RECLAMATION

Managing Water in the West

Technical Memorandum No. 86-68321-2008-13

2007 Status Report
Paradox Valley Seismic Network
Paradox Valley Project, Colorado

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

June 2008

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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Technical Service Center
Seismotectonics and Geophysics Group

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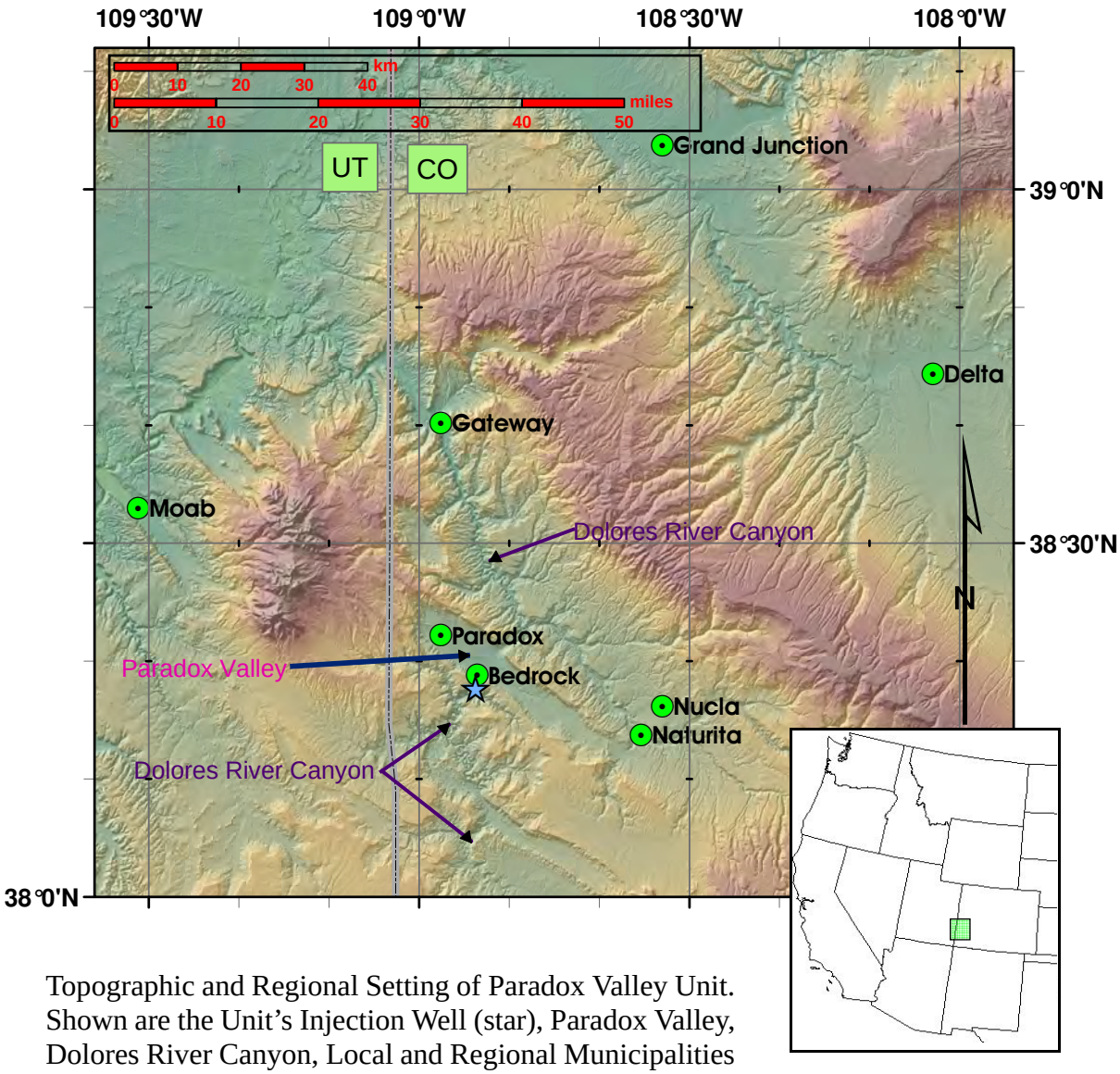
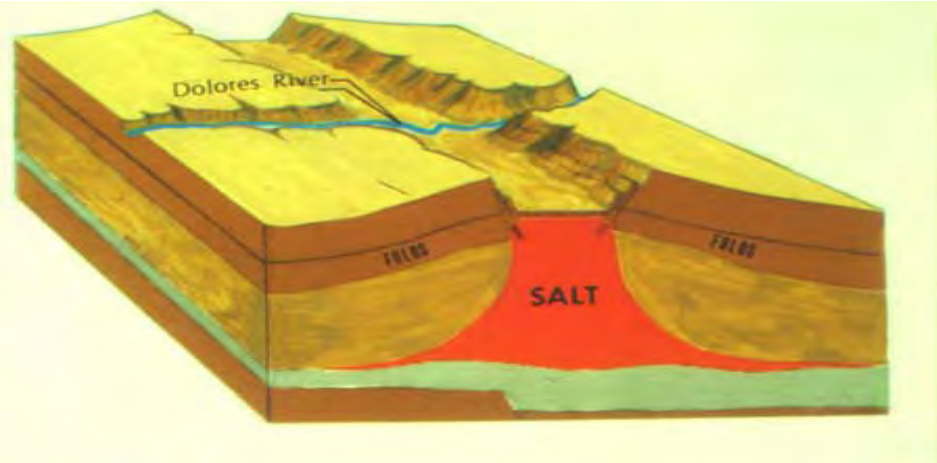
Acknowledgements

The work described in this report and the continuous operations of the Paradox Valley Seismic Network are made possible through the generous support of Andy Nicholas, site Project Manager at the Paradox Valley Unit, Bedrock, CO. We recognize Dave Copeland (US Bureau of Reclamation, Denver, CO) for his tireless field support. Over the history of this project, we have also benefitted from stimulating discussions with Jim Bundy (Subsurface Technology, Inc., Houston, TX).



Topographic and Regional Setting of Paradox Valley Unit. Shown are the Unit's 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 Western US Multi-State Region (insert).



Cartoon of Dolores Canyon and River, Paradox Valley, and Regional Cross Section. View is from the south looking north.

Dolores Canyon and River plus 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 and injection data from the Bureau of Reclamation's Paradox Valley Unit's (PVU) deep-well injection project for calendar year 2007, (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 these data. Included with the report is a compact disk (CD) of past annual reports of the PVSN (PDF files); a Microsoft Excel file listing each recorded, injection-induced seismic event by occurrence time, calculated location, and magnitude; and an Excel file animating, in cross section and map view, the (calculated) locations of the injection-induced seismicity and the injection pressure (i.e., surface pressure) as a function of time.

1.1 2007 - Highlights

(1) In 2007, PVSN recorded 27 microearthquakes 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 other zone is ~8 km northwest of the injection well with an aseismic gap between those two zones. Of the 27 induced events recorded, 12 occurred in the seismogenic zone ~8 km northwest of the injection well.

(2) 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.

(3) There is no indication of the injected fluid migrating to the surface. Nearly all induced seismic events with well-constrained locations recorded since 1991, including those recorded in 2007, locate more than 3 km below the surface (**Figure 1-2**).

(4) No large (magnitude **M**3.0 or greater) events occurred during 2007; the largest event recorded in 2007 within the two identified zones of induced seismicity was a magnitude **M**2.3.

(5) Injection controls (i.e., reduced injection rate and biannual 20-day shut-downs) were continued during 2007, and the rate of seismic event production remains very low compared to the early years of continuous pumping.

(6) During 2007, PVSN recorded 10 events approximately 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 2007 range from -0.2 to 2.6.

1.2 Cumulative Findings

The first seismic event induced by continuous pumping occurred 111 days after pumping began in late July, 1996. During the 7 injection tests (1991-95), seismic activity began the same day or within a few days of the onset of injection.

Injection has induced two distinct, separated 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

The secondary seismogenic zone lies along the trend of the local fault system, the Wray

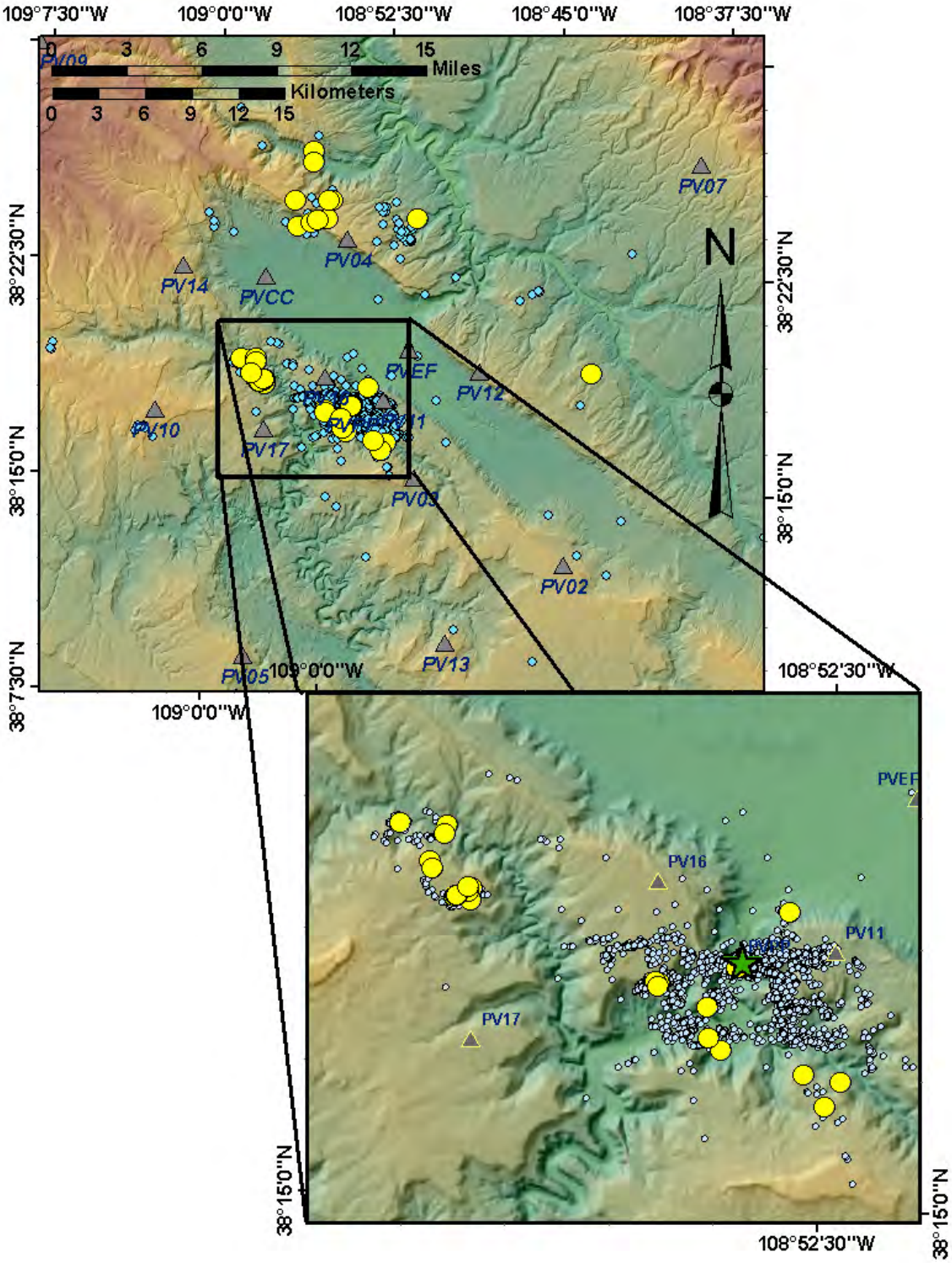


Figure 1-1 Epicenters of seismic events (yellow dots) recorded by PVSN during 2007. Light blue dots are all events recorded since 1991. Star is PVU injection well. Pullout shows the near-wellbore region of the injection well and the injection-induced events. Labeled triangles are PVSN stations.

