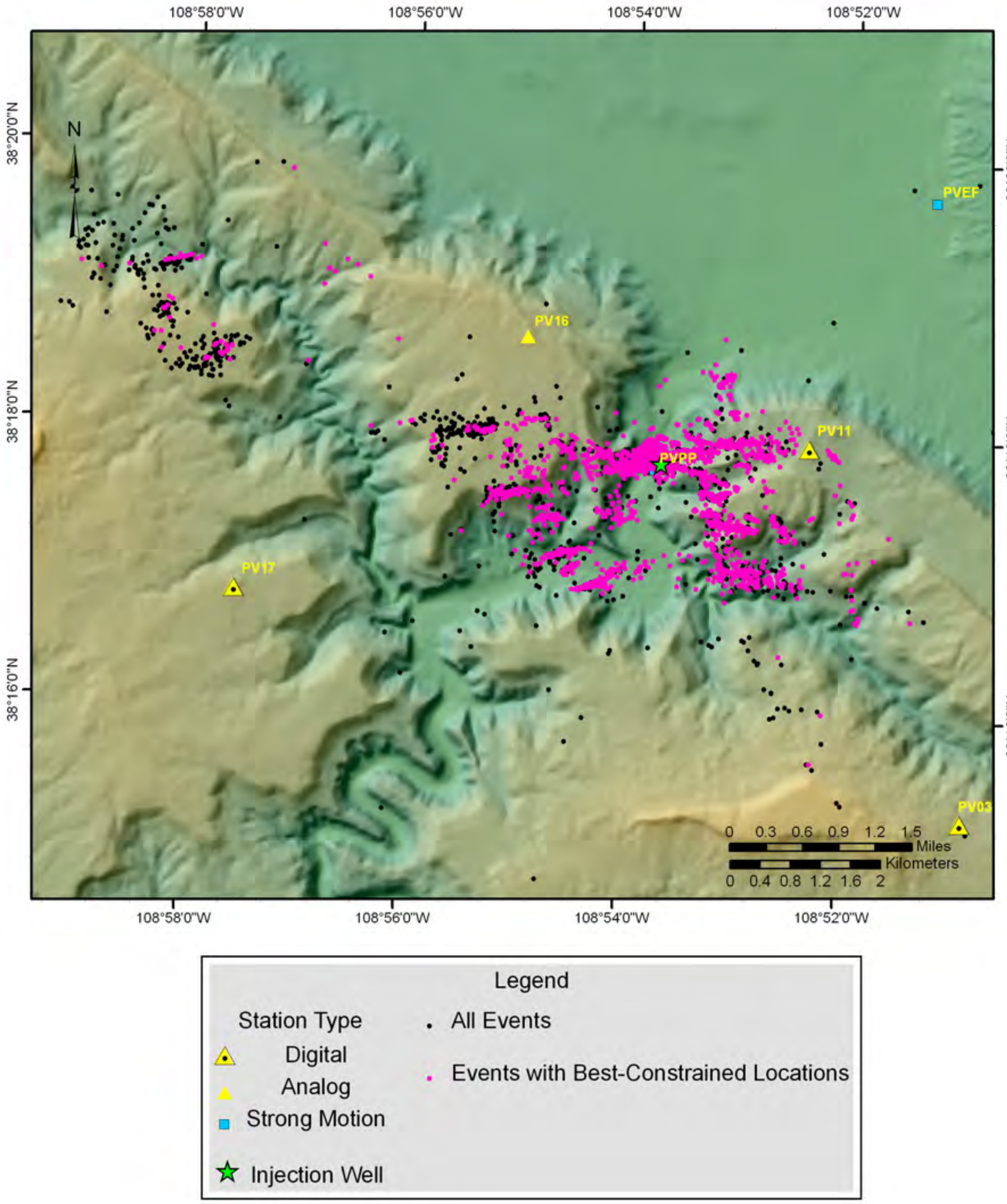


Figure 9-8 Epicenters of earthquakes recorded from 1991 through 2008.

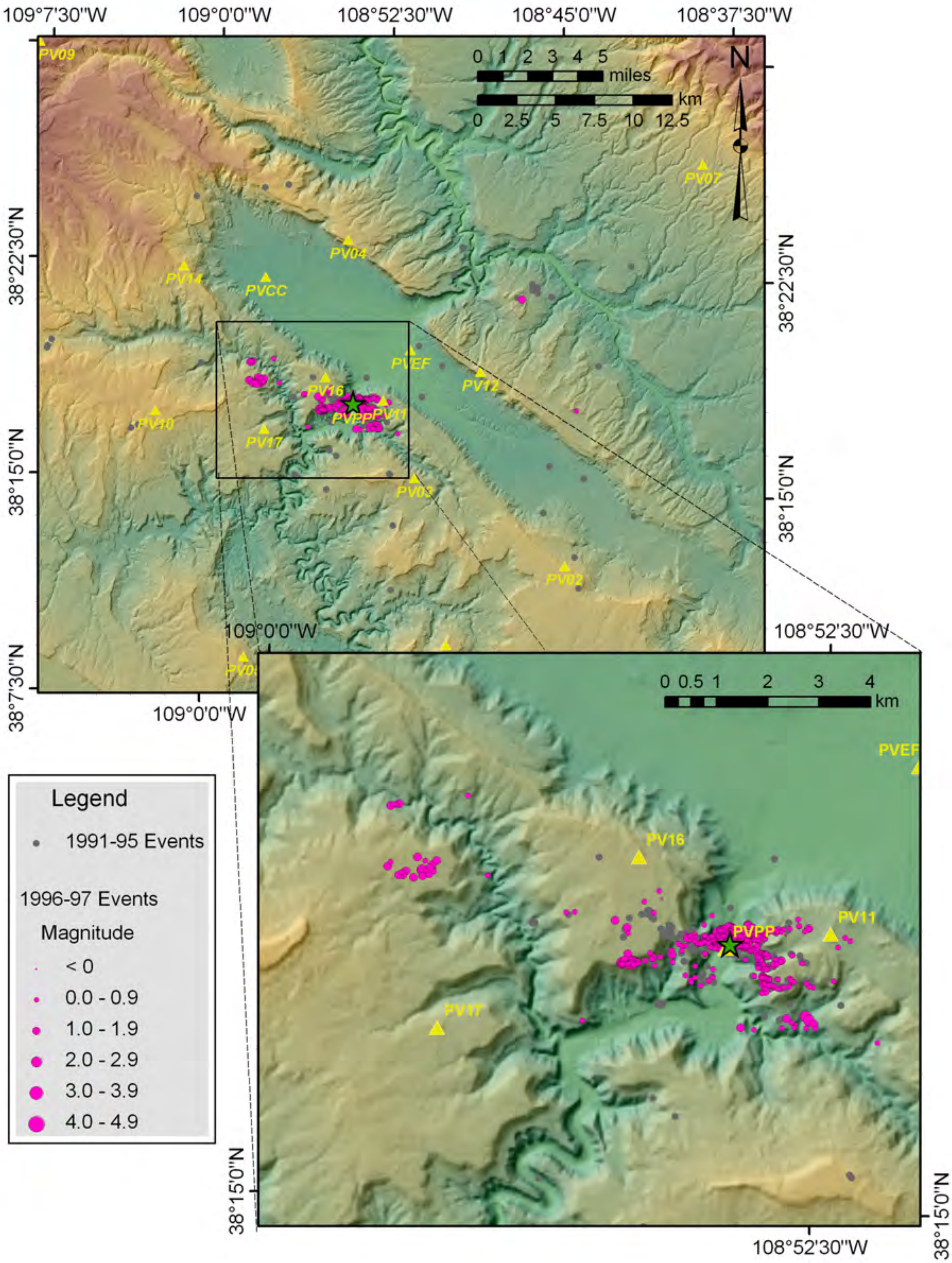


Figure 9-9 1996-1997 Epicenters. Star is injection wellhead.

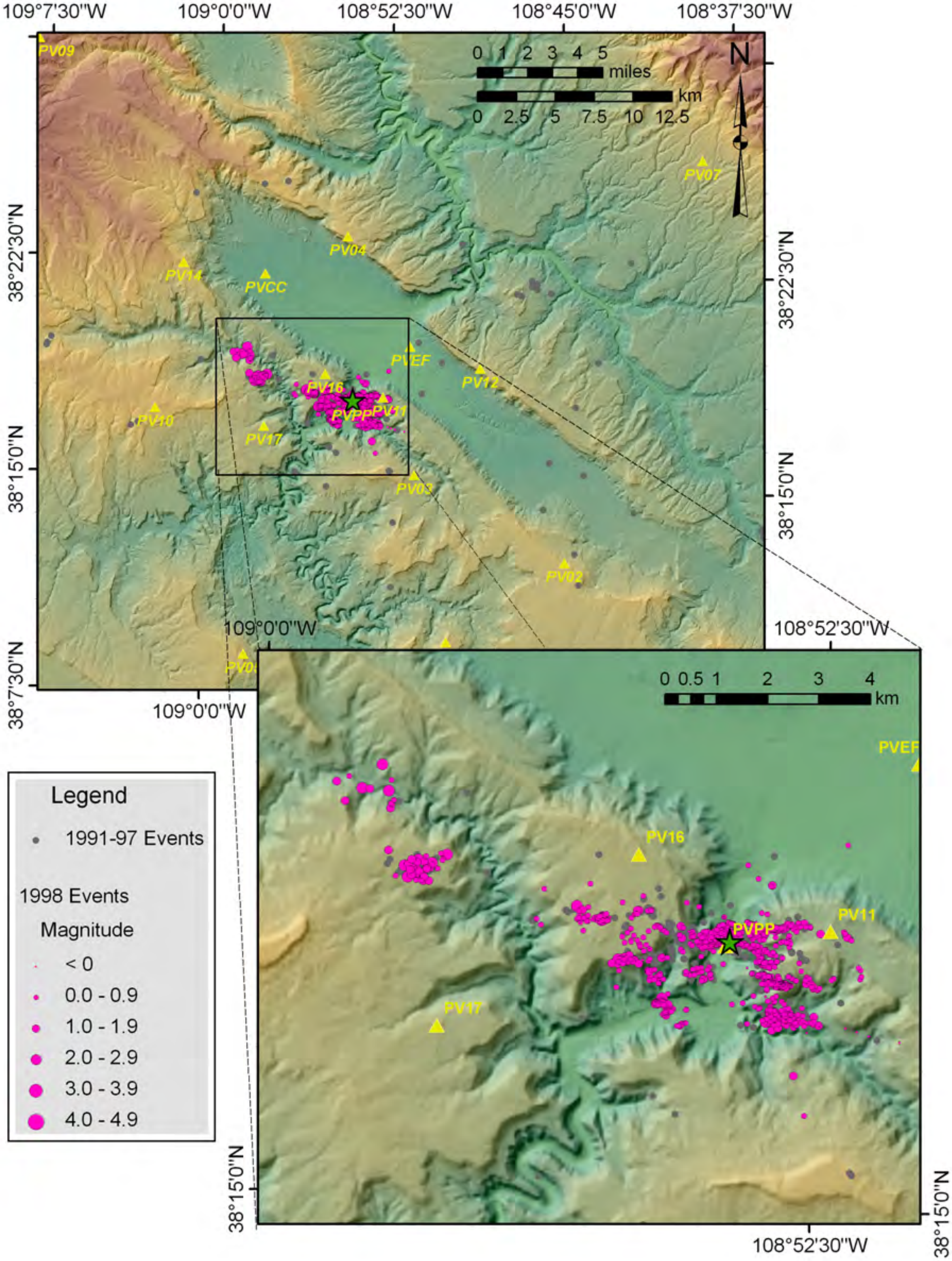


Figure 9-10 1998 Epicenters. Star is injection wellhead.