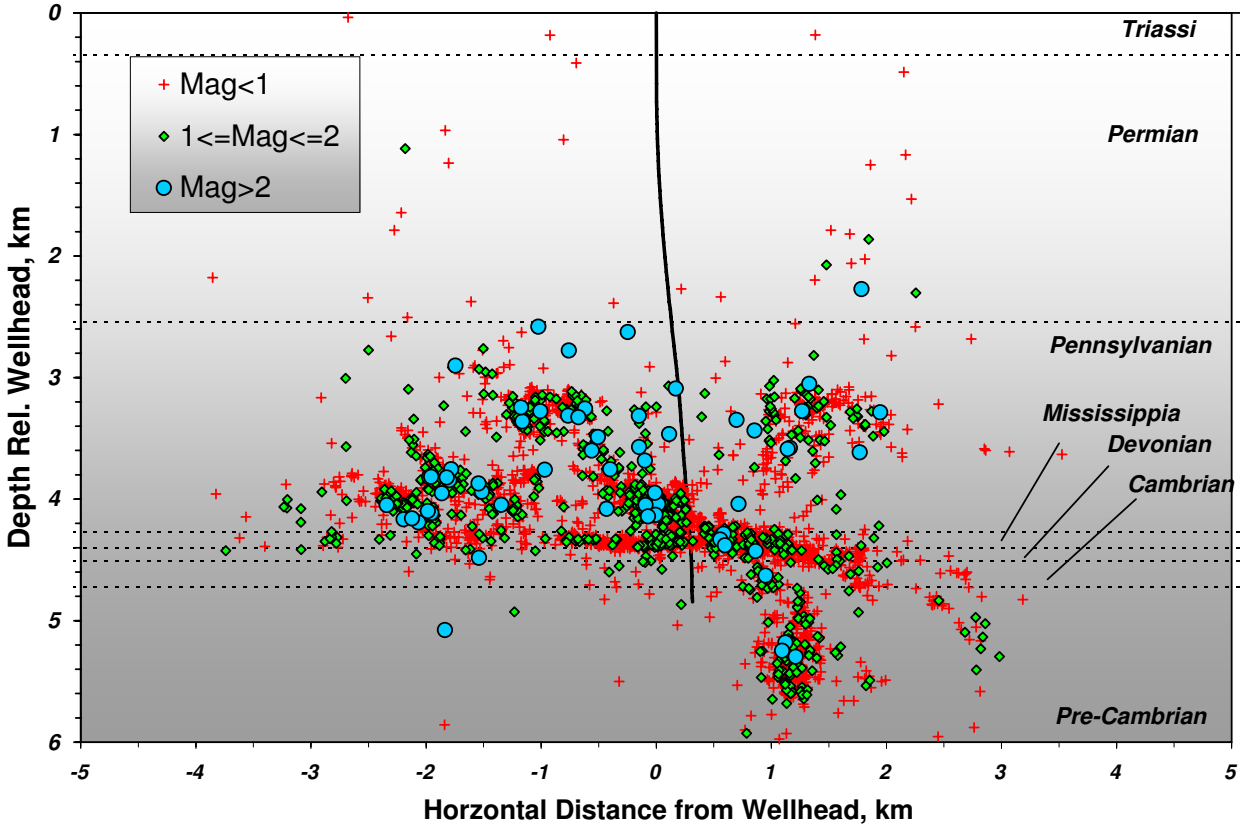


Figure 1-2 Cross section of all injection-induced seismicity recorded since 1991; View-point is looking north. Curved line in middle of figure is the injection wellbore. Seismic events are plotted as a function of magnitude. Stratigraphy is horizontally extrapolated from injection well logs. Note that the depths of events locating shallower than 2.5 km are poorly constrained.

Mesa system, from the primary seismogenic zone.

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 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).

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 recorded induced seismic events are vertically contained between ~3 km and ~6 km depth below the wellhead.

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.

More than 99.9% of the over 4,300 surface-recorded events induced by the Paradox Valley injection since 1991 have magnitudes less than **M**2.0. In this region, the human detection threshold is ~ **M**2.5; since 1991, approximately 20 events have had local reports of felt ground motion.

The largest seismic event (**M**4.3 in May 2000) occurred after ~4 years of continuous injection.

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, liberating 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.

Based on comparing the PVSN seismic data with seismic data recorded at other deep injections (monitored with sensors in observation (i.e., *in situ)* 10's to 100's of meters from the injection), we estimate that PVU has induced more than ~2 million events with magnitudes **M**-3.0 or greater. Based on extrapolating the PVSN event recurrence, we estimate that PVU has induced ~300,000 events with magnitudes **M**-3.0 or greater. Both of these methods have large errors. However, the conclusion is that PVSN records between ~1.0% and ~0.1% of the events PVU induces. The smallest events are probably shear and tensile (i.e., fracture-opening) events, while the larger events are all shear events.

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 2007, PVU had injected 1458 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 May, 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 injec-

tion parameters; (7) maintaining a database of both events and injection parameters; and (8) reporting findings both internally and to the scientific community.

By the end of December, 2007, PVSN had recorded over 4,300 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 8 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 (~12,000 psi). This corresponds to surface pressures between 30 and 34 MPa (4,400 and 4,950+ 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 8 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 2007

3.1 Seismic Network Inventory and Survey

Because the PVSN seismic stations had not been undergoing regularly-scheduled, documented preventive maintenance for the past few years, and because only 9 of the 15 active high-gain PVSN seismic stations were online at the beginning of May, 2007, the status of the seismic network was thoroughly evaluated in the spring of 2007. During the course of two field trips in May and early June, 2007, each of the PVSN seismic stations was visited. A detailed inventory of components at each station was completed, and the radio telemetry for each station was measured. Access to each station was documented, including surveying GPS tracks to the stations to aid in future station access.

In conjunction with the network inventory, the locations of all PVSN seismic stations (including sensor vaults, instrument enclosures, antenna masts, etc) were surveyed to a common horizontal and vertical datum (WGS84 and NAVD88, respectively) with an accuracy of less than 0.1 m both horizontally and vertically (Jones and Wood, 2008). Seismic stations that were not part of the active array at the time (PV06 and PV08) were also surveyed, since data recorded at those sites are still used in locating past earthquakes. The injection wellhead was also surveyed, since its location is used to constrain the hypocenters of several of the earliest injection-induced events. Based on the results from this survey, previous PVSN station locations, mostly those determined from paper topographic maps, were found to be in error by as much as 780 m horizontally. (Earthquake locations have since been re-computed using the new surveyed station coordinates.)

3.2 Seismic Station Maintenance and Upgrades

Critical preventive maintenance and/or repairs were performed at all existing seismic stations during 2007. Maintenance and repairs included replacing batteries, voltage regulators, solar panels, wiring, and shelves, adjusting amplifier gains and transmitter settings, and performing other routine servicing of the analog stations. As a result of these repairs, two seismic stations (PV03 and PV07) that had been down for 14 to 20 months, were brought back online, and other stations (notably PV01 and PV16) that had been reliably functioning only during daylight hours because of dead batteries were made fully functional.

Two seismic stations, PV04 and PV14, were upgraded from single-component short-period analog stations to three-component broadband digital stations. (Prior to these upgrades, station PV04 had been offline for 11 months and station PV14 had been offline for 5 years.) Also, the clock at digital station PV17 was repaired, and this station began providing reliable absolute seismic arrival times for the first time since it was installed in November, 2005. Although these digital station upgrades and repairs were completed during May and June, 2007, problems with data dropouts from the digital stations were a serious problem throughout the summer and early fall of 2007. This problem was resolved in late October, 2007, when the digital radio telemetry was reconfigured. The four digital stations (including PV12, installed in November, 2005) have been providing reliable data since then.

Station PV08 was re-installed in October, 2007, as a 3-component analog station. This station had originally been installed as a 3-component analog station prior to 1985 (as part of the original 10-station network). The horizontal components were removed in September, 1989 (prior to PVU injection operations), and the remaining vertical component was removed in October, 2003. Because of PV08's large distance from the injection well, along with it's noisy site conditions, it is not valuable in locating induced events. However, it is valuable in constraining the locations of earthquakes that occur around the northern end of Paradox Valley and was re-installed specifically to help monitor these events.

In preparation for digital station upgrades scheduled for the summer of 2008, new infrastructure was installed next to four existing seismic stations: PV02, PV03, PV10, and PV11. The installed infrastructure includes seismometer vaults, radio tower bases, and buried conduits for wiring. The work was completed in late July and early August, 2007, with the help of personnel from the U.S. Geological Survey.

3.3 Network Performance

Overall, PVSN performance was poor for 2007, because of both individual station failures and total network downtime. Network performance is plotted as a function of date in **Figure 3-1** and by individual seismic data channel in **Figure 3-2**. Note that these charts were constructed by manually examining waveforms recorded by each channel during triggered seismic events and reflect the degree to which each station provided seismic waveform data for those events. Since we have a limited number of recorded events, occurring over short intermittent periods of time, these charts do not completely reflect station operating status. (For example, poor performance of stations that fail only at night because of dying batteries may be under-represented in the charts.) The significant increase in the percentage of seismic data channels providing data between early May and mid-June (from approximately 65% to 90%, **Figure 3-1**) was due to the extensive station repairs discussed above. The consistently high performance beginning in late October occurred after the radio telemetry for the four digital stations was reconfigured, eliminating data dropouts from these stations.

Failures of individual seismic stations, mainly during the first half of the year, were due to deferred station maintenance during the last several years and aging equipment. The extensive maintenance and repairs conducted at the individual seismic stations during the spring and summer of 2007 (described above and in the site visit reports included in Appendix A) addressed this problem. The upgrading of old analog seismic stations to new digital stations, which begun in 2005 and saw renewed efforts in 2007, will address this problem in the long-term. Because of the age of the existing analog seismic stations and the problem with obtaining replacement parts, these digital upgrades must be a high priority for PVSN operations for the foreseeable future. Regular maintenance of the stations must also continue in order to prevent simultaneous failure of multiple stations in the future.

During 2007, there were approximately 37 days (including partial days) of total network downtime. These total network failures were due to multiple causes. Overheating of equipment at the

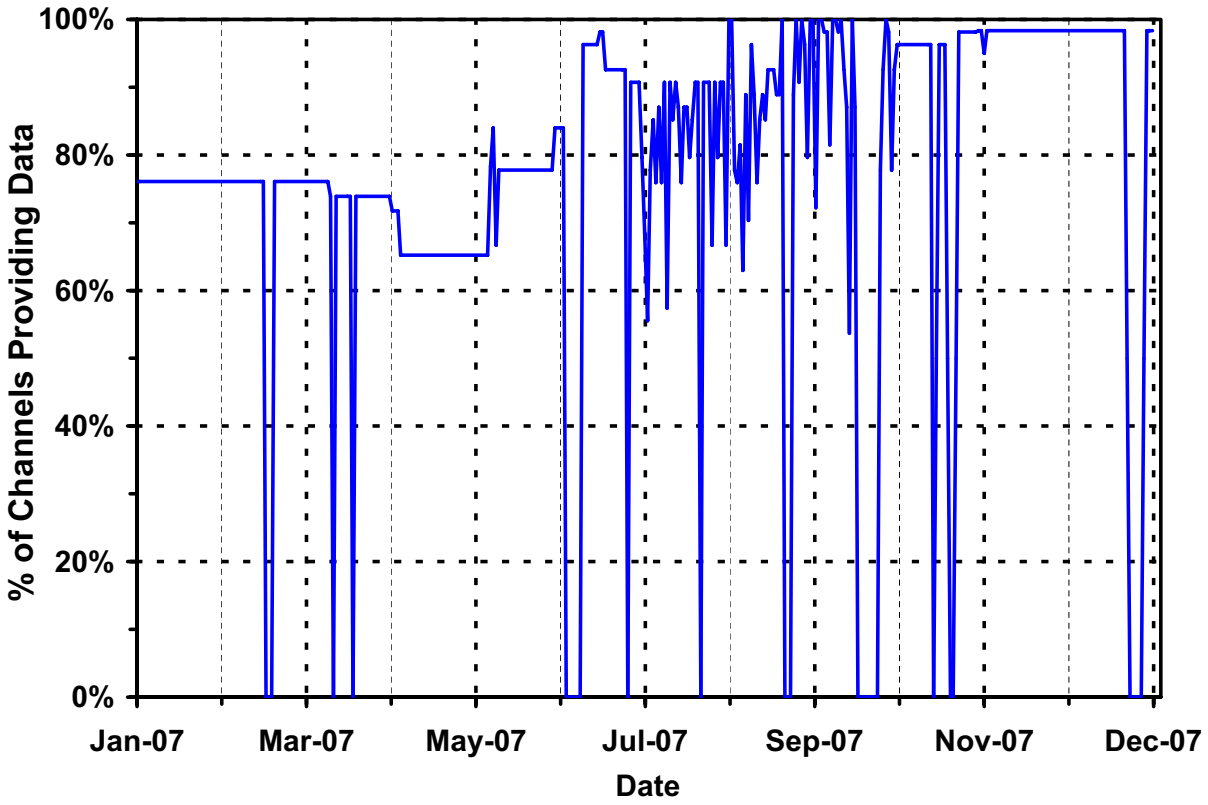


Figure 3-1 Percentage of PVSN data channels providing seismic data during 2007, plotted by date.

Hopkins Field Airport in Nucla, where signals are received from the individual seismic stations and transmitted to Denver, was responsible for some of the failures. The air conditioning in the equipment room at the airport was found to be malfunctioning in late July and has been repaired. Other failures are believed to be due to routine scanning of the computer systems performed by IT security personnel in Reclamation's Technical Service Center (TSC) in Denver. Upgrading of the data acquisition system software late in 2007 seems to have made the system much less sensitive to these disruptions. Other downtimes were due to failure of the phone lines and building-wide power failures at the TSC. These problems are unpreventable, although having additional personnel trained in the operation of the data acquisition systems may help get the PVSN network back online in a more timely manner after such disruptions occur. Finally, a lightning strike at Hopkins Field caused extensive damage to PVSN equipment on Sept. 16, 2007. The network was down for 9 days because of the damage and subsequent repairs required.