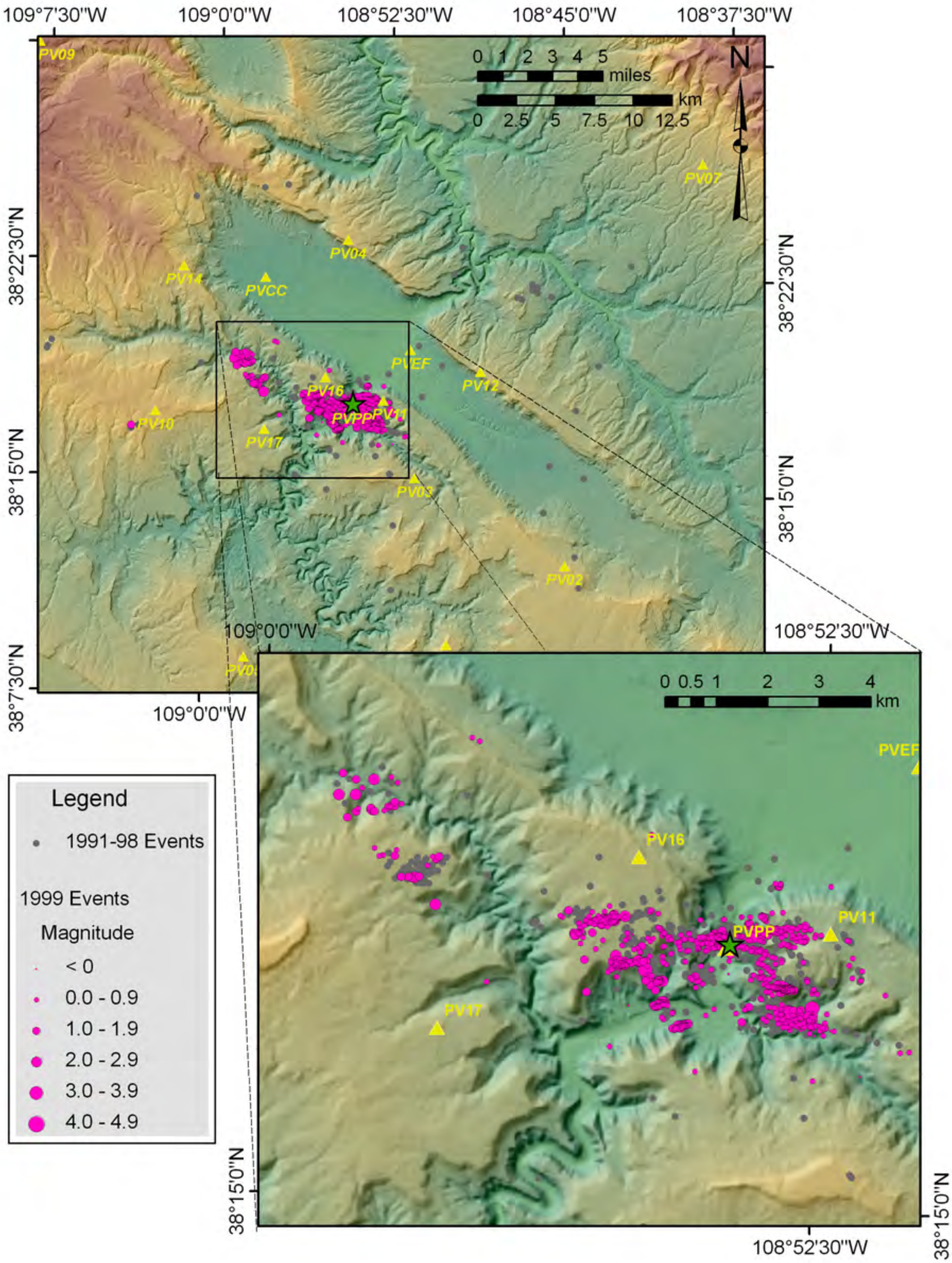


Figure 9-11 1999 Epicenters. Star is injection wellhead.

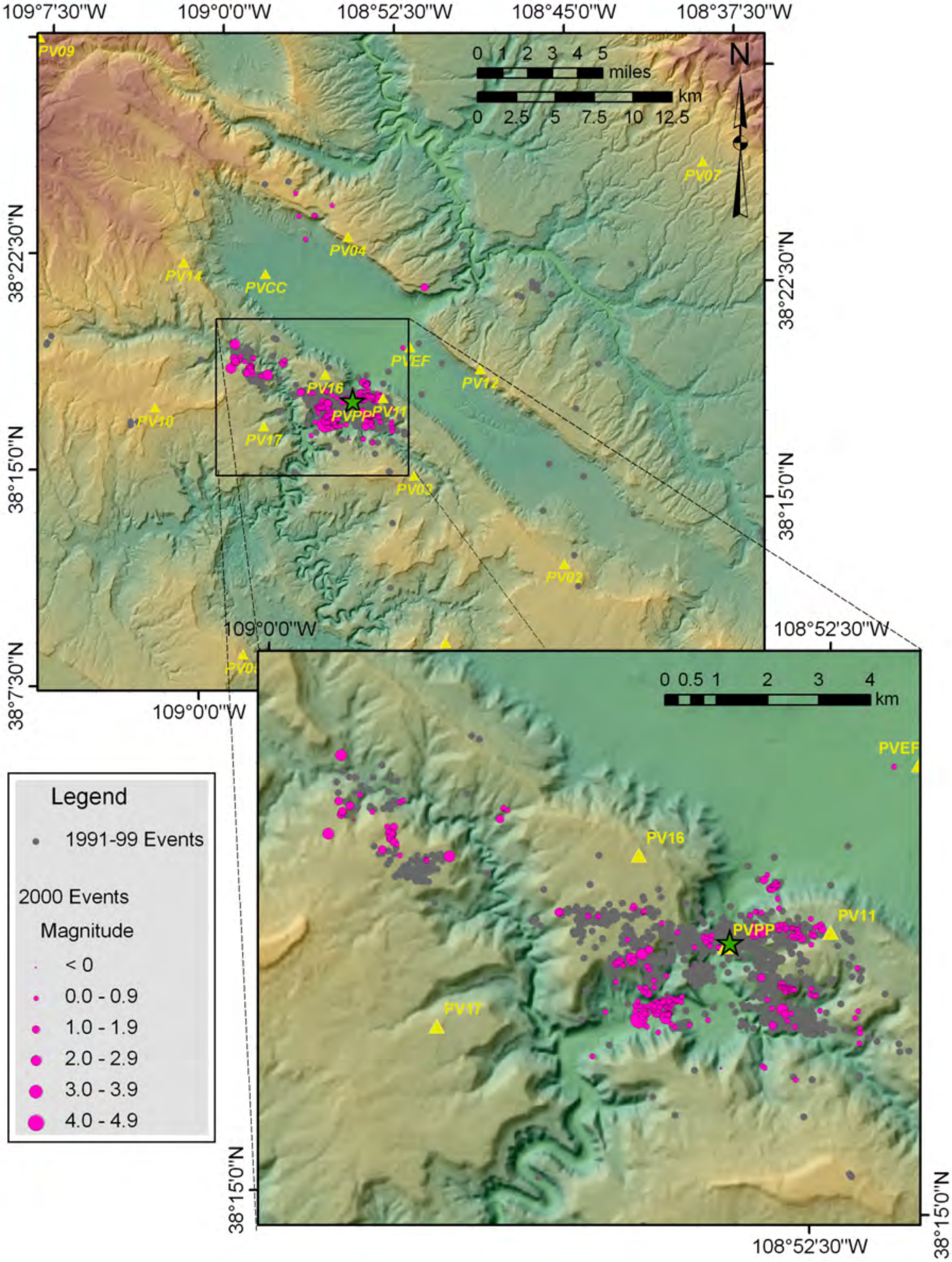


Figure 9-12 2000 Epicenters. Star is injection wellhead.

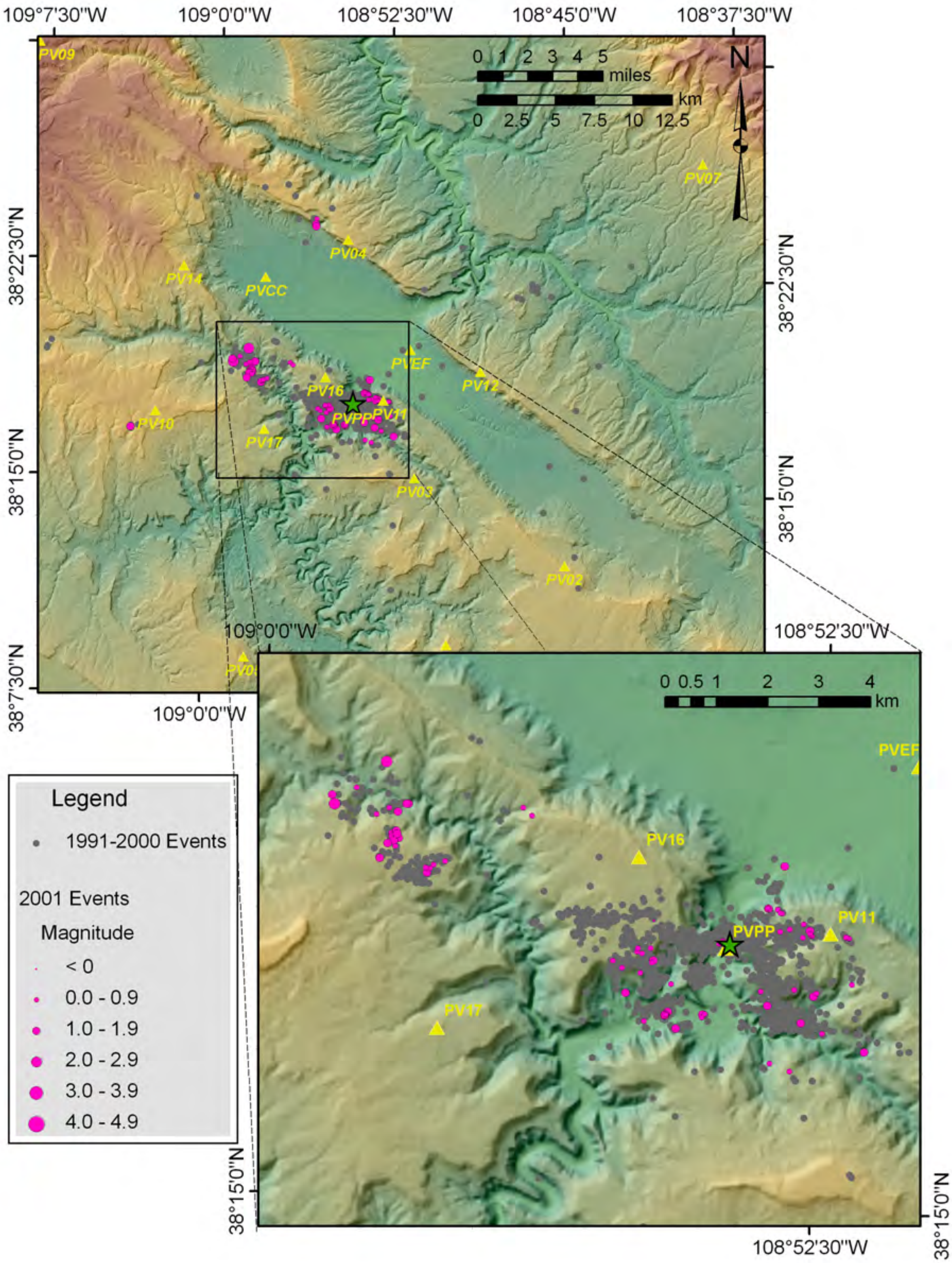


Figure 9-13 2001 Epicenters. Star is injection wellhead.

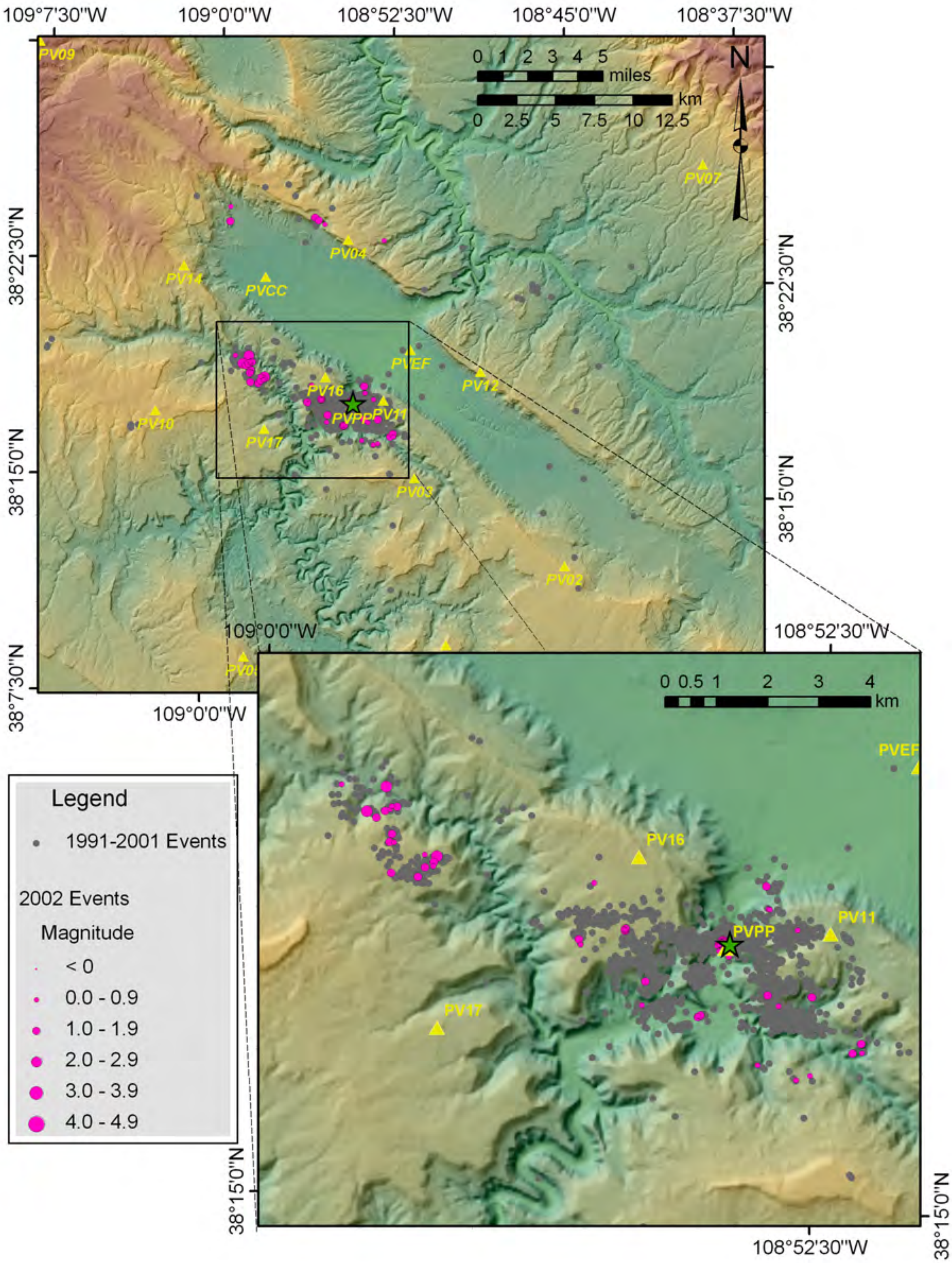


Figure 9-14 2002 Epicenters. Star is injection wellhead.

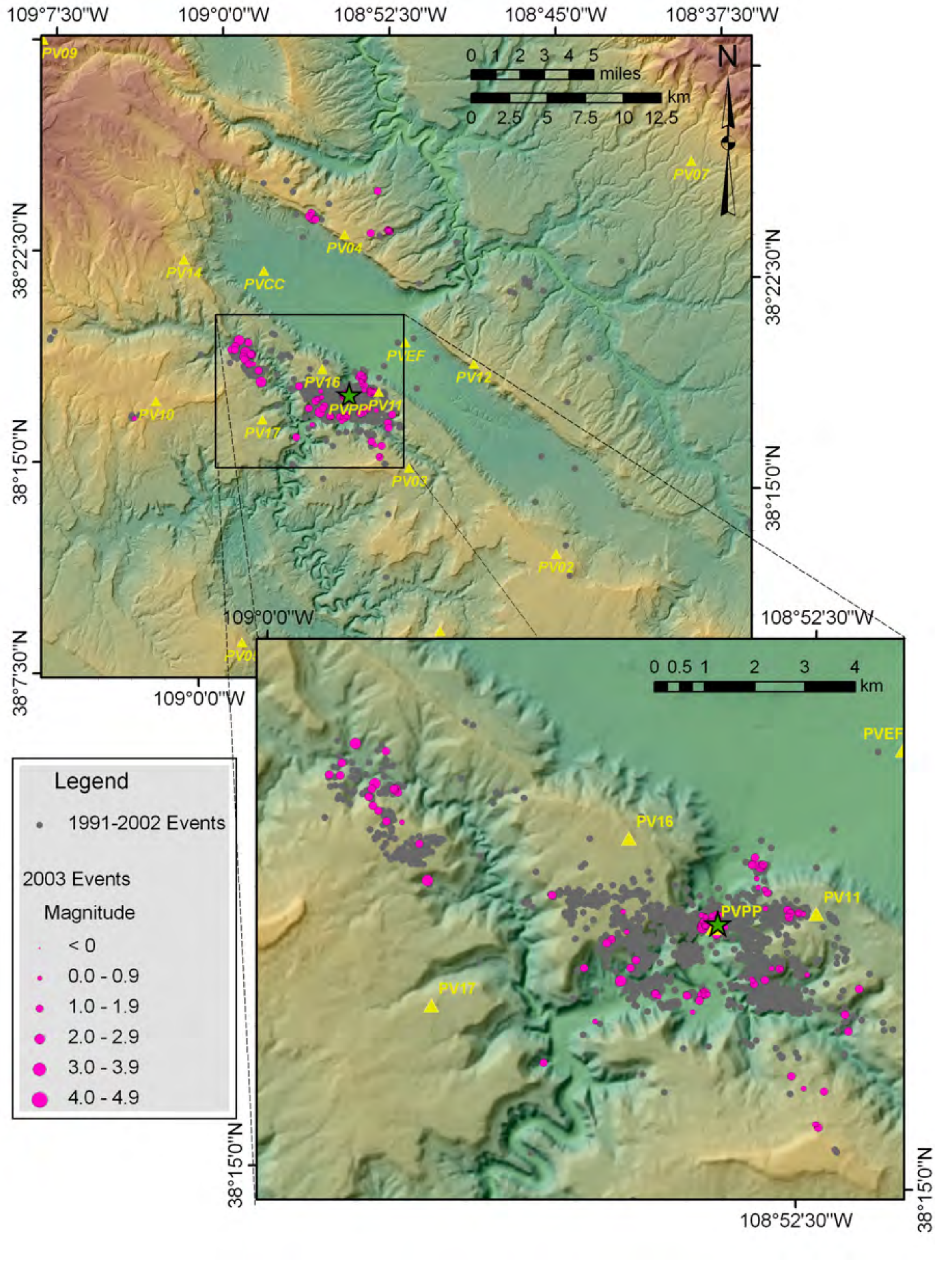


Figure 9-15 2003 Epicenters. Star is injection wellhead.

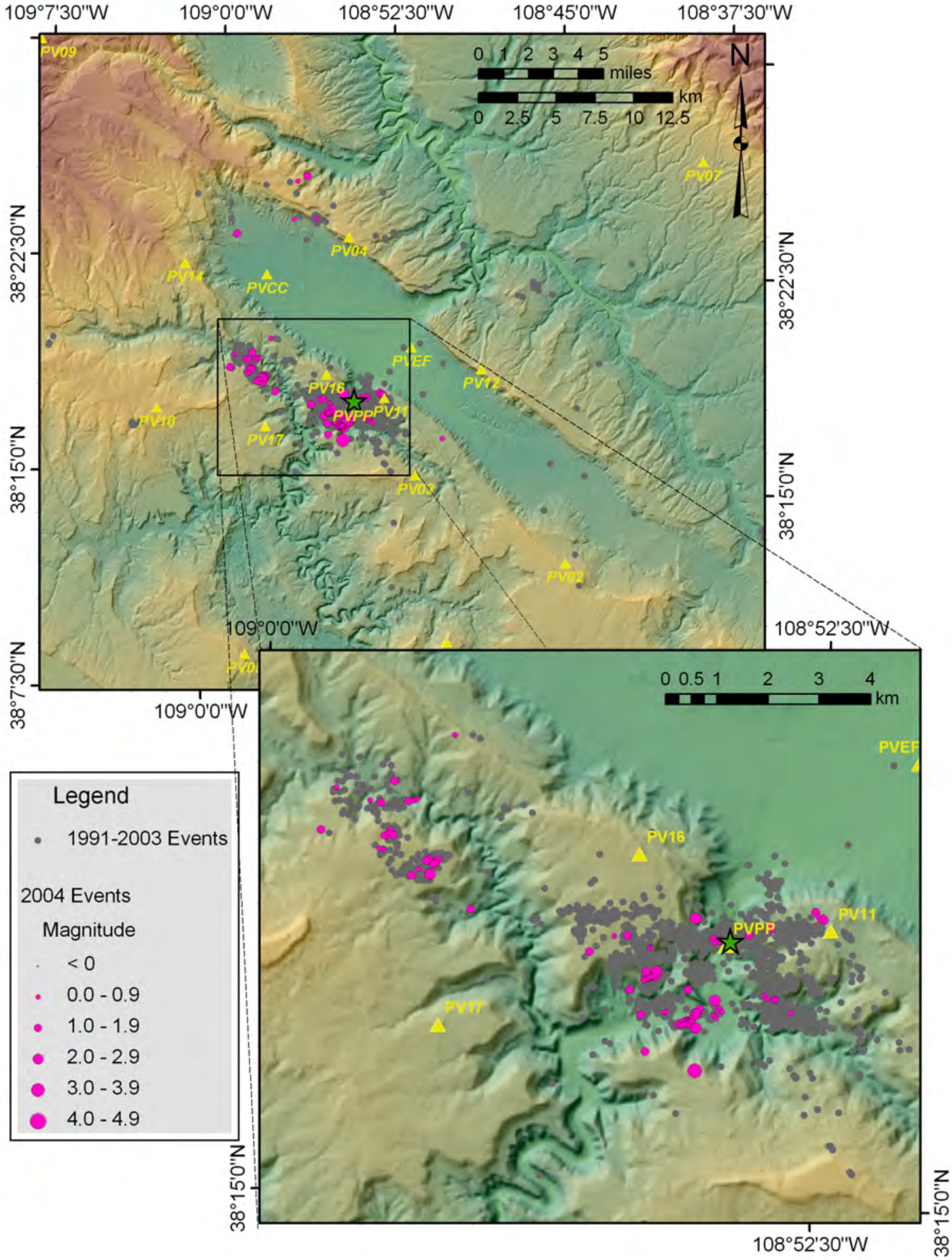


Figure 9-16 2004 Epicenters. Star is injection wellhead.