3.4 Improved Event Triggering

The triggering parameters, which determine when the data acquisition system records a seismic event, were adjusted in mid-November, 2007. The triggering was made more sensitive, so that events which trigger fewer stations and at a lower amplitude level than previously set, are now recorded. In addition, the parameters were tuned to optimally detect small-magnitude seismic events specifically occurring near the injection well. These changes have resulted in a decreased

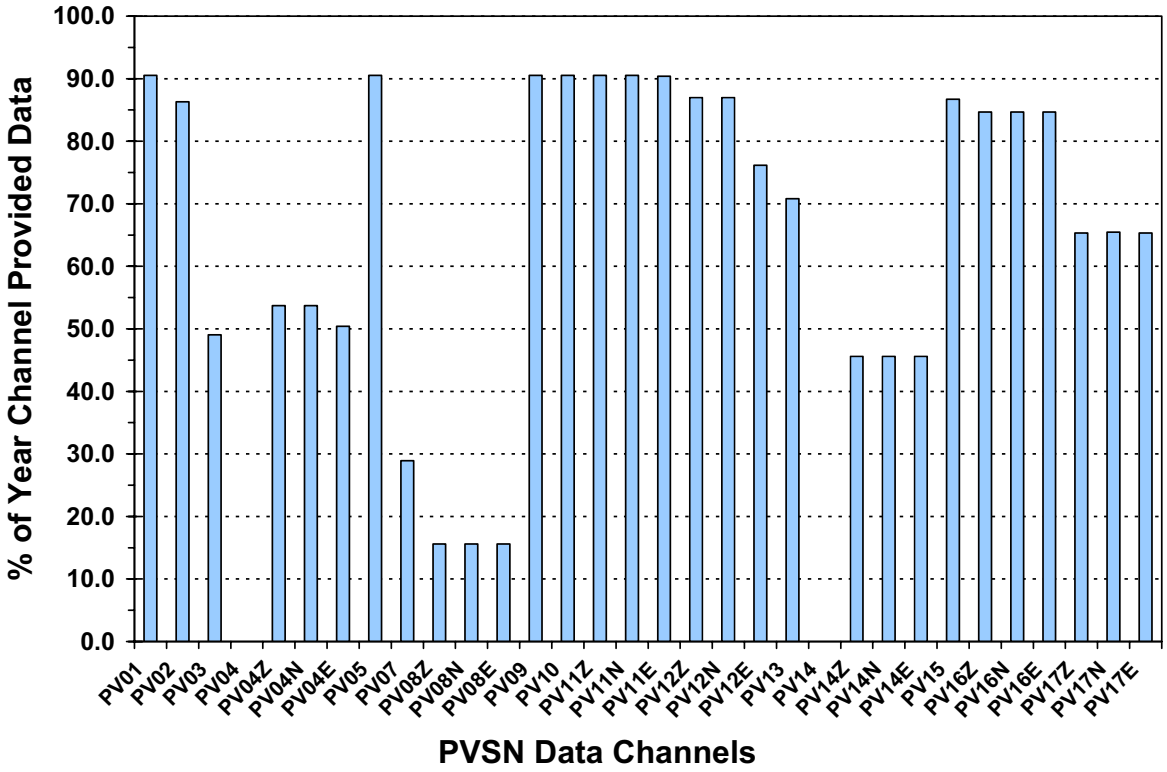


Figure 3-2 Performance of individual PVSN seismic data channels during 2007. The percentage plotted is the percentage of the entire year for which each channel provided useable seismic data. Note that single-component analog stations PV04 and PV14 were offline for the entire year and were replaced by digital 3-component stations (with channels PV04Z, PV04N, PV04E, PV14Z, PV14N, and PV14E) in May and June, respectively. Station PV08 was offline for most of 2007 and was re-installed in late October, 2007.

PVSN detection threshold, allowing the network to more reliably trigger on very low-magnitude events, especially those in the vicinity of the injection well.

3.5 Project Management Activities

In an effort to improve communication and documentation of PVSN activities, a formal written monthly status report was established in May, 2007. The report includes a brief description of any site visits conducted, network operating status, local earthquakes recorded, recent data analysis, other ongoing or near-term activities, and budget reports. In addition, site visit reports were established to document in greater detail network maintenance, repairs, and upgrades.

4.0 SEISMIC DATA RECORDED IN 2007

4.1 Annual Summary

Thirty-eight earthquakes were recorded within the perimeter of PVSN during 2007. 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 to 8 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” - isolated seismic event, currently interpreted as a naturally-occurring local earthquake, not associated with any of the other three categories listed above. The numbers and magnitudes of the events recorded by PVSN during 2007 for each of these four location categories are summarized in **Table 4-2**, and their epicenters are plotted on the map in **Figure 4-1**.

The local earthquakes recorded during 2007 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 the end dates of the 6 site visits performed during 2007 for network maintenance and upgrades (vertical black lines), the date when the triggering of the data acquisition system was made more sensitive (vertical dashed light blue line in mid-November), network down-times (green marks across the top of the chart), and injection well shut-ins (blue marks at the top of the chart). (These operational activities are described in section 3.) The most striking feature of this chart is the almost complete lack of seismicity during the first five months of 2007. The rate of recorded seismicity increased abruptly when the second site visit was performed in early June. During the first two site visits in 2007, three seismic stations that had been down for nearly a year or longer were brought back online (PV03, PV04, and PV14), two stations that had been down for only 1 to 2 months were brought online (PV13 and PV17), and critical maintenance was performed at two other stations (PV02 and PV07). The abrupt onset of recorded seismicity immediately after these repairs were completed strongly suggests that the detection threshold of the network was improved as a direct result of these repairs. Hence, we must conclude that the performance of the network was compromised during the first five months of 2007. Before the data acquisition triggering parameters were adjusted in November, 2007, PVSN required five seismic stations to trigger independently before a seismic event would be recorded. It appears from these observations that the number of fully operational stations located close enough to the injection well to trigger on an induced event less than about magnitude 2 fell below this threshold level of five sometime before the beginning of 2007. Since most of the seismicity currently being induced by injection operations is less than magnitude 2 (as indicated by the seismicity that has been recorded since June, 2007), most of the seismicity induced during the first five months of 2007 would likely not have been detected by PVSN. Furthermore, since it is

Table 4-1 Local earthquakes recorded by the PVSN during 2007

Date	Time[1]	Latitude (deg.)	Longitude (deg.)	Elevation[2] (km)	Depth[3] (km)	Duration Magnitude	Location Category[4]
04/05/07	12:40:47	38.3986	-108.9405	-8.1	9.6	2	northern valley
05/18/07	9:10:25	38.2797	-108.8996	-0.9	2.4	0.7	near-well
06/12/07	1:46:16	38.2744	-108.8706	0.4	1.2	0.3	near-well
06/12/07	22:53:11	38.2697	-108.8741	0.3	1.2	-0.3	near-well
06/14/07	2:01:49	38.3135	-108.9713	-2.8	4.4	0.6	NW cluster
06/16/07	20:28:10	38.2961	-108.8954	-2.5	4.0	0.5	near-well
06/19/07	10:23:51	38.2955	-108.8960	-2.5	4.0	1.1	near-well
06/19/07	10:39:15	38.2954	-108.8963	-2.5	4.0	1.1	near-well
The injection well was shut in on June 20 (surface pressure: 4796 psi).							
07/01/07	11:28:54	38.2819	-108.9026	-2.1	3.6	1.2	near-well
07/08/07	15:29:14	38.3187	-108.7210	-8.3	9.8	1	other (east)
Injection resumed on July 10 (surface pressure:1232 psi).							
07/20/07	0:14:17	38.3206	-108.9787	-3.0	4.5	2.3	NW cluster
08/01/07	7:46:06	38.4420	-108.9308	-10.8	12.3	2.5	northern valley
08/06/07	23:44:14	38.4010	-108.9310	-6.9	8.4	2.2	northern valley
08/13/07	11:04:54	38.3087	-108.9611	-2.6	4.1	1	NW cluster
08/13/07	19:51:12	38.2920	-108.9152	-2.6	4.1	0.7	near-well
08/19/07	0:32:33	38.3206	-108.9676	-3.3	4.8	1.6	NW cluster
08/20/07	6:41:14	38.4120	-108.9156	-4.3	5.8	1.4	northern valley
08/29/07	17:02:31	38.3063	-108.9612	-2.5	4.0	1.9	NW cluster
08/29/07	18:10:40	38.3081	-108.9618	-2.5	4.1	1	NW cluster
09/09/07	23:43:23	38.4055	-108.9194	-4.4	5.9	0.5	northern valley
10/05/07	0:38:53	38.4134	-108.9432	-4.8	6.3	1.7	northern valley
10/15/07	17:32:39	38.3071	-108.9650	-2.5	4.1	1.4	NW cluster
10/15/07	18:46:45	38.3072	-108.9648	-2.5	4.1	1.3	NW cluster
10/15/07	19:16:54	38.3073	-108.9644	-2.6	4.1	0.8	NW cluster
10/17/07	1:08:10	38.3064	-108.8843	-2.9	4.4	0.6	near-well
10/23/07	0:24:54	38.3188	-108.9682	-3.0	4.5	1.5	NW cluster
11/15/07	15:37:53	38.3090	-108.9618	-2.6	4.2	0.8	NW cluster
11/17/07	3:43:32	38.2756	-108.8796	1.3	0.2	-0.1	near-well
11/20/07	13:00:05	38.2755	-108.8797	1.7	-0.2	-0.7	near-well
11/20/07	13:00:11	38.2757	-108.8799	1.8	-0.3	0.1	near-well
11/26/07	20:51:12	38.4051	-108.8531	-2.3	3.8	-0.2	northern valley
11/28/07	8:29:46	38.4136	-108.9188	-4.5	6.1	0.7	northern valley
12/16/07	5:17:58	38.4005	-108.9254	-3.0	4.5	1.6	northern valley
12/18/07	22:14:47	38.2923	-108.9158	-2.8	4.3	0.9	near-well
12/18/07	22:15:40	38.2913	-108.9153	-2.6	4.2	-0.2	near-well
The injection well was shut in on December 19 (surface pressure: 4716 psi).							
12/20/07	21:49:15	38.4351	-108.9306	-6.9	8.4	0.2	northern valley
12/21/07	16:38:12	38.2877	-108.9034	-2.5	4.1	0.4	near-well
12/31/07	12:00:00	38.3123	-108.9707	-3.3	4.9	0.8	NW cluster

Footnotes for Table 4-1:

[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: isolated local earthquake

Table 4-2 Summary of events recorded during 2007 in the four defined location categories

Location Category[1]	Number of Earthquakes	Magnitude Range	Median Magnitude
near-well	15	-0.7 to 1.2	0.50
NW cluster	12	0.6 to 2.3	1.15
northern valley	10	-0.2 to 2.6	1.35
Other	1	1.0	1.00
TOTAL	38	-0.3 to 2.6	0.85

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

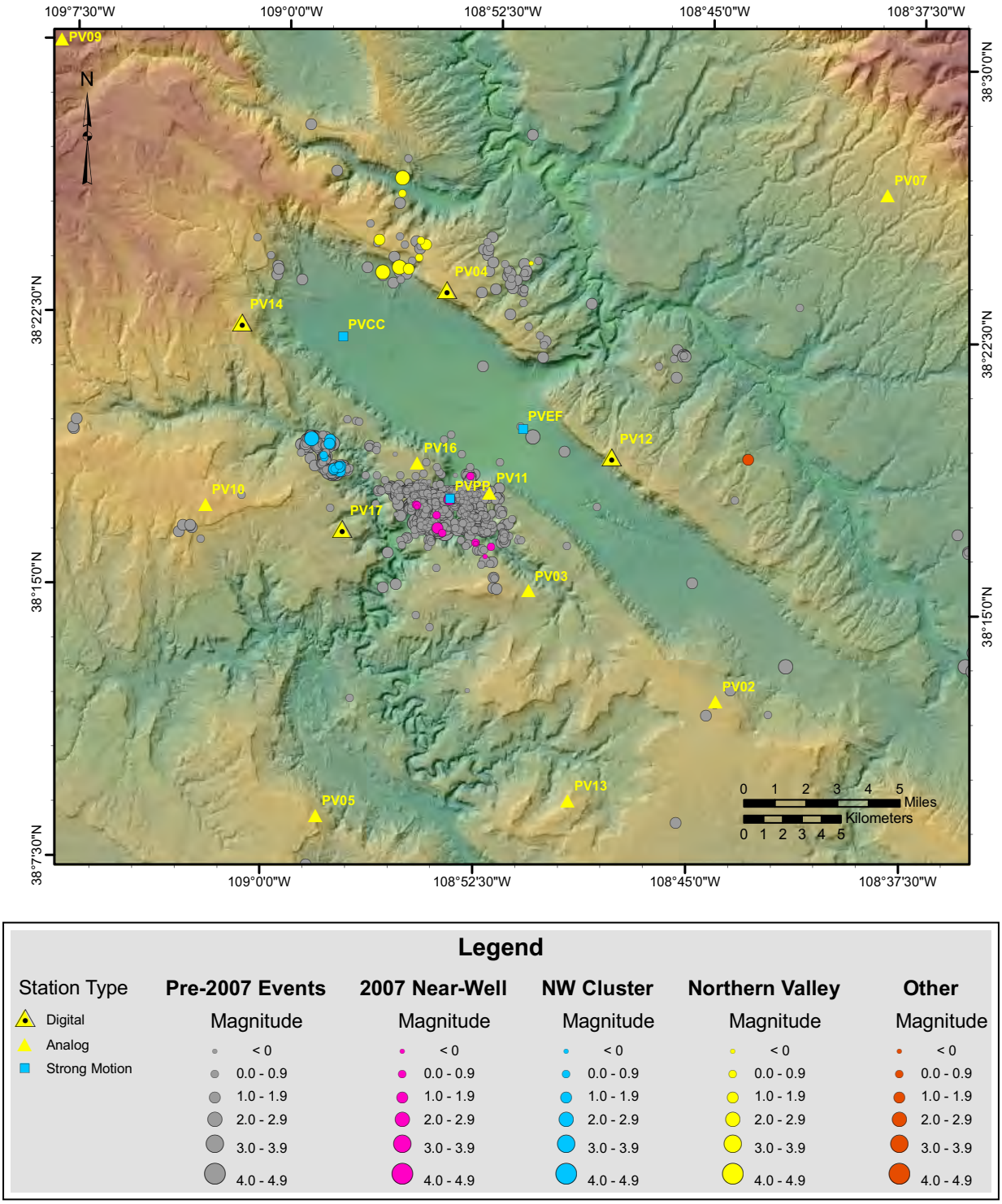


Figure 4-1 Locations of local earthquakes recorded by PVSN during 2007 (colored circles) and previous years (gray circles). Note that some of the pre-2007 local events shown may be explosions that have not been properly classified in the data files.