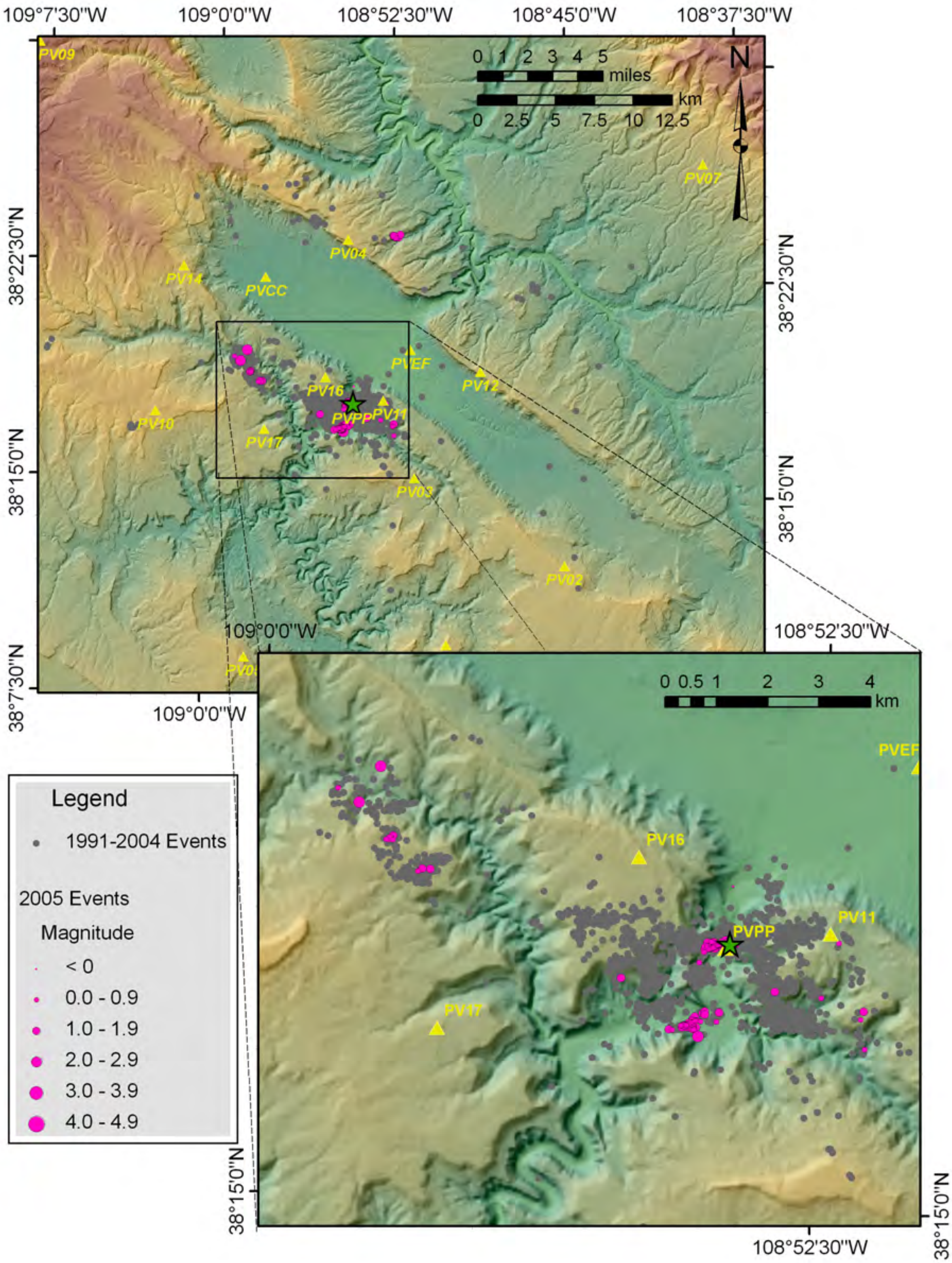


Figure 9-17 2005 Epicenters. Star is injection wellhead

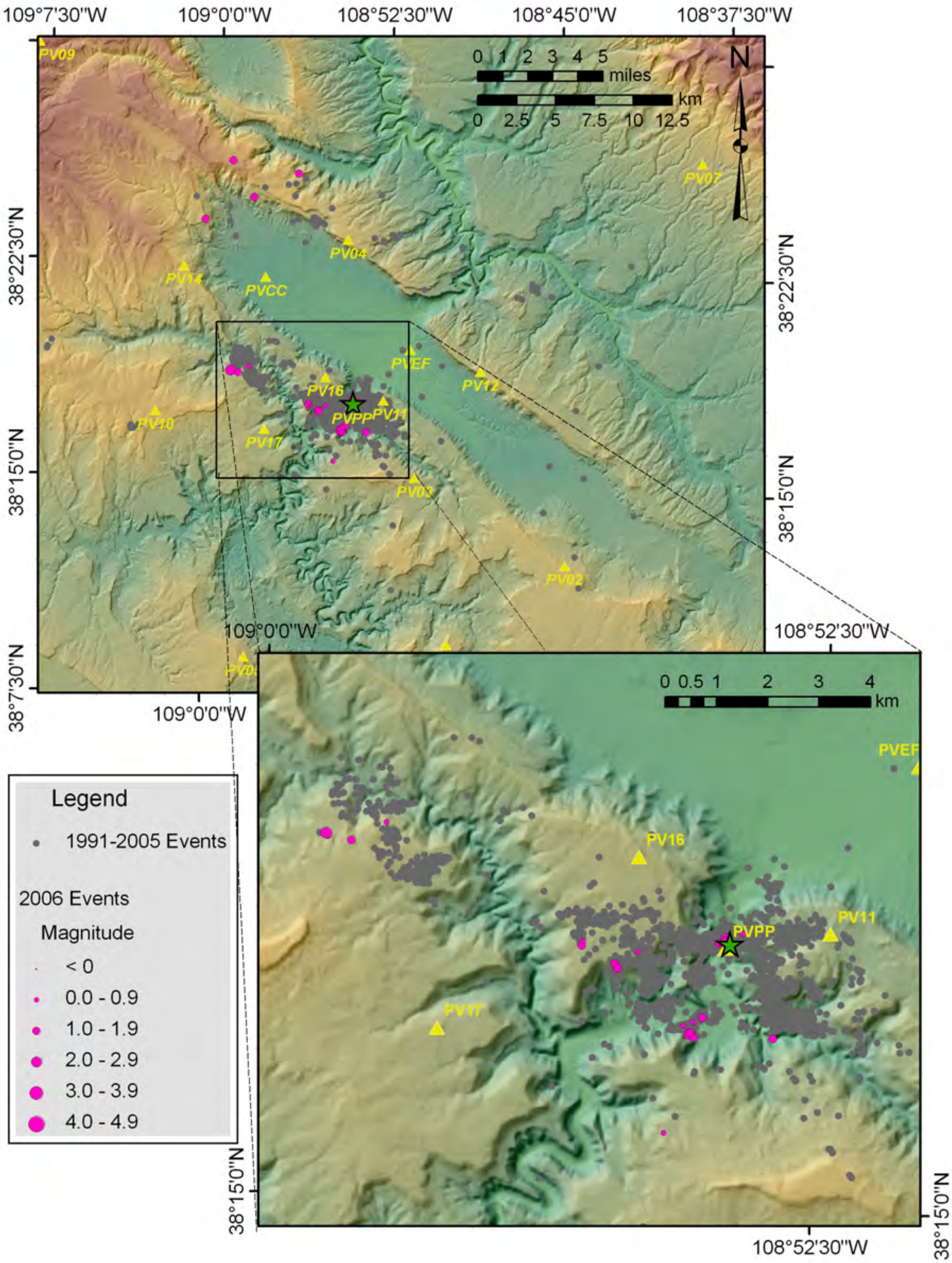


Figure 9-18 2006 Epicenters. Star is injection wellhead

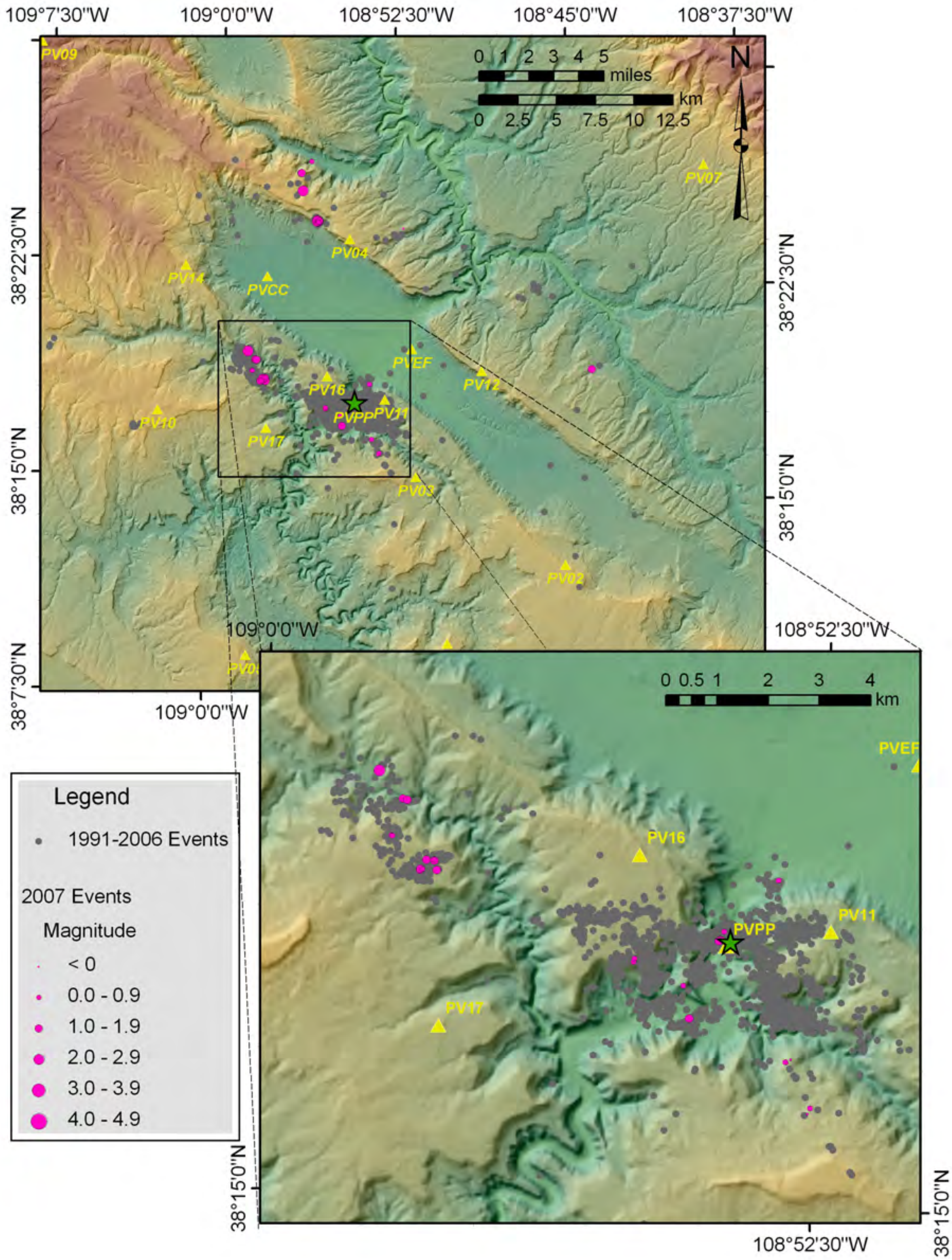


Figure 9-19   2007 Epicenters. Star is injection wellhead

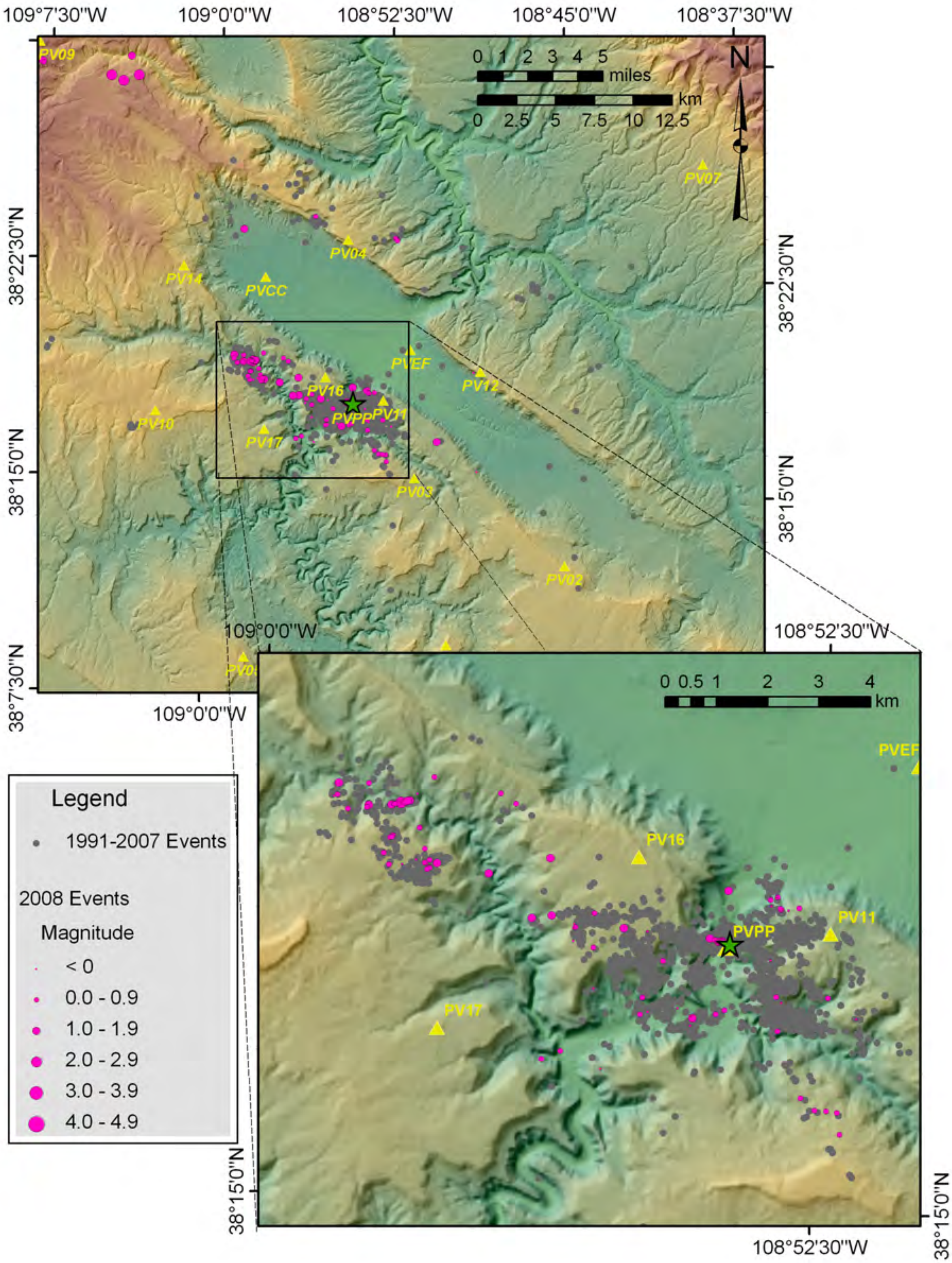


Figure 9-20 2008 Epicenters. Star is injection wellhead

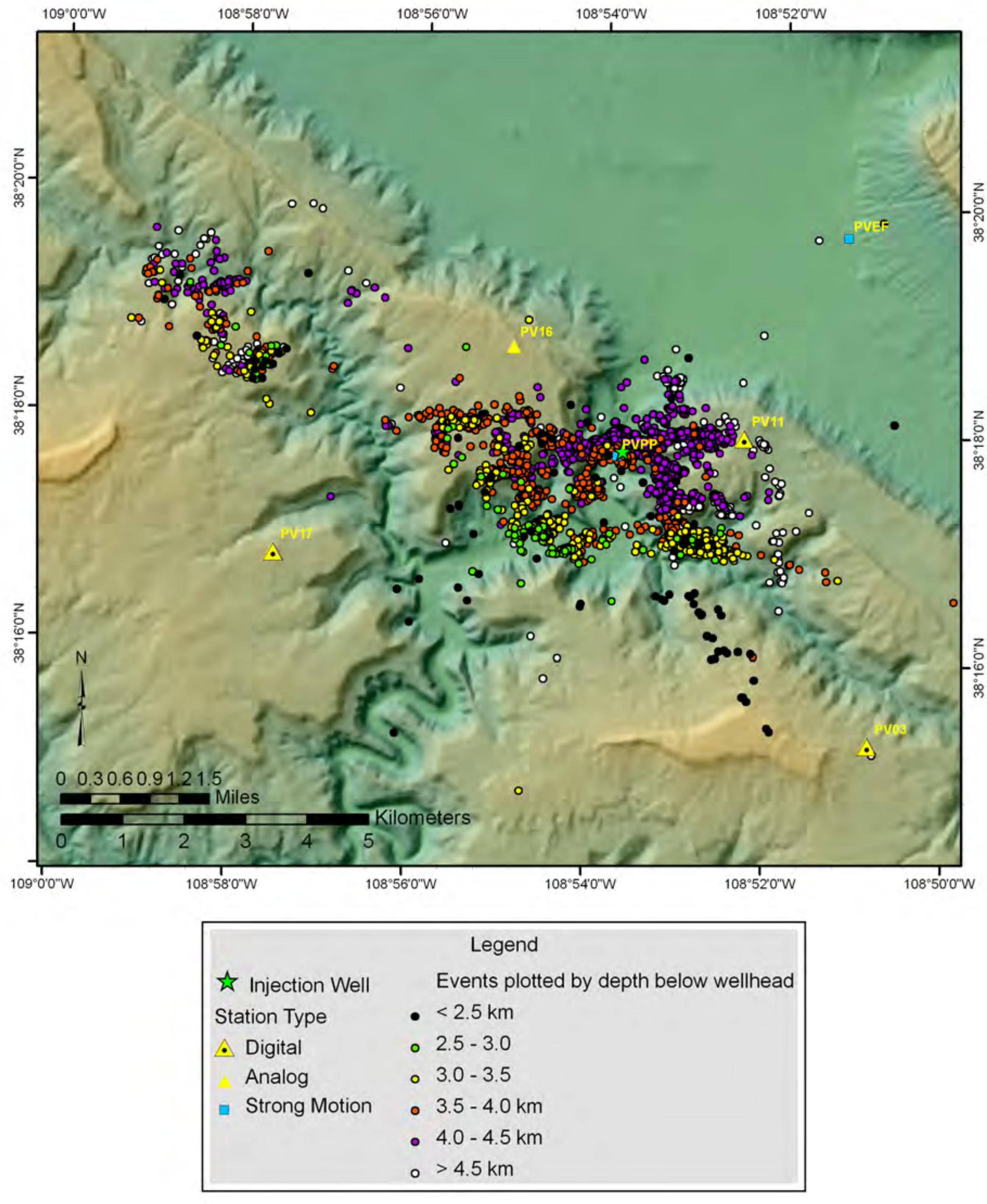


Figure 9-21 Epicenters color-coded by depth relative to the ground surface at the injection well (star).

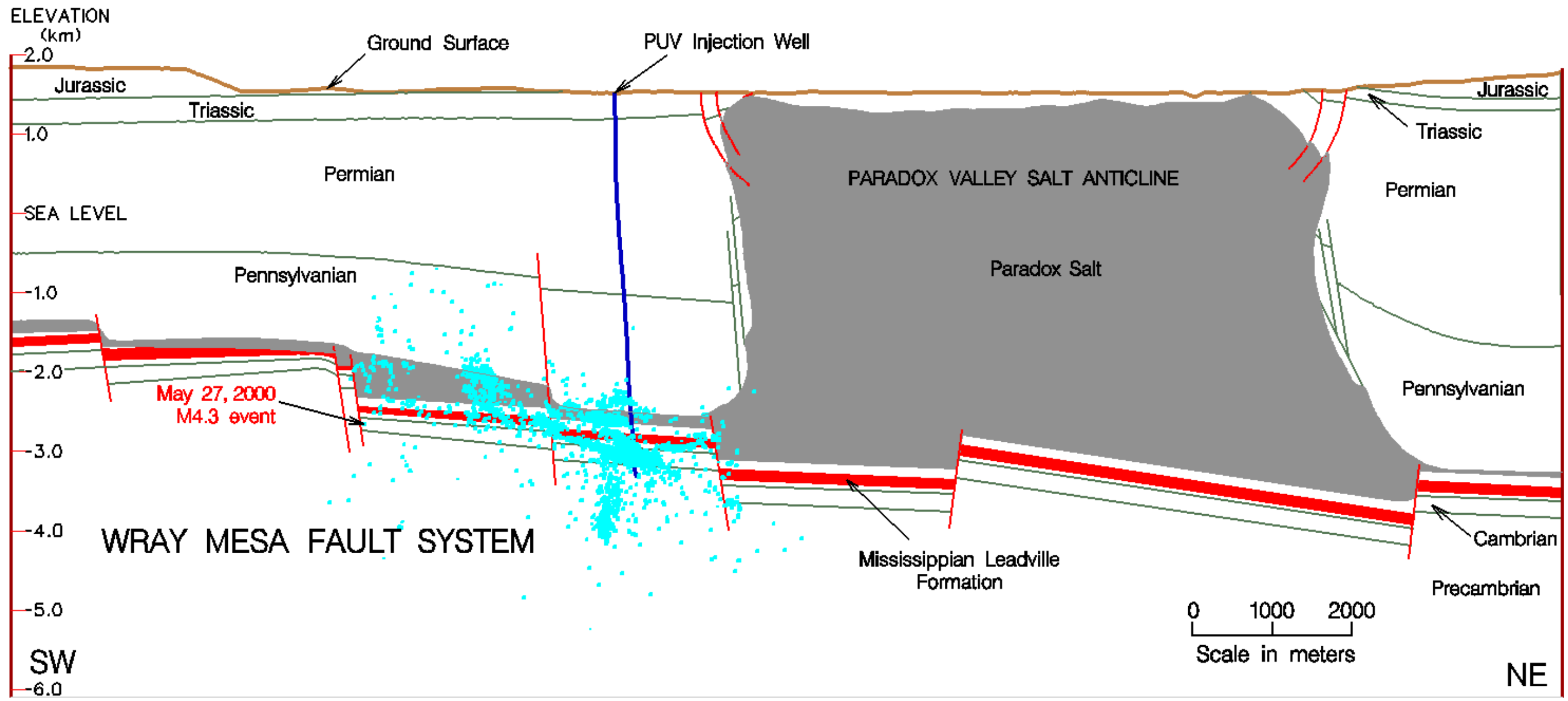


Figure 9-22 Bremkamp and Harr (1988) Cross Section Interpretation of Paradox Valley and Bordering Stratigraphy. Section passes through PVU injection well and runs normal to strike of the valley. Projected on to cross section are seismic events (1991-2002) within 1.5 km of the viewed plane.

Harr's (1988) original interpretation. Projected on the cross section are all events from 1991 through the end of 2002 and within 1.5 km of the viewed plane. **Figure 9-22** shows a number of features. First, it shows two vertical groupings of events: one in the Precambrian just southwest of the injection well and one starting in the Leadville and rising through the salt about 2 km southwest of well. Most likely the second grouping is the actual location of the fault Bremkamp and Harr (1988) speculated to lie about 1 km west of the well. **Figure 9-22** also shows that many events near the well occur at depths between the top of the Mississippi-aged Leadville Formation, the primary injection horizon (4.3 km below ground surface) and the bottom of the well. This seismicity shallows to the southwest in agreement with the inferred shallowing of the Leadville Formation (Bremkamp and Harr, 1988). The figure also shows that the actual shallowing may be steeper than originally interpreted by Bremkamp and Harr.