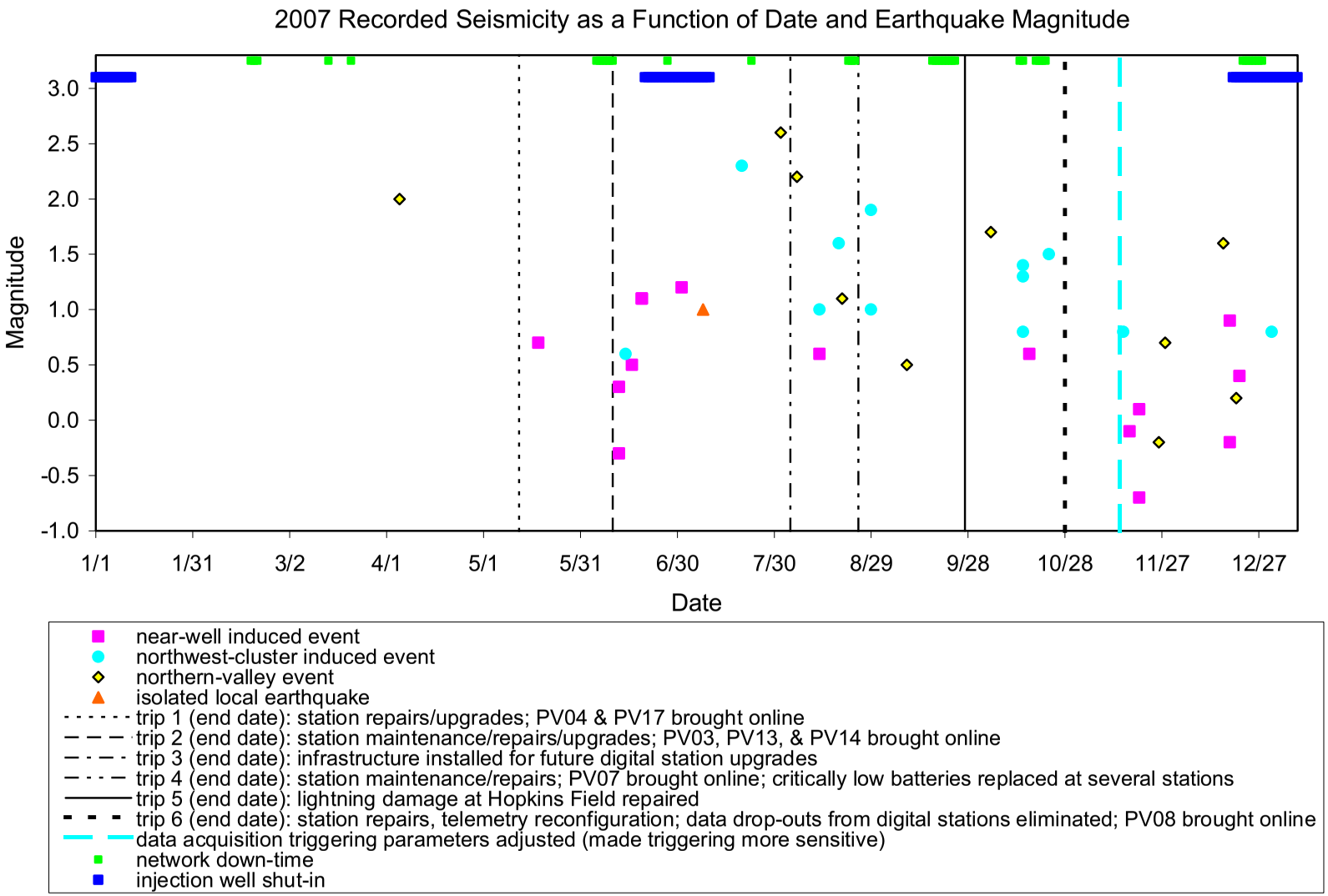


Figure 4-2 Earthquakes recorded by PVSN during 2007, plotted as a function of date, magnitude, and event location category. The dates of total network down-times, injection well shut-ins, and other significant activities such as PVSN site visits are included as indicated by the legend.

extremely unlikely that seismic stations would fail exactly at the beginning of a new calendar year, we must also conclude that the network performance was compromised for some period of time in 2006 as well.

The chart in **Figure 4-2** also illustrates the improved detection capability that was achieved by adjusting the data acquisition system event triggering parameters in mid-November, 2007. Prior to mid-November, only one event smaller than magnitude 0.3 was recorded. In the short time period between mid-November, when the triggering parameters were adjusted, to the end of December, six events smaller than magnitude 0.3 were recorded, the smallest being a magnitude -0.7 event. This time window between mid-November and the end of December, 2007, is too short to define the new triggering threshold. (This will be further evaluated after more data have been acquired). However, these observations suggest that the adjustments made to the triggering parameters have decreased the magnitude threshold for PVSN event detection. This improved sensitivity is true not only for induced events in the vicinity of the injection well, but for all events occurring within or near PVSN. This point is illustrated by the magnitude -0.2 earthquake that was detected in the northern Paradox Valley region in late November, 2007 (**Table 4-1; Figure 4-2**).

4.2 Injection-Induced Earthquakes

Twenty-seven of the events recorded during 2007 occurred within the two zones of injection-induced seismicity, 15 in the near-well region and 12 in the zone centered about 8 km northwest of the injection well. Since PVSN performance was significantly compromised during the first five months of 2007, we cannot know the actual rate of occurrence of injection-induced earthquakes during this time period. Hence, in computing an annual rate of induced seismicity for 2007, for comparison to rates from other years, we must use data only from that portion of the year when the network was sufficiently operational. Based on the observations shown in **Figure 4-2**, along with the understanding of the station repairs that were completed during the first two PVSN site visits in 2007, we believe that the majority of induced earthquakes larger than approximately **M**0.3 have been detected by PVSN since the second site visit was completed (i.e., beginning June 11, 2007). Between June 11, 2007 and the end of December, 2007, PVSN was operational for 178 days (accounting for 26 days of network down-time during this time interval, as shown in **Figure 4-2**). Using the number of induced earthquakes recorded during that time period, the average daily rate of induced seismicity for events with magnitudes greater than **M**0 is 0.124. The rate computed using all induced events, regardless of magnitude, is 0.146. These rates, as well as rates computed independently for each event location category, are listed in **Table 4-3**.

As can be seen in the event summary in **Table 4-2** and the magnitude histograms presented in **Figure 4-3**, the induced events which occurred in the northwest region (NW cluster) tend to be higher in magnitude (ranging from **M**0.6 to **M**2.3, with a median value of **M**1.15) compared to those near the injection well (**M**-0.7 to **M**1.2; median = **M**0.5). This difference in magnitudes indicates a difference in conditions within the fractured reservoir. The magnitude difference implies that slip is occurring across larger fault or fracture surfaces in the region northwest of the injection well than in the region immediately surrounding it.

Table 4-3 Average daily seismicity rates of local earthquakes recorded by PVSN during 2007. These rates were computed using only that portion of the year for which the network was sufficiently operational (178 days), as discussed in the text.

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	14	0.079	10	0.056
NW-cluster induced events	12	0.067	12	0.067
all induced events	26	0.146	22	0.124
northern valley events	9	0.050	8	0.045
other (isolated local earthquake)	1	0.006	1	0.006
TOTAL	36	0.202	31	0.174

The majority of the induced events recorded during 2007 locate in areas of previous seismic activity, as seen in the expanded-scale map presented in **Figure 4-4** and the cross section in **Figure 4-5**. In these figures, only the pre-2007 induced earthquakes with the most reliable relative locations are shown (black circles; see section 8 for a description of the event relative location method). (These earthquakes 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). The induced earthquakes recorded during 2007 having the most reliable relative locations (using the same criteria as for the pre-2007 data, listed above) are plotted with red circles, and the induced earthquakes recorded during 2007 with less reliable relative locations are plotted with white circles. As can be seen, the majority of events recorded during 2007 occur on or very near previously-active fractures. The exceptions are five events that plot southeast of most of the reliable pre-2007 event locations (three in a tight cluster). None of these events are well-constrained in the event relative location and all of them have very small magnitudes (**M**-0.7 to **M**0.3). Because of the small size of these events, the number of recorded waveforms having good signal-to-noise levels is limited. Their locations may be biased by poor arrival times picked on noisy waveforms, erroneous cross-correlation time differences, or simply inadequate ray coverage. Hence, these locations are not considered reliable.

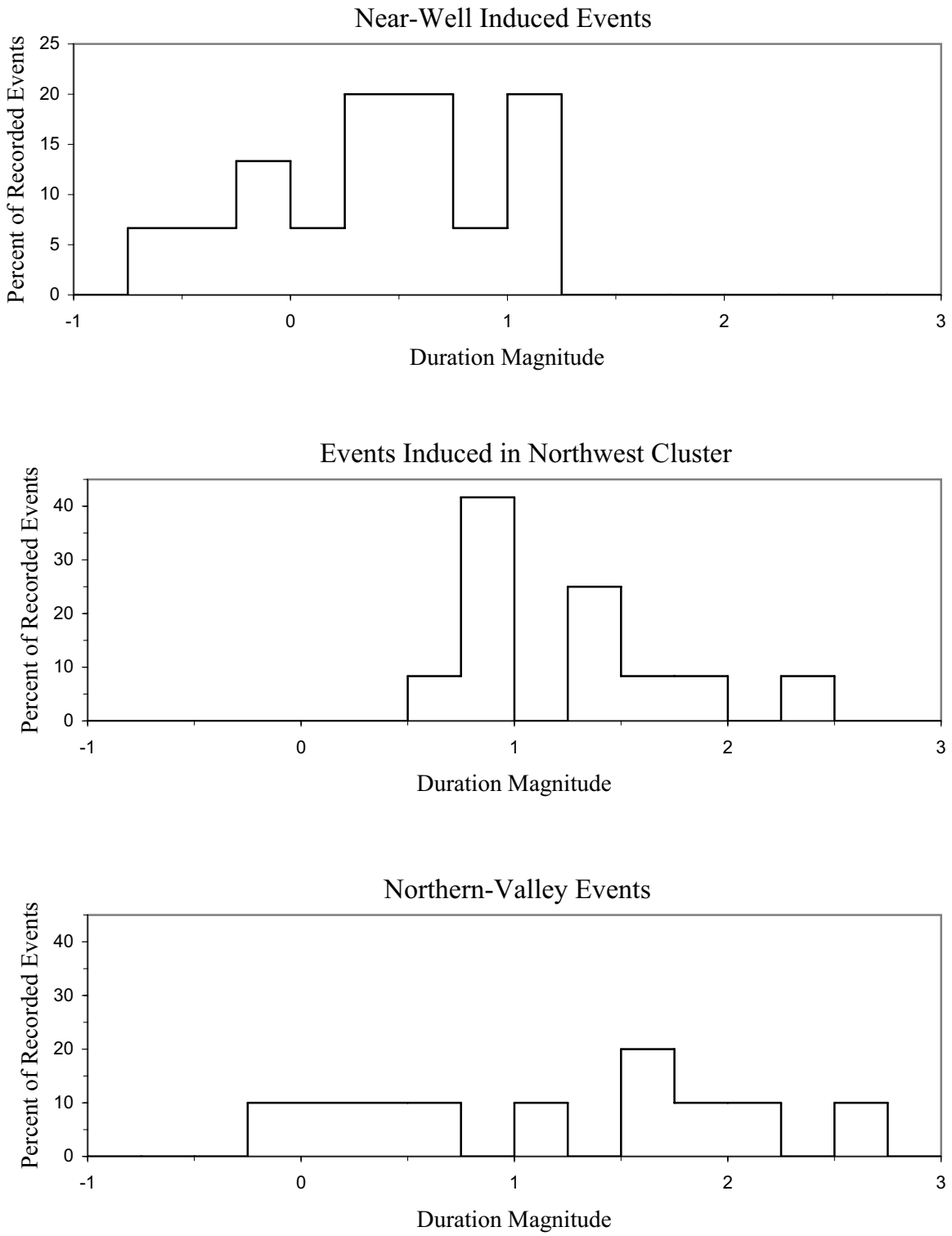


Figure 4-3 Magnitude histograms for events recorded in the near-well region (top), in the northwest zone of induced seismicity (middle), and in or near northern Paradox Valley (bottom).