Figure 9-22 shows that a significant number of earthquakes occur below the bottom of the well in the Precambrian basement rocks. Seismicity was first induced in the Precambrian during the last injection test (no. 7, which ran from August, 1994 to April, 1995). The seismicity in the Precambrian, as a percentage of the total induced seismicity, peaked in 1999. In that year, approximately 22% of all induced earthquakes occurred at depths greater than 4.8 km (relative to the wellhead), the depth to the top of the Precambrian at the well. The Precambrian seismicity, as a percentage of all induced seismicity, declined slightly in 2000 to 17%, and subsequently declined more rapidly. During 2001 to 2003, events locating deeper than 4.8 km account for approximately 10% of all induced events each year. Since 2004, the percentage of induced events locating deeper than 4.8 km ranges from 4% to 6%, with the exception of 2006. No events were located deeper than 4.8 km during that year. Probably not coincidentally, the injection well was shut down for an unusually large number of days (more than 70) during 2006. (Note that since the top of the Precambrian is not horizontal over the extent of the areas of induced seismicity, these numbers represent an approximate number of events in the Precambrian). The trend noted above indicates that the relative amount of deeper seismic activity (i.e., seismicity in the Precambrian) has decreased since the biannual 20-day injection well shut-ins began in 1999 and the injection rate was reduced by 33% in 2000. Hence, these PVU operating adjustments have had a relatively greater affect on the deeper (Precambrian) seismicity rates than on the shallower (mainly Leadville Formation) seismicity rates.

Three-dimensional (3-D) views of induced earthquake hypocenters, the injection wellbore, and surface topography are presented in **Figure 9-23.** The earthquakes shown are the near-well events only (located within approximately 4 km of the injection well), recorded between July, 1991 and December, 2008, and having generally better-constrained locations. (These earthquakes tie into the relative earthquake location method with a maximum azimuthal gap <= 90 deg.) A series of views are shown, looking slightly down and in azimuths ranging from northwest (view a), to west (view d), to south (view h), to southeast (view l). The green circle on the wellbore represents the approximate depth of the Leadville Formation at the well. A number of features can be seen in these views. View a, which looks to the northwest, sub-parallel to Paradox Valley, shows the shallowing of hypocenters to the southwest discussed above (left side of view). The events that occur at depth within the Precambrian can be seen, especially in views a and b, where many of them appear to define a rather compact planar group. As the view is rotated, the earthquakes that align along distinct fracture planes come into focus, especially when looking toward the west-southwest (views c through f). When looking toward the south-southeast, a sub-horizontal align-

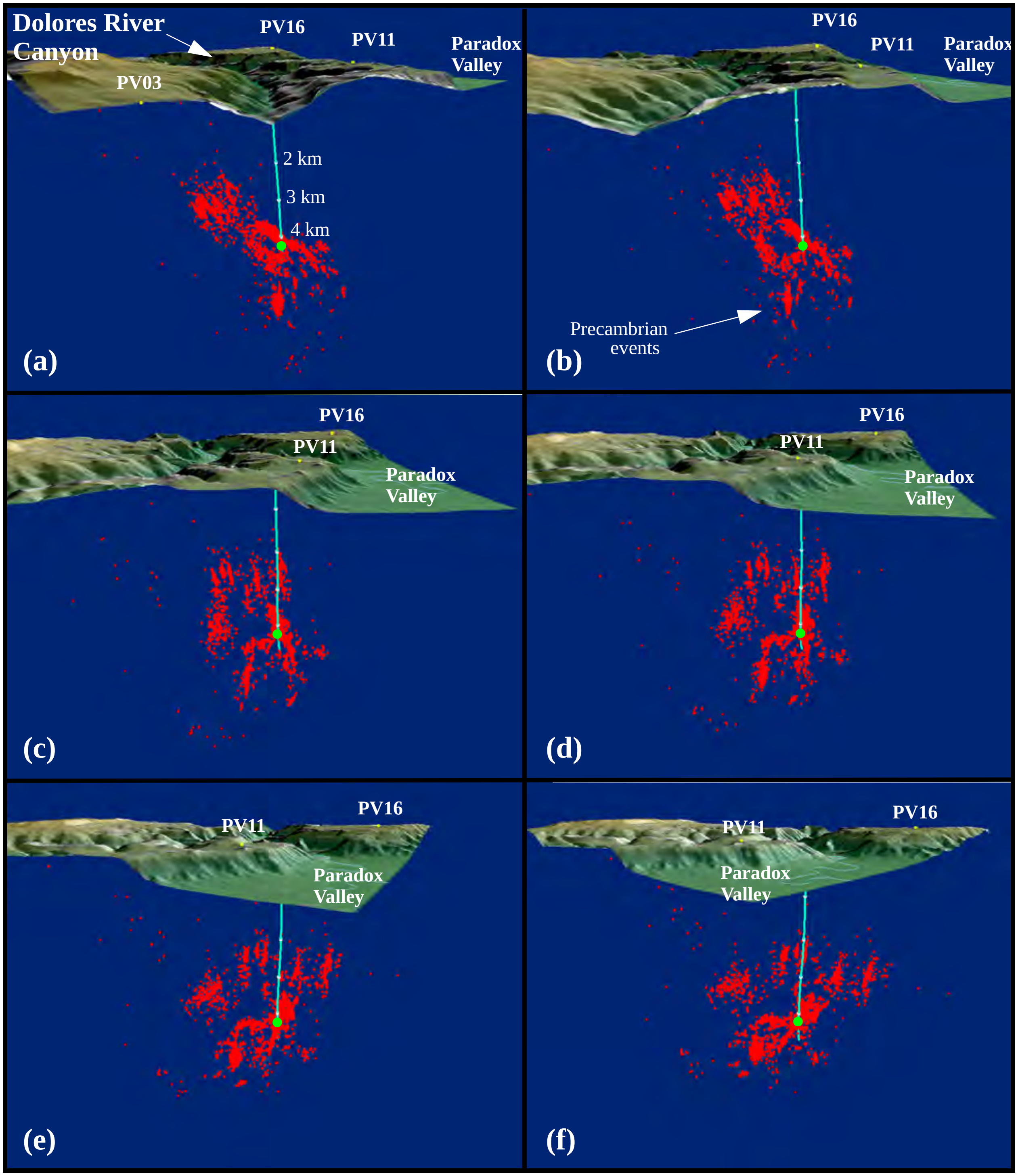


Figure 9-23 Sequence of 3-D oblique views (no vertical exaggeration) of the Paradox Valley injection well (light blue line), induced seismicity (red dots), and surface topography (shaded surface). White markers along the wellbore indicate each 1 km in depth from the wellhead. The green circle on the wellbore represents the approximate depth of the Leadville Formation at the well. Labeled yellow squares are seismic stations. Views are looking in the northwest through southeast directions, counterclockwise. Views (a) through (c) are looking NW; views (d) through (f) are looking W to SW.

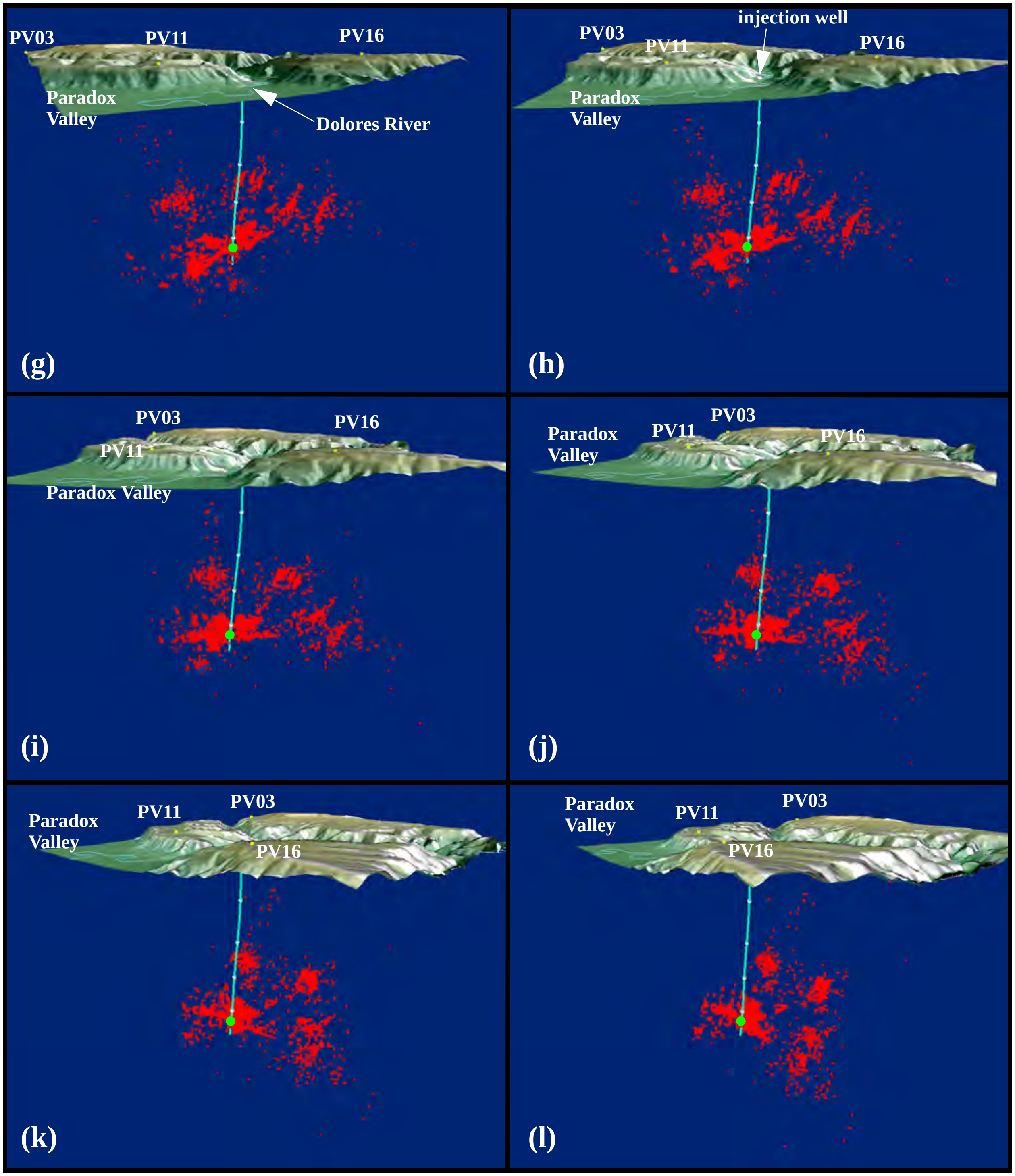


Figure 9-23 , continued. Views (g) and (h) are looking SW to S; views (i) through (l) are looking S to SE.

ment of hypocenters is seen at the approximate depth of the Leadville Formation, suggesting that fluid is moving through the Leadville away from the well (views i through k).

9.5 Seismic Focal Mechanisms

In 2003, focal mechanisms were systematically computed for all induced events, recorded up to that point in time, which had a sufficient number of high-quality waveforms. The focal mechanisms were calculated using *P*-wave first motion polarities and S_V/P amplitude ratios on vertical-component seismograms (Kisslinger, 1980; Kisslinger and others, 1981). A simulated annealing downhill simplex algorithm (Press and others, 1992) was used to calculate double-couple focal mechanisms, as described in detail in the 2003 PVSN Status Report (Mahrer et al., 2004). Criteria involving the number of P-wave first motions, the total number of P-wave first motions and S_V/P amplitudes ratios, the first-motion misfit, and the sensitivity of the final solution to the starting model were used to define a set of the 1345 best-constrained focal mechanisms. From this set of well-constrained focal mechanisms, the earthquakes with strike-slip mechanisms were then selected (1196 events, 89% of all earthquakes with well-constrained mechanisms). This set of identified strike-slip focal mechanisms was interpreted to consist of two main orientations, with median azimuths of 266 degrees (mean = 266 deg. (N94W), standard deviation = 19 deg.) and 311 degrees (mean = 311 deg. (N49W), standard deviation = 3.5 deg.). 88% of the identified strike-slip events have the 266 deg. azimuth. This azimuth is consistent with the west-southwest orientation of many of the epicenter lineations (**Figure 9-8**). The remaining 12% of the identified strike-slip events have the 311 degree azimuth, which is very close to the estimated 305 deg. azimuth of the major Wray Mesa faults. The remaining well-constrained focal mechanisms consist of normal-oblique and reverse-oblique events with azimuths ranging from 227 to 355 degrees.