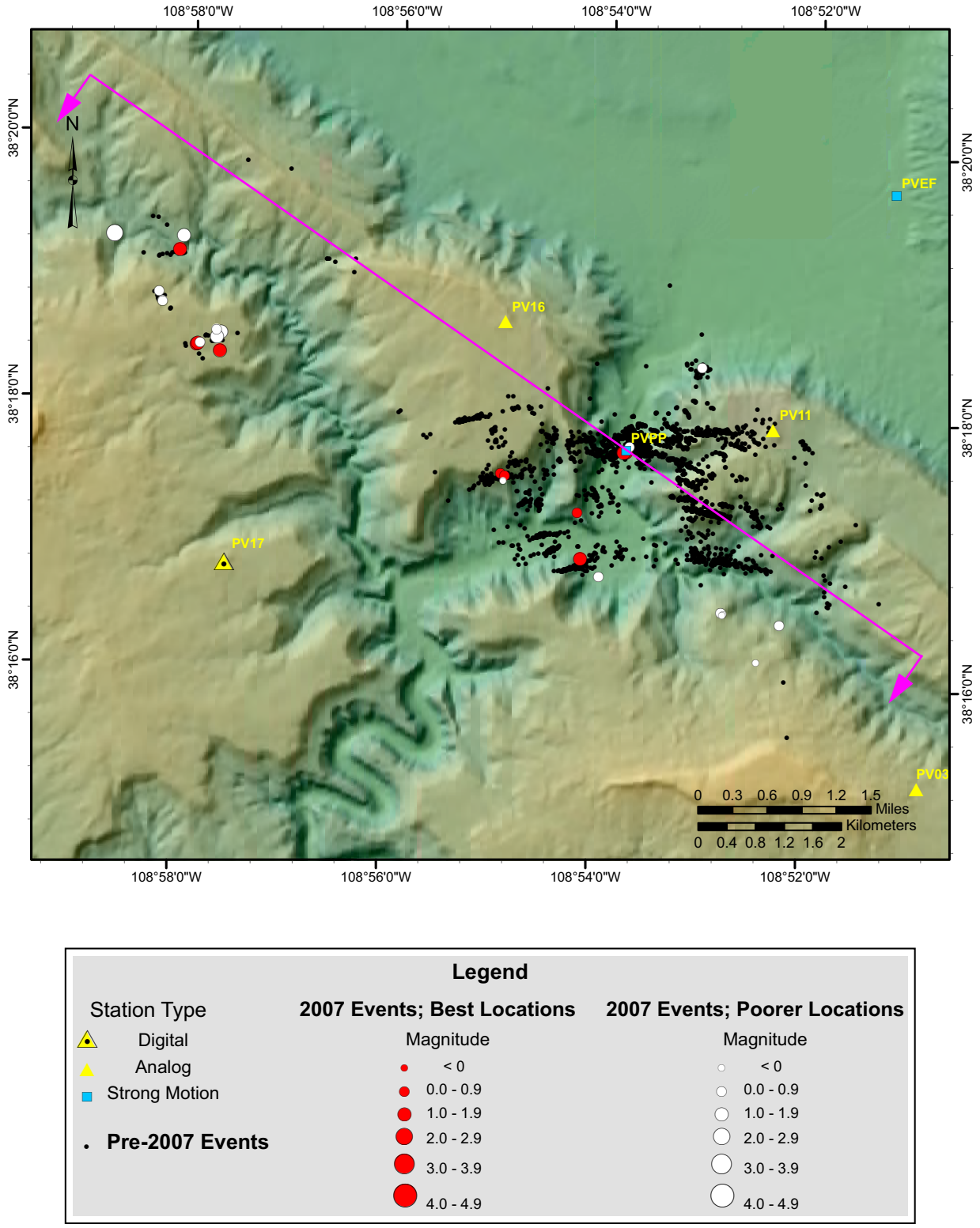


Figure 4-4 Map showing the locations of induced earthquakes recorded in 2007, compared to the best-constrained locations of previously-induced events. The magenta line indicates the orientation of the cross section presented in Figure 4-5.

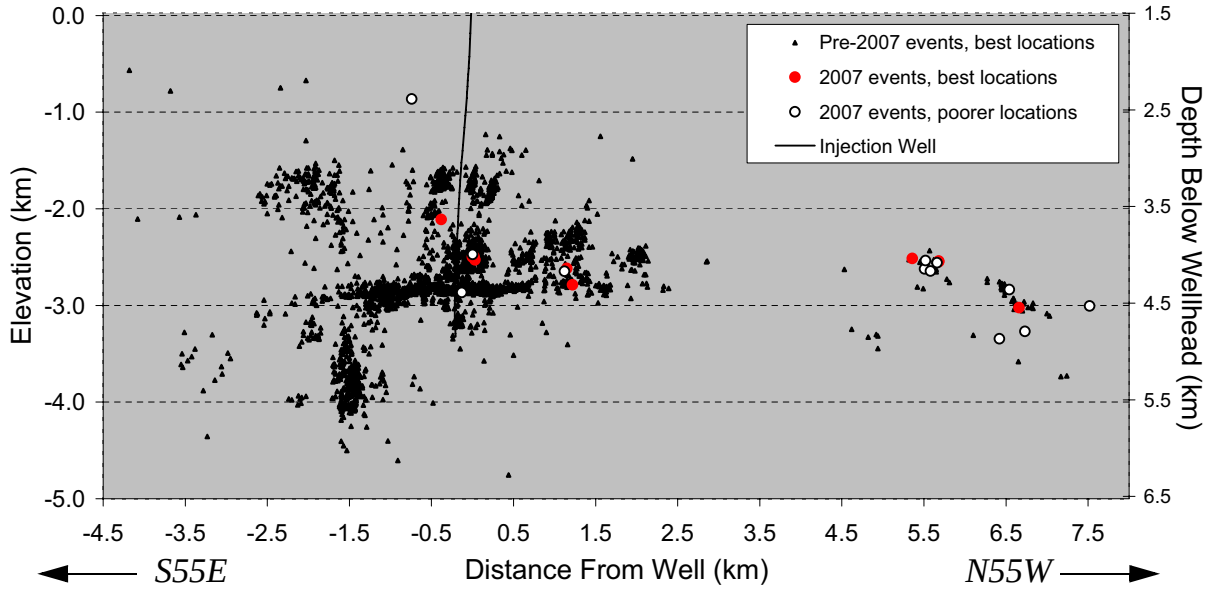


Figure 4-5 Cross section looking to the southwest showing the locations of induced earthquakes recorded in 2007, compared to the best-constrained locations of previously-induced events. (The orientation of the cross section is indicated by the magenta line in Figure 4-4. Note that events locating shallower than 1.5 km depth are not presented here because their computed locations are not reliable.)

4.3 Northern-Valley Earthquakes

Ten earthquakes were detected in the northern Paradox Valley region during 2007. Magnitudes range from -0.2 to 2.6 (**Table 4-2** and **Figure 4-3**). The earthquakes which have been detected in the northern Paradox Valley region in recent years appear to locate in three separate groups: (1) events located about 3 km east of station PV04, (2) dispersed events located northwest of station PV04, and (3) a smaller group of events located approximately 3 to 4 km northeast of station PV14. Nine of the events detected in 2007 occurred in group 2, northwest of station PV04. One event, the smallest northern valley event detected in 2007 (**M**-0.2), occurred near group 1, northeast of PV04 (**Figure 4-1**).

Because these events occur near the perimeter of PVSN, their computed depths have large uncertainties. The recent conversion of stations PV04 and PV14, which are located along the northern edges of Paradox valley, from vertical-component stations to three-component stations is now providing S-wave arrival times, which help constrain earthquake depth estimates. However, although these stations were upgraded in May and June, 2007, problems with data drop-outs from the new broadband digital stations were not fully resolved until late October, 2007. In addition, a local S-wave velocity model for the northern Paradox Valley area has not yet been developed. (The S-wave arrival times from all three-component stations are currently being processed using an S-wave velocity model which was developed only for the smaller region of induced seismicity near the injection well; see section 8 for more details.) Hence, the benefit of the conversion of stations PV04 and PV14 to three-component in helping to constrain the depths of the northern Paradox Valley events has only been partially realized. In addition, the re-installation of station

PV08 in late October, 2007 should provide additional constraints on the locations of events occurring in this area in the future.

Given the uncertainties in depth estimates for the majority of the northern valley events recorded to date, the few events that have the best-constrained depths were selected based on the following criteria: maximum gap in azimuthal ray coverage <= 180 degrees and at least one S-wave arrival time from either station PV04 or PV14. The four northern valley events recorded in 2007 on 10/5, 11/28, 12/16, and 12/20 meet these criteria. The ray coverage for these events is fairly good, with between 17 and 19 arrival times being available for each event from 13 to 15 seismic stations. Maximum gaps in azimuthal ray coverage range from 112 to 162 degrees. The estimated elevations of these events range from -2.8 km to -5.8 km (msl), which corresponds to approximately 5.0 to 8.0 km depth below local ground surface (using the elevation of the closest seismic station, PV04 at elevation 2.176 km, as a reference). The median depth is 6.1 km. Note that this is significantly shallower than the 10 to 15 km depth range previously reported for the northern valley events, which was estimated from data with marginal ray coverage before S-wave arrival times were available from nearby seismic stations.

4.4 Isolated Local Earthquake

One isolated local earthquake, not associated with the northern valley events discussed above, was recorded by PVSN on July 8, 2007. The event has a fairly small magnitude of **M**1.0. The earthquake is located east of station PV12, at an estimated depth of approximately 10 km below local ground surface. However, the location of this event, including the estimated depth, is very poorly constrained. No signals were provided by station PV15 to the east or station PV07 to the northeast, and station PV08 had not yet been re-installed. Hence, this event occurred outside the perimeter of the operational seismic network (the maximum gap in azimuthal ray coverage is 200 degrees), and it’s location cannot be well-constrained.

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** & **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.

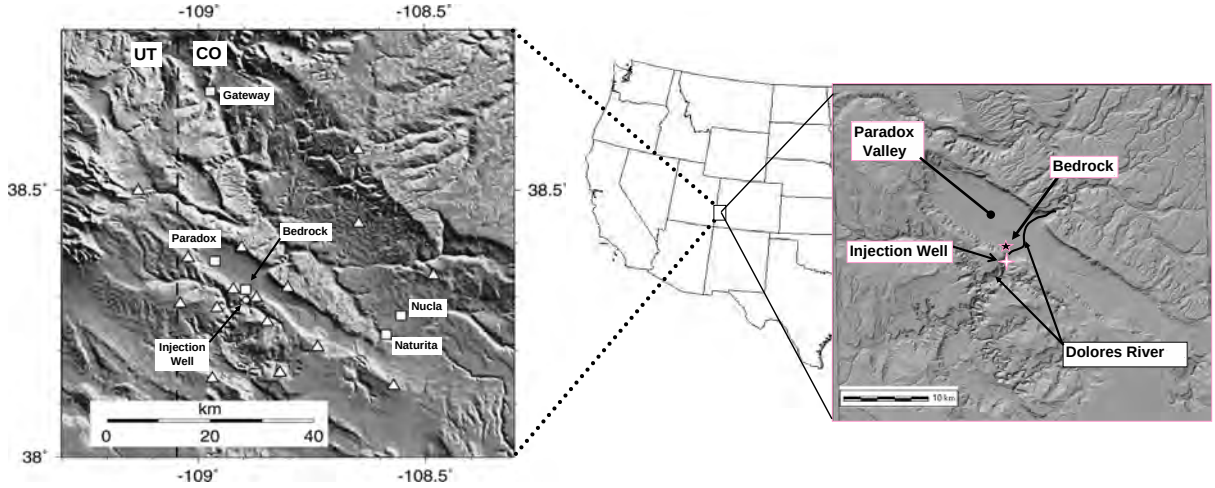


Figure 5-1 Location Map of Paradox Valley Unit, Dolores River, and Local Topography. See Figure 5-2 for expanded version of map.

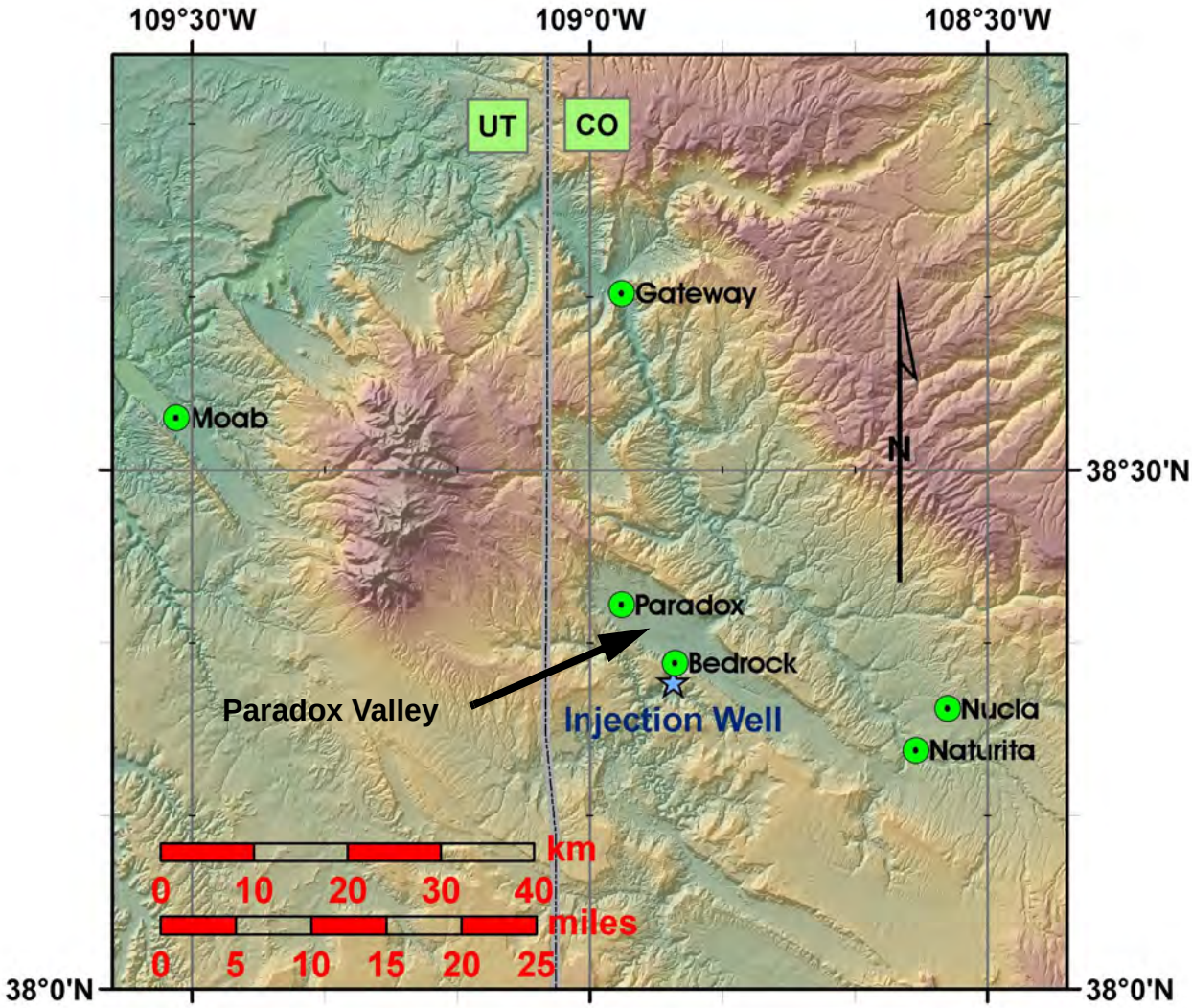


Figure 5-2 Local Topographic Setting of PVU Injection Well, Paradox Valley, Local and Regional Municipalities, and the La Sal Mountains between Paradox and Moab.

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

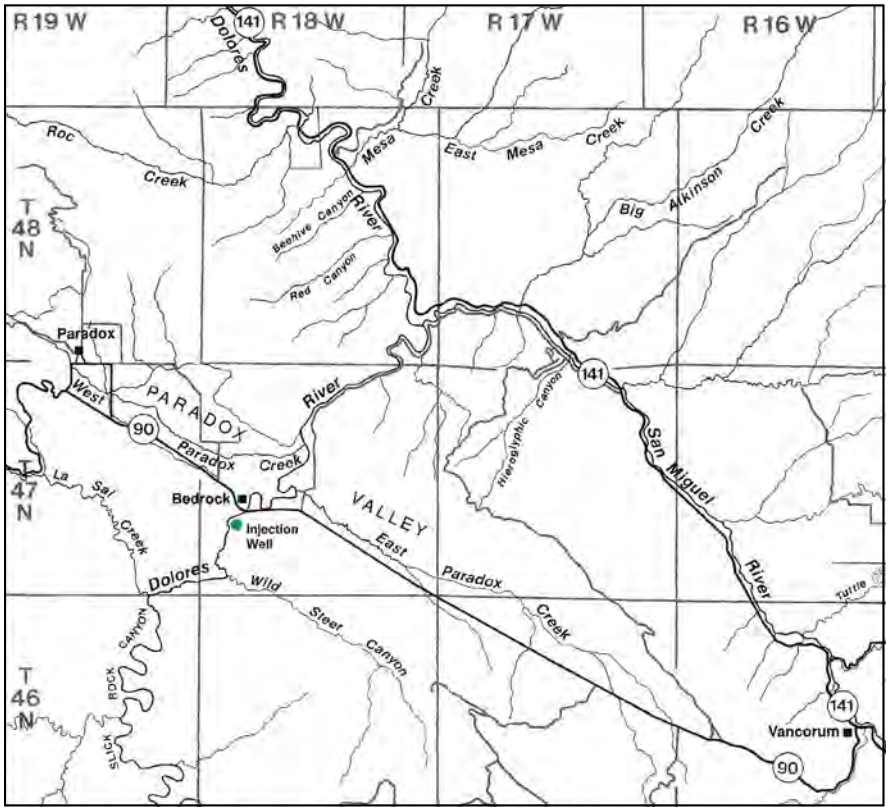


Figure 5-3 Paradox Valley Unit Injection Well and Local Geography. Figure is adapted from Parker (1992). Each square is approximately 10 km by 10 km.

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., Par-

adox 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.]

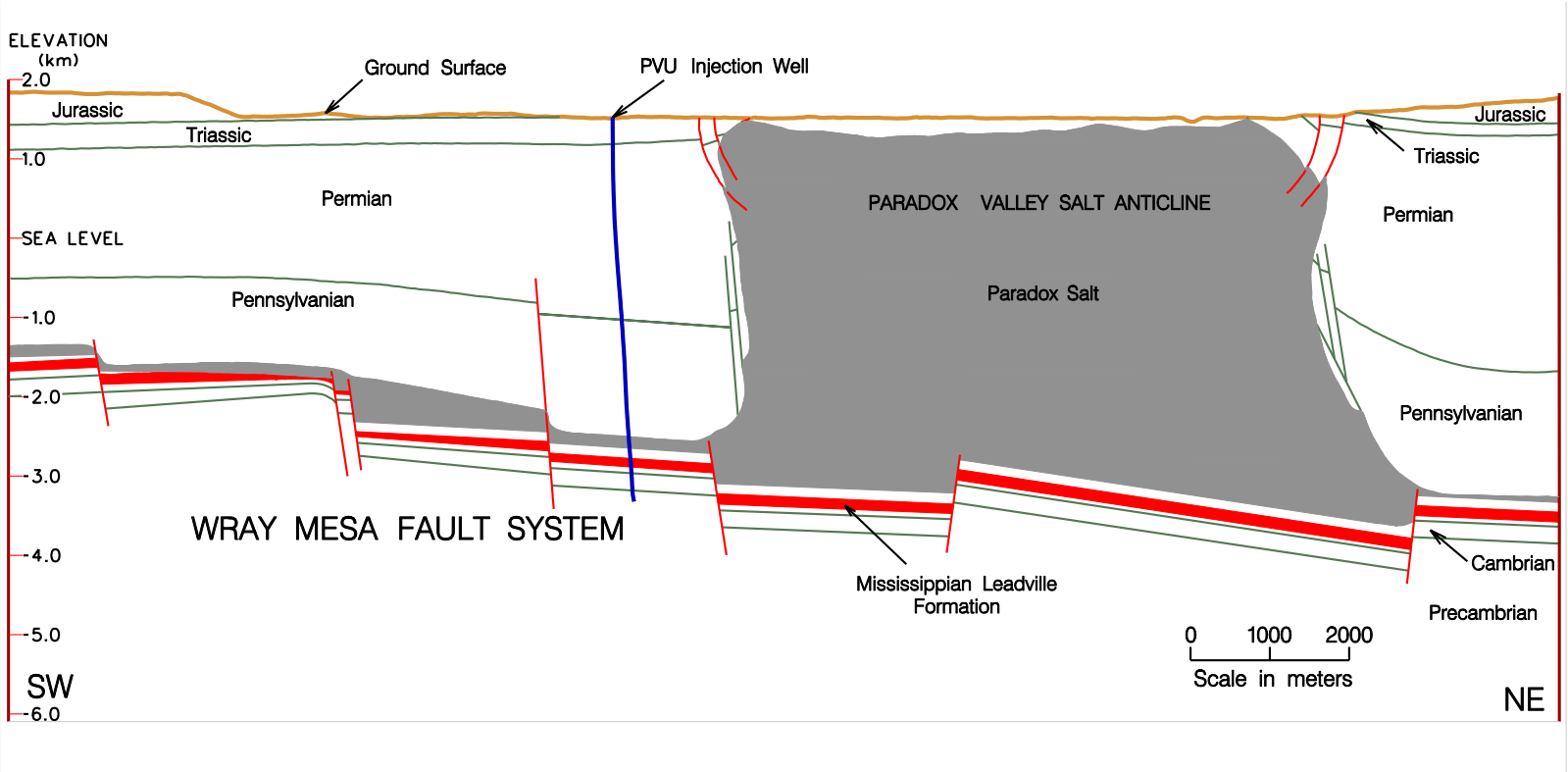


Figure 5-4 Bremkamp and Harr's (1988) Northeast-Southwest Cross Section Through Paradox Valley and its Bordering Region. Cross Section runs through the injection well and surface topography reflects surveyors path up the canyon of the Dolores River and not the local mesa topography.

6.0 PARADOX VALLEY SEISMIC NETWORK

6.1 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 6-1**). 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 6-1**. More detailed information about the stations is provided in **Table 6-1** including installation date, station type, and number of components; **Table 6-2** lists descriptive information about the telemetered

Table 6-2 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

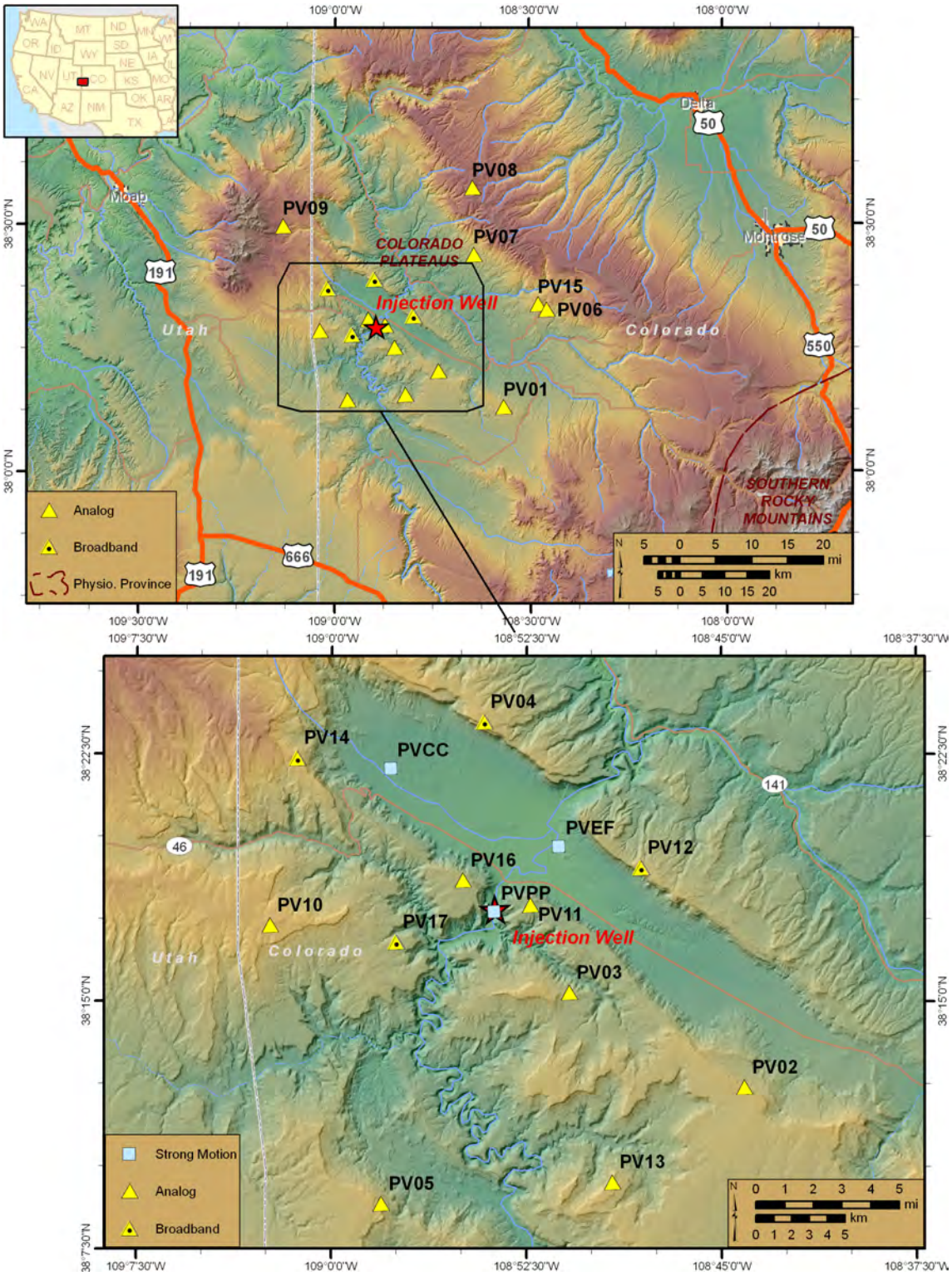


Figure 6-1 Locations of the Paradox Valley Seismic Network stations and the Paradox Valley Unit injection well. PVCC, PVEF & PVPP are the strong motion stations. Station PV06 was replaced by PV15. Physiographic provinces from Fenneman and Johnson (1946).