9.6 Event Magnitudes

A listing of induced earthquakes by magnitude range is presented in **Table 9-4**. Approximately 75% of the induced seismic events recorded to date are less than magnitude **M**1.0. Nearly all of the remaining events are less than **M**2.5. Only 22 events, about 0.5% of the data, have magnitudes greater than or equal to **M**2.5. In general, these events, with **M** >= 2.5, are the ones that have been reported felt by local residents. Of these 22 events with **M** >= 2.5, only 5 have occurred since the injection rate was reduced by 33% in June, 2000. Only 4 induced earthquakes with magnitude greater than or equal to **M**3.0 have occurred in the history of PVU operations. All but one of these occurred prior to the mid-2000 decrease in injection rate, including the largest induced event - an **M**4.3 event which occurred on May, 2000. The single event with magnitude larger than **M**3.0 that has occurred since the injection rate was decreased was an **M**3.9 event, which occurred in November, 2004.

The larger-magnitude induced seismic events are not uniformly distributed throughout the two seismic source zones, but preferentially occur on some fault segments. **Figure 9-24 and Figure 9-25** show all events with magnitudes **M**1.7 and greater plotted against a background of all the events. **Figure 9-24** is a plan view and **Figure 9-25** is a cross section parallel to Paradox Valley (looking to the southwest). Note in these figures that not all of the seismically-illuminated, linear features (i.e., the faults and fractures seismically activated by PVU injection) produce larger events. Only a subclass of the fractures and faults have larger events. Also, some of the fractures

Table 9-4 Induced earthquakes detected by PVSN since injection began in 1991, listed by magnitude range.

Magnitude Range	No. of Recorded Induced Events	Percent of Recorded Induced Events	Cumulative Magnitude	No. of Recorded Induced Events	Percent of Recorded Induced Events
M < 0	225	4.9%	**M** < 0	225	4.9%
0 <= **M** < 0.5	1475	32.3%	**M** < 0.5	1700	37.2%
0.5 <= **M** < 1.0	1698	37.2%	**M** < 1.0	3398	74.4%
1.0 <= **M** < 1.5	784	17.2%	**M** < 1.5	4182	91.5%
1.5 <= **M** < 2.0	255	5.6%	**M** < 2.0	4437	97.1%
2.0 <= **M** < 2.5	110	2.4%	**M** < 2.5	4547	99.5%
2.5 <= **M** < 3.0	18	0.4%	**M** < 3.0	4565	99.91%
3.0 <= **M** < 3.5	0	0.0%	**M** < 3.5	4565	99.91%
3.5 <= **M** < 4.0	3	0.07%	**M** < 4.0	4568	99.98%
4.0 <= **M** < 4.5	1	0.02%	**M** < 4.5	4569	100.0%

and faults have many larger events and some have only one or two. Also note that a disproportionately greater number of larger events occur in the secondary seismogenic region northwest of the injection well, compared to the primary zone. No statistical analysis of the focal mechanism results discussed above has been performed to determine whether the larger-magnitude events have a tendency to occur with a specific type of focal mechanism (strike-slip, normal-oblique, reverse-oblique) or with a preferred nodal plane orientation.

9.7 Northern Valley Events

Recurring seismicity located at the northern end of Paradox Valley is shown in **Figure 9-26**, color-coded by year of earthquake occurrence. PVSN has detected several earthquakes in this region every year since 2000. Extremely few earthquakes from this northern valley area are currently in PVSN's database for years prior to 2000. We currently do not know if this apparent abrupt increase in seismicity in 2000 is real, if earthquakes from earlier years have been mis-classified or mis-located, or if the sudden increase in recorded seismicity in this area is strictly attributable to PVSN's increased detection sensitivity that occurred after major improvements where made to the data acquisition systems in October, 2000 (discussed in section 7.7).

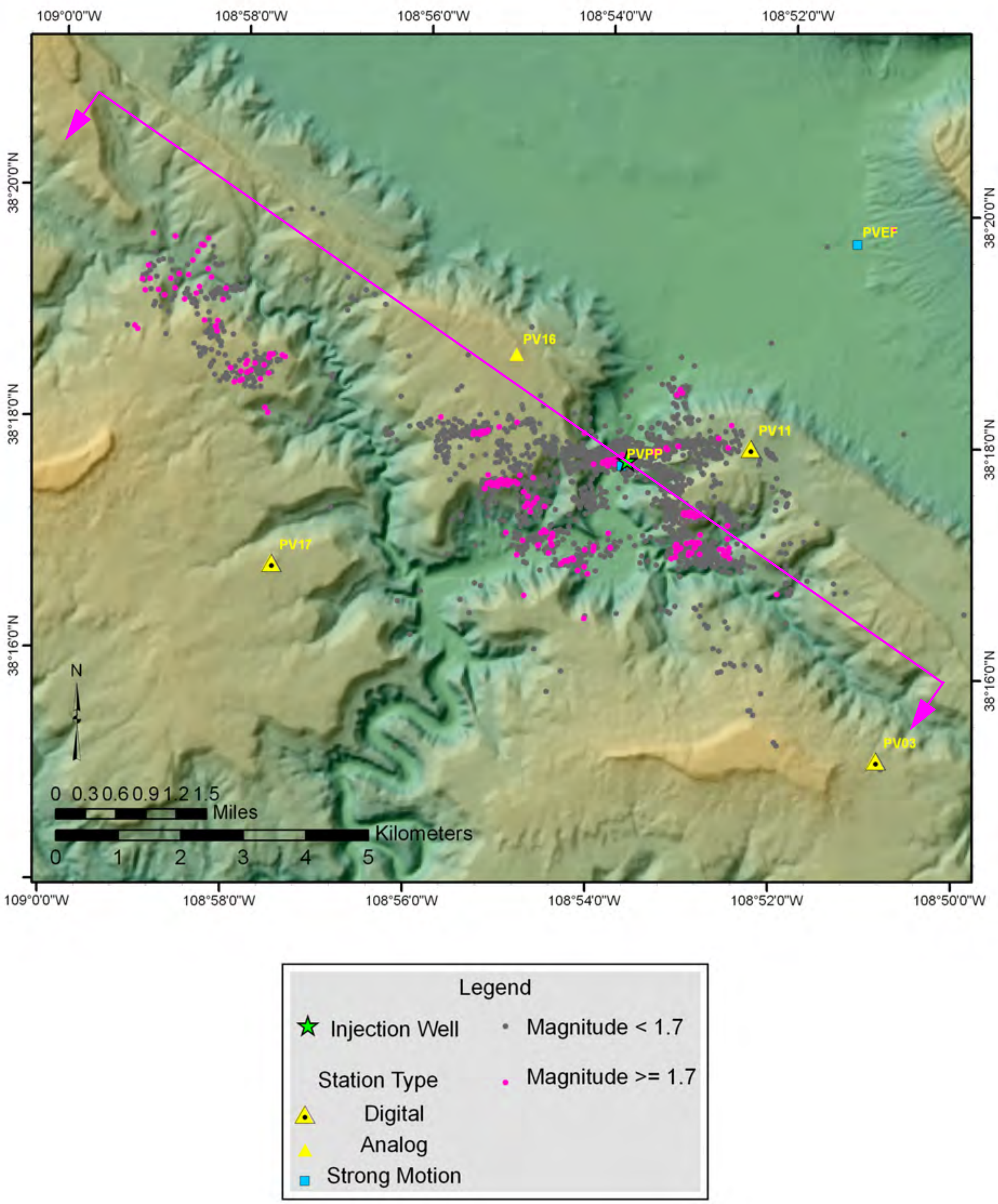


*Figure 9-24 Events with magnitude **M**1.7 and greater (magenta circles) superimposed on all of the seismicity (gray circles), 1991-2008. The magenta line indicates the orientation of the cross section presented in Figure 9-25.*

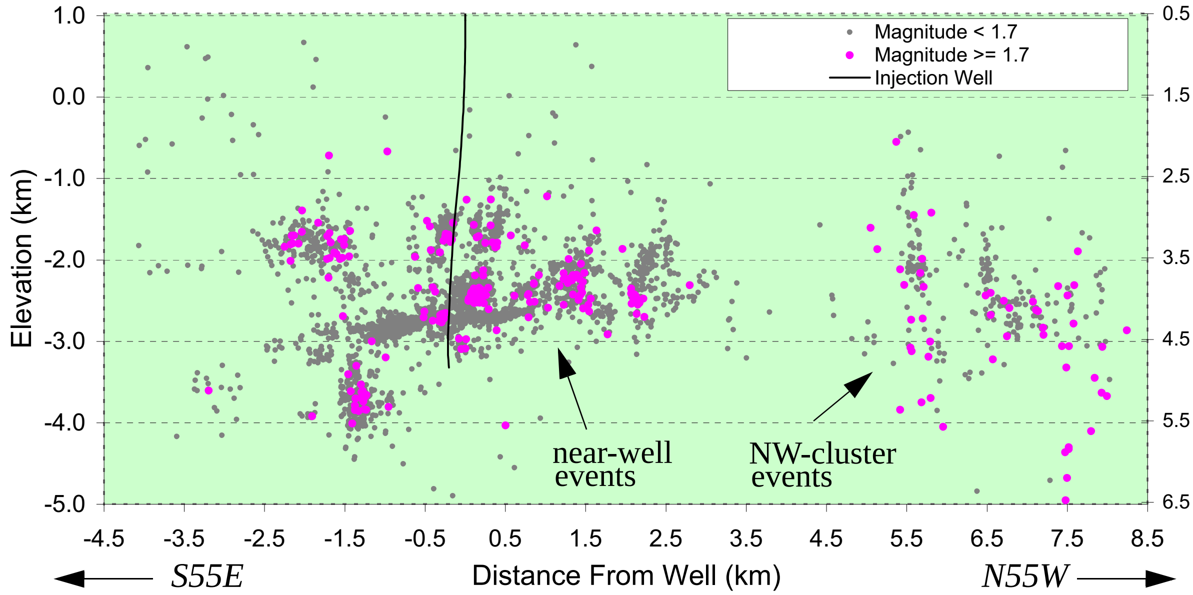


Figure 9-25 Cross section parallel to Paradox Valley (looking to the southwest) showing the locations of events with magnitude >= 1.7, compared to the locations of all induced events. (The orientation of the cross section is indicated by the magenta line in Figure 9-24. Note that the depths of events locating shallower than approximately 2 km are poorly constrained.)

Because of the limited station coverage in this area, the lack of 3-component stations to provide S-wave arrival times prior to late 2007, and the current lack of a 3-dimensional S-wave velocity model, the computed locations of these earthquakes are poorly constrained. However, based on the available data and analysis performed to date, the earthquakes appear to occur in at least three areas:

1. Events located about 3 km east and southeast of station PV04. The majority of the events in this area occurred in swarms over the course of just a few days: Sept. 12-17, 2003 (17 events), Oct. 1-3, 2005 (10 events), and July 19-21, 2008 (5 events). The locations of most of these events form a tight cluster (laterally and in depth).

2. Events located northwest of station PV04. Several events in this area have been recorded each year since 2000. Several of the events form a tight cluster located about 2.5 km northwest of PV04, but others are scattered farther to the northwest.