Table 6-1 PVSN Station Locations and Characteristics

Station Name	Latitude deg., N	Longitude deg., W	Elev. m	Dates of Operation	Station Type	Sensor Direction
PV01	38.13	108.57	2191	5/83-present	short-period	vertical
PV02	38.21	108.74	2177	5/83-present	short-period	vertical
PV03	38.25	108.85	1972	5/83-present	short-period	vertical
PV04	38.39	108.90	2176	5/83-present	broad-band	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-present	short-period	triaxial
PV09	38.50	109.13	2662	6/83-present	short-period	vertical
PV10	38.29	109.04	2266	6/83-present	short-period	vertical
PV11	38.30	108.87	1882	12/89-present	short-period	triaxial
PV12	38.32	108.80	2092	12/89-present	broad-band	triaxial
PV13	38.16	108.82	2158	12/89-present	short-period	vertical
PV14	38.37	109.02	2234	12/89-present	broad-band	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. The station types and sensor directions listed here are current as of the end of 2007. 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).

stations, including a legal descriptions of the station locations.

6.2 Network History

Local seismic monitoring of Paradox Valley began in late 1983 with the installation of a 10-station telemetered array (stations PV01-PV10, see **Figure 6-1**). 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 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.

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 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.

The path the analog data took from the remote seismic stations in Paradox Valley to reach the processing facilities near Denver 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 reconfigured to eliminate many of the analog telemetry links. A local data collection facility was established at Hopkins Field in Nucla, Colorado to receive the FM radio signals from all 16 seismograph stations, demodulate the seismic signals from the carrier tones used for telemetry, and then digitize (with higher-resolution 16-bit analog-

to-digital converters) the seismic data from each station. A wide-area network (WAN) link was established at Hopkins Field 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 a modified version of the event detection algorithm used in the previous data acquisition systems, and remains the current data acquisition system used 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. Three other existing stations have also been converted to digital broad-band instrumentation since 2005: PV12 in November, 2005, PV04 in May, 2007, and PV14 in June 2007. Site preparations to accommodate digital upgrades at four additional stations (PV02, PV03, PV10, and PV11) were completed in July, 2007, with complete conversion scheduled for July, 2008.

6.3 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, the spacing decreased to about 5-8 km for the 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.

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

Instrumentation for 12 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 6-2**).

Of the 12 analog, short-period stations, 9 record ground motion in the vertical direction only. The remaining three stations have three seismometers each: one vertical, and two horizontal (these are

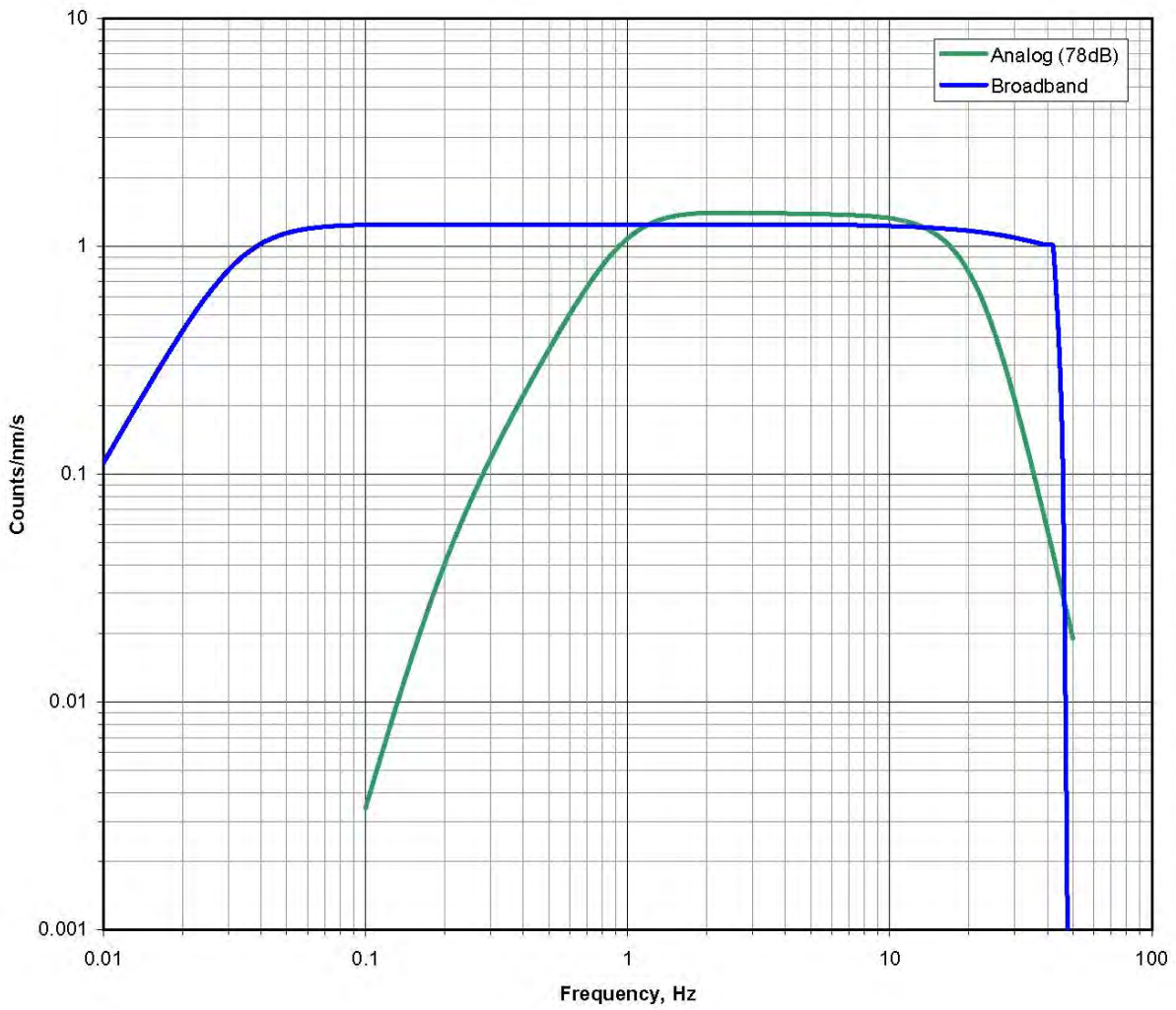


Figure 6-2 Typical velocity response as a function of frequency for an analog PVSN station (Teledyne Geotech S-13 seismometer and external electronics) and a broadband station (Guralp CMG-40TD seismometer with integrated electronics).

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.

6.5 High-gain Array - Digital Broad-band Instrumentation

Beginning in 2005, three of the original analog short-period stations were upgraded to digital broad-band (PV04, 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 reconfigured 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 6-2**; 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.

6.6 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.

6.7 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; better methods are needed and planned for the future. The annual numbers of days of total network downtime, for years beginning in 2000, are listed in **Table 6-3.** 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 has increased in recent years, ranging from 34 to 47 days during the last three years (corresponding to 87.1% to 90.7% uptime). The reasons for these downtimes, which include equipment overheating, sensitivity of computer systems to security scans, power failures, phone line disruptions, lack of cross-training among PVSN personnel, and lightning strikes, are being evaluated and rectified to the extent possible.

Table 6-3 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%

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

7.0 PVU INJECTION OPERATIONS

7.1 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 7-1**.

7.2 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 May 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 and evaluatable injection "*phase*". 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 7-1** summarizes the injection phases. In the table the averaging of values includes both active pumping and shutdown days.

7.2.1 Phase I - (22-May 1996 through 26-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

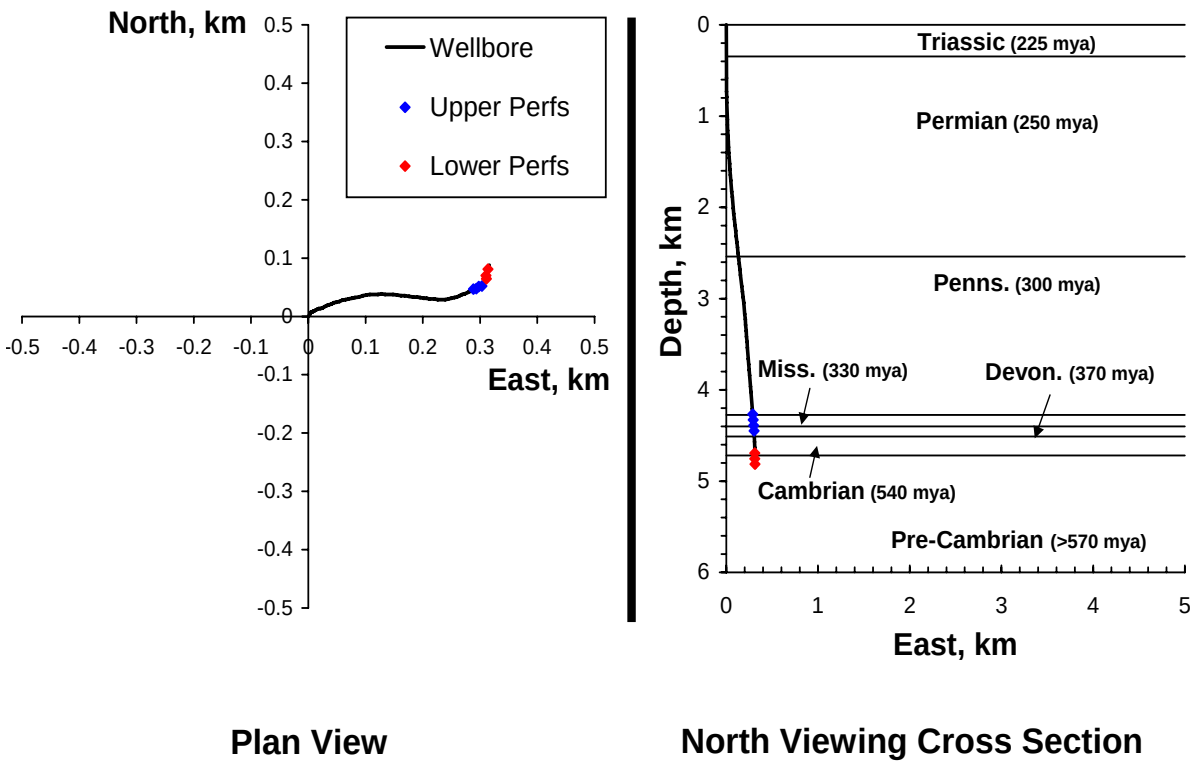


Figure 7-1 PVU Injection Well: Salinity Control Well No. 1in Plan View (left) and North-Viewing Cross Section (right). Figures include the near-wellbore stratigraphic column, based on well logging of Salinity Control Well No. 1, and locations of the upper and lower casing perforations.

~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.

7.2.2 Phase II - (27-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

Table 7-1 Phases of Pumping, Associated Time-Averaged Injection Parameters, and Injection Characteristics since 1996

Phases	Approx. Duration	Avg. Wellhead Pressure	Avg. Pressure @ 4,300 m* depth	Avg. Inj. Rate	Injectate *PVB%: H_2O%*	Biannual 20-day Shutdowns	Approx. No. Recorded Seismic Events***
	days	(MPa)	(MPa)	(lpm)		y/n	
I	1161	29.6	76.7	1029.6	70:30	No	2502
II	332	29.3	76.3	934.6	70:30	Yes	441
III	564	27.5	74.6	732	70:30	Yes	219
IV	2184**	28.3	78.2	731	100:0	Yes	457

*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
**Number includes days through 12/31/07
***Includes all events not only events with magnitude M>=0, as used in later analysis.
"**MPa**" = megapascals & 1 MPa = 145 psi; "**lpm**" = liter/minute & 1 lpm = 0.26 gal/minute

wellbore) reduced during and following unscheduled maintenance shutdowns and during the 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*.

7.2.3 Phase III - (23-June 2000 through 7-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.

7.2.4 Phase IV - (8-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 8, 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.

7.3 PVU Injection History By Year

Table 7-2 summarizes PVU Well No. 1's annual injection history. The values in **Table 7-2** are in standard units of millions of gallons (Mgal) and thousands of tons (ktons).

Table 7-2 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

Table 7-2 Annualized Summary of PVU Injection

Year	Phase	Injectate (approx.)	Paradox Valley Brine (approx.)	Salt Disposed (approx.)
		Mgal	**Mgal**	**ktons**
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
TOTAL	**--**	**1,458**	**1,194**	**1,295**

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 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

Accurately locating earthquakes requires (1) appropriate array geometry, (2) identification of arrival times of specific phases in the recorded signals, and (3) an accurate velocity model of the region through which the signals travel. Seismologists manually pick the arrival times for all local earthquakes recorded by PVSN. We do this to minimize uncertainty frequently found in automated (i.e., software-based) phase identification and arrival time picking. We require a minimum of four arrival times from at least three stations to locate an event. In the PVSN analysis, we determine the compressional-wave (P-wave) arrival times from the vertical-component seismograms at all stations with acceptable signal-to-noise ratios. We only pick the shear-wave (S-wave) arrival times at the three-component stations (PV04, PV08, PV11, PV12, PV14, PV16, and PV17), since S-wave arrival times can only be reliably determined from horizontal-component seismograms.