3. A smaller group of events located approximately 3 to 4 km northeast of station PV14. The locations of these events are more poorly constrained than those in the other two groups. Many of them occurred when station PV14 was offline, which significantly impacts the accuracy of their

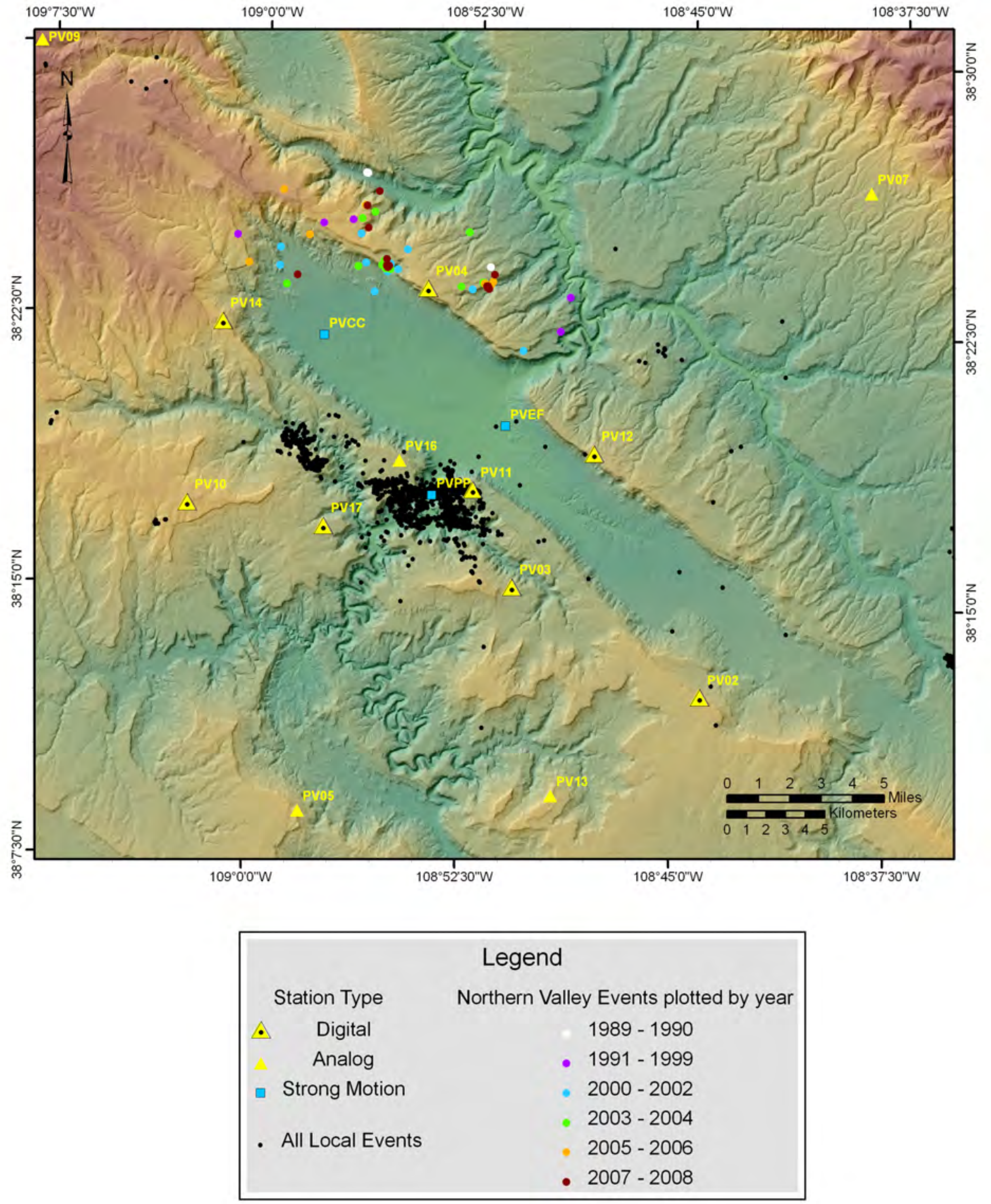


Figure 9-26 Seismicity occurring at the northern end of Paradox Valley, color-coded by year of occurrence.

computed locations. The locations of the events currently being shown beneath the floor of Paradox Valley east of station PV14 are not believed to be reliable.

In general, the depth estimates for earthquakes occurring at the northern end of Paradox Valley since late 2007 are significantly better than those for earlier events. In late 2007, two 3-component digital stations, PV04 and PV14 (converted from single-component analog stations), became fully functional. Also, station PV08, located to the northeast of Paradox Valley, was reinstalled (as a 3-component station) after having been offline since 2003. The events with reasonably-constrained locations that have been detected in this region since late 2007 range in depth from approximately 4.5 to 8 km (relative to local ground surface).

10.0 CONCLUSIONS

Observations from seismic data recorded in 2008 include:

(1) The 97 induced microearthquakes recorded in 2008 generally locate within the two seismogenic zones defined by previous years' microearthquake locations.

(2) A few events that were recorded in 2008 locate between the primary zone of induced seismicity surrounding the injection well and the secondary zone located about 7.5 km northwest of the well. This suggests that the historical aseismic gap between the two zones of induced seismicity may be closing.

(3) Five earthquakes that occurred in 2008 locate south and slightly east of the primary zone of induced seismicity, toward station PV03. Five events also occurred in this area in the previous year. This suggests that fluid pressure from the injection well may be migrating farther south.

(4) As in previous years, the spatial patterns of observed seismic sources seem to follow the Wray Mesa fault and fracture system.

(5) No large (magnitude **M**3.0 or greater) induced events occurred during 2008. The largest induced event recorded in 2008 had a magnitude of **M**2.1.

(6) Injection controls (i.e., reduced injection rate and biannual 20-day shut-downs) were continued during 2008, and the rate of seismic event production remains very low compared to the early years of continuous pumping.

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APPENDIX A

2008 SITE VISIT REPORTS

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: 2008-2 **Departure Date:** 3/24/2008 **Return Date:** 3/28/2008

Prepared By: Chris Wood, Geophysicist/Team Leader, 86-68321

Purpose: Upgrade and reconfigure main electronics rack at Hopkins Field

Work Summary: A new electronics rack and wiring were installed at Hopkins Field to improve reliability, make the equipment more serviceable, reduce analog telemetry noise, prepare for digital seismic station upgrades, and to accomodate a data acquisition server. The new equipment rack was prepared in Denver and transported to Hopkins field. The old rack was removed, and equipment was installed in the new rack. Old non-shielded signal cables for the existing analog radios were completely removed and replaced with a properly shielded and grounded modular system. A new power distribution system and upgraded uninterruptible power supply were also installed.

Post-visit Instrumentation Status: All stations are on-line and the equipment at Hopkins Field is completely functional. Data from analog stations PV16 and PV11 seems to have less noise than before. The east-west horizontal component of station PV12 continues to malfunction, and PV14 appears to have excessive electronics noise, but the stations are providing usable data.

Action Items:

1	Schedule servicing of PV16 seismometer and PV04 improvements for next field maintenance trip, likely in May of 2008.
2	Schedule completion of the digital upgrade of PV02, PV03, PV11, and PV10.
3	Install data acquisition server at Hopkins Field.
4	Assess costs/benefits of adding one or more stations at Blue Mesa and areas to the west, and start necessary planning activities if additional station(s) appear warranted.

Personnel:

	Name	Organization
1	Dave Copeland	Reclamation, Seismotectonics & Geophysics, 86-68321

Work by Site:

	Site	Work Accomplished
12	Hopkins Field	Removed old rack. Removed unshielded analog signal cables, including miswired Y-pigtails, from Monitron radio cabinet. Removed old UPS. Removed old 5-port microswitch. Removed old 12VDC power system. Installed new modular cable management system. Installed new shielded, low-cap cables. Installed dual fused 12DVC power distribution panels; one for radios and one for A/D converters. Installed new managed Cisco switch. Installed new rack-mount UPS. Installed remote power switching unit and controller. Moved discriminator racks, A/D converters, Cisco router, Lantronix MSS-100s, and power supplies to new rack. QA and testing.

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: 2008-3 **Departure Date:** 8/25/2008 **Return Date:** 8/31/2008

Prepared By: Chris Wood, Geophysicist/Team Leader, 86-68321

Purpose: Install digital stations at PV02, PV03, PV10, and PV11

Work Summary: Digital stations were installed at four stations where site preparations had been completed in FY2007. The work consisted of installing a tower, antennas, solar panel, station enclosure, seismometer, data logger, radios, conduit, cable, and surge protection. At PV10, the station installation was fully completed, programmed and tested. At the other stations, about 1/2 day of work remains for wiring, testing, and programming.

Post-visit Instrumentation Status: The new stations are fully assembled and the seismometers installed. PV10 is complete, and about 1/2-day of work remains at PV02, PV10, and PV11 to complete installation and testing.

Action Items:

1	Schedule completion of the digital upgrade of PV02, PV03, PV11, and PV10, including adding a server in Nucla to receive the new stations, which will bring them on-line.
2	Schedule maintenance for PV04, PV08 and PV12.
3	Install data acquisition server at Hopkins Field.
4	Secure antenna mounting bracket and cables at Hopkins Field

Personnel:

	Name	Organization
1	Chris Wood	Reclamation, Seismotectonics & Geophysics, 86-68321
2	Mark Meremonte	USGS, Golden
3	Jeff Fox	USGS, Golden

Work by Site:

	Site	Work Accomplished
1	PV02	Install tower, antennas, enclosures, cables, conduits, break-out-boxes, seismometer, data logger, solar panel, and batteries.
2	PV03	Install tower, antennas, enclosures, cables, conduits, break-out-boxes, seismometer, data logger, solar panel, and batteries.
3	PV10	Install new tower base. Install tower, antennas, enclosures, cables, conduits, break-out-boxes, seismometer, data logger, solar panel, and batteries. Test cables. Program data logger and radio. Test seismometer.
4	PV11	Install tower, antennas, enclosures, cables, conduits, break-out-boxes, seismometer, data logger, solar panel, and batteries.

Work by Site:

Site	Work Accomplished

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: 2009-1 **Departure Date:** 10/19/2008 **Return Date:** 10/25/2008

Prepared By: Chris Wood, Geophysicist/Team Leader, 86-68321

Purpose: Activation of digital stations at PV02, PV03, PV10, and PV11. Hopkins Field upgrades, and other maintenance.

Work Summary: Station installation was fully completed, programmed and tested at PV02, PV03, and PV11. Cabling and digital radios were added at PV04 and PV12 to relay signals from the new stations. Servers and an IP KVM switch were installed at Hopkins Field, and the Guralp data acquisition program was brought online. Other necessary maintenance work was done at Hopkins Field, including securing antennas and cabling on the tower. A malfunctioning seismometer was replaced at PV14, and cabling was upgraded. PV08 was repaired and brought online.

Post-visit Instrumentation Status: Broad-band digital data from all four upgraded stations (PV02, PV03, PV10, and PV11) is being recorded and used in routine PVSN data analysis. Digital stations relayed through PV12 (PV03, PV17, and PV12) show occasional data dropouts, likely due to the radio link between PV12 and Hopkins Field. Digital broadband seismometers at PV10 and PV12 each have one noisy component, although useful data is being collected.

Action Items:

1	Decide whether an additional repair trip is warranted before May, 2009 to replace seismometers at PV10 and PV12, and boost RF power levels for PV12.

Personnel:

	Name	Organization
1	Chris Wood	Reclamation, Seismotectonics & Geophysics, 86-68321
2	Mark Meremonte	USGS, Golden

Work by Site:

	Site	Work Accomplished
1	Hopkins Field	Install Windows and Linux servers. Install IP KVM switch. Install FreeWave radios. Remove CRMs and Lantronix MSS-100 devices. Install Digi USB 8-port serial device. Recable all serial digitizer links. Reconfigure rack. Install 9 dB Yagi for PV02, and remove Omni. Secure all cables on tower.
2	PV02	Terminate and run automatic cable tester on seismometer and GPS cables. Program and install FreeWave Radios. Program and install CRM-6. Orient and level seismometer. Seal and bury seismometer vault.
3	PV03	Terminate and run automatic cable tester on seismometer and GPS cables. Program and install FreeWave Radios. Orient and level seismometer. Seal and bury seismometer vault.
4	PV04	Install Yagi, antenna cable, and radio for PV03. Replace antenna cables with Heliax. Reprogram CRM to include data from PV03.
5	PV08	Replace field package and analog amplifier. Re-orient horizontal S-13 seismometers.
6	PV11	Terminate and run automatic cable tester on seismometer and GPS cables. Program and install FreeWave Radios. Orient and level seismometer. Seal and bury seismometer vault.
7	PV12	Install Yagi, antenna cable, and radio for PV11. Replace antenna cables with Heliax. Reprogram CRM to include data from PV11. Replace seismometer.
8	PV14	Replace seismometer. Install low-noise cable and current low-noise DM-24 BOB and sensor vault BOB. Terminate and run automatic cable tester on seismometer and GPS cables.

APPENDIX B
ELECTRONIC FILES

Affixed to the inside of the back cover of this report should be a compact disk (CD). This CD contains:

(1) A Microsoft Excel file of the PVSN seismic data (i.e., time, date, and location of events) and PVU injection data

(2) PDF files of previous PVSN annual reports