We compute preliminary earthquake locations for all events occurring within the perimeter of PVSN using the manual arrival time picks and a three-dimensional (3-D) P-wave velocity model. The S-wave velocity model used is calculated from the 3-D P-wave velocity model and a horizontally-layered model of the ratio of P-wave to S-wave velocity (Vp/Vs). The 3-D P-wave velocity model and layered 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, we used a data set consisting of 1256 injection-induced events having: magnitudes greater than or equal to **M**0.7, 10 or more arrival times including at least one S-wave arrival time (at either station PV11 or PV16), a maximum gap in the azimuthal ray coverage less than or equal to 100°, and distance from epicenter to nearest recording station divided by the focal depth less than or equal to 1.0. In addition, we supplemented these data with 19 regional earthquakes and 51 identified mine blasts. Note that at the time that this data set was constructed, the overwhelming majority of available S-wave arrival

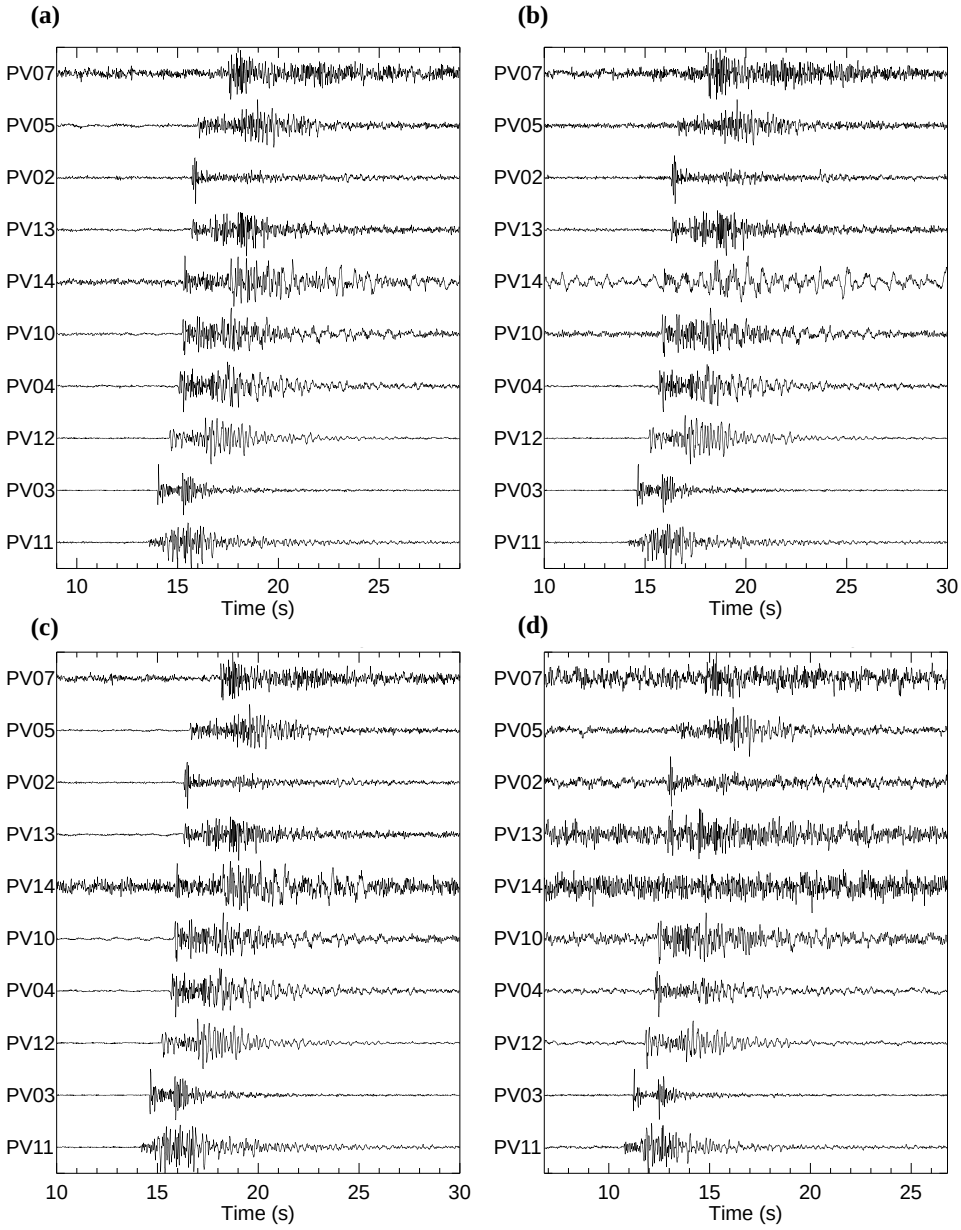


Figure 8-1 Examples of Vertical-Component Seismograms from Four Closely-Spaced Events Recorded by the Indicated PVSN stations.

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 layered 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 processing the S-wave arrival time data from all the current 3-component stations, including those located at considerable distances from the injection well (i.e., PV04, PV08, PV12, and PV14).

For the induced events 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 20 million arrival time differences were used simultaneously to compute highly-accurate relative locations of the induced events recorded between July, 1991 (when the first injection test was performed) and the end of 2007. Nearly 98% of the induced events had sufficient signal-to-noise ratios and azimuthal ray coverage to be included in the relative relocation. For the remaining induced events, as well as the local earthquakes and explosions, we use the locations computed from the manual arrival time picks.

8.4 Seismicity and Injection Pressure

One PVSN mandate has been to relate the induced seismicity to the injection parameters. To this end, on a long-time scale, we have been moderately successful resulting in reduced levels of seismicity (see section 8). Unfortunately, we have not been able to relate individual seismic events and injection data on an event time scale. One reason for this may be that microseismic events occur on a scale of seconds and the injection data has been reported as a single daily average. In contrast, **Figure 8-2** shows an example of PVU wellhead pressure recorded at one-second sampling (“high-sample rate” data) plus the occurrence times of 3 microseismic events. In the figure we have horizontal dashed lines giving the single daily averaged pressure. Graphically the figure shows why we cannot correlate an individual seismic event with daily-averaged pressure. Pressure during one day can vary almost 30 psi, while daily-average data gives one value for this range. To date very little work has been completed relating injection data recorded at a high-sample rate and the microseismic data of PVSN. During 2007, Reclamation obtained the software for receiving and displaying the high-sample-rate data. By the end of 2007, the implementation of this software was not completed.

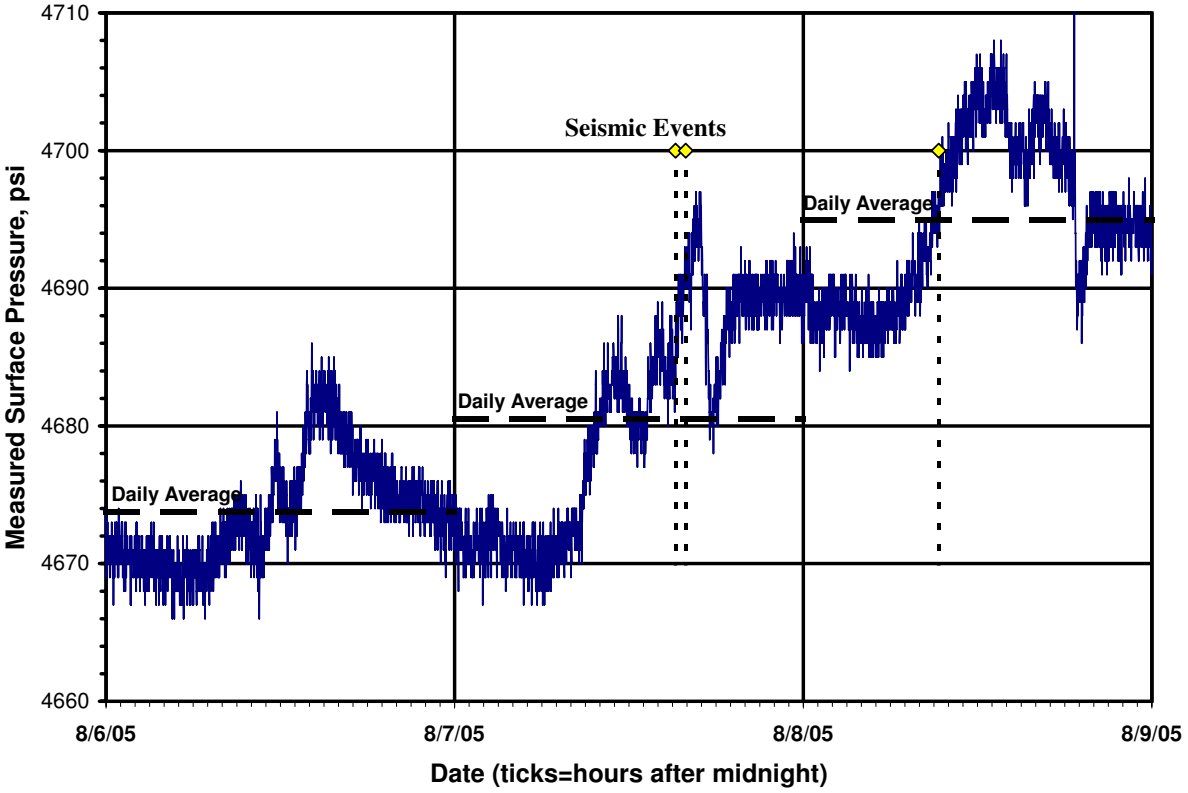


Figure 8-2 Comparison of 1-Second Sampled Pressure (blue) and (Reported) Daily Averaged Pressure (horizontal dashed) and Occurrences of 3 Seismic Events (diamonds) over a 3-Day Period.

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.

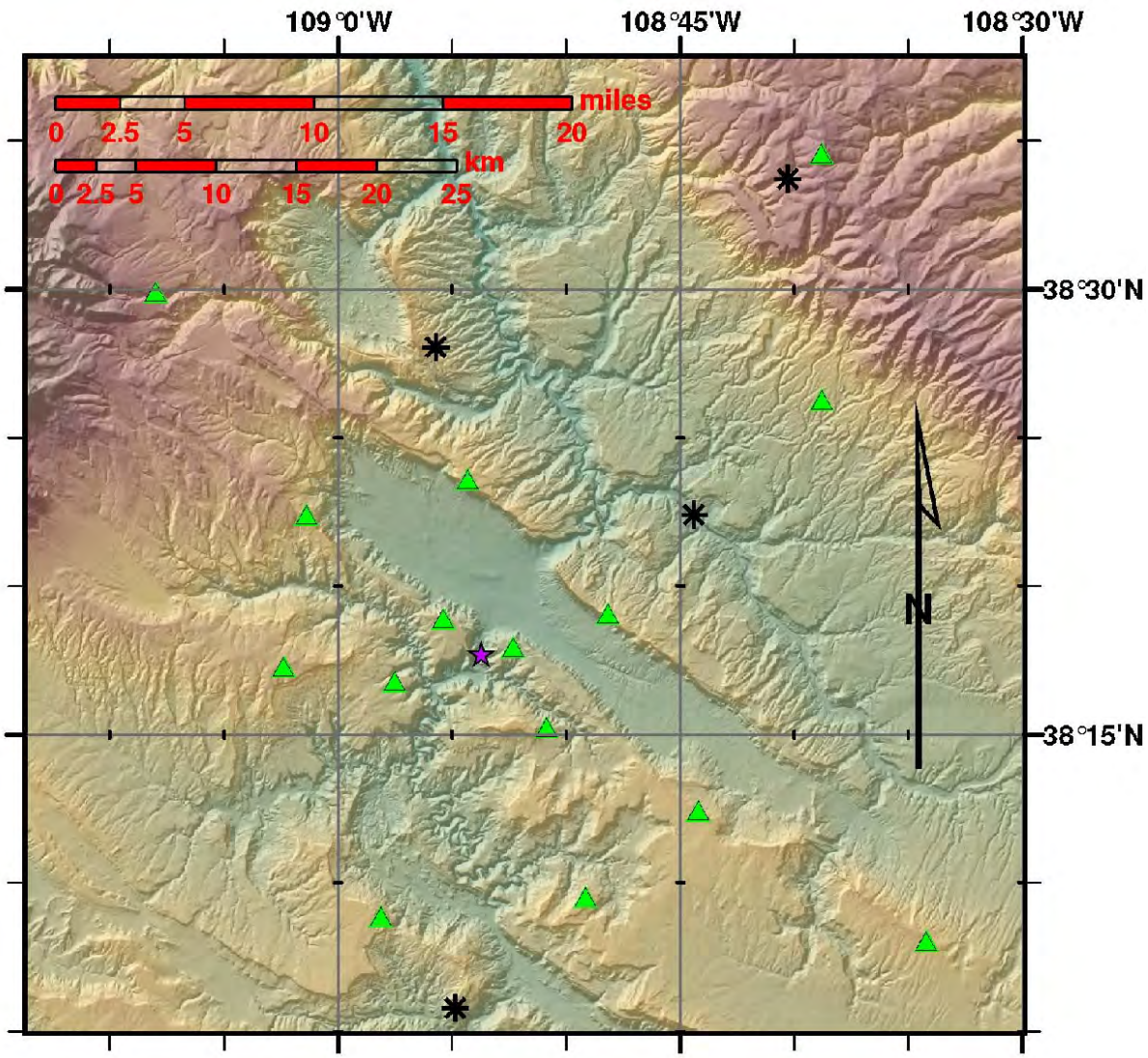


Figure 9-1 Paradox Region Natural Seismicity Recorded in 1985-1991. Asterisks are the epicenters of the natural seismicity, triangles show PVSN sites (active during 2007), and the star is the injection well.

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 Event
	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.

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 (Enviro-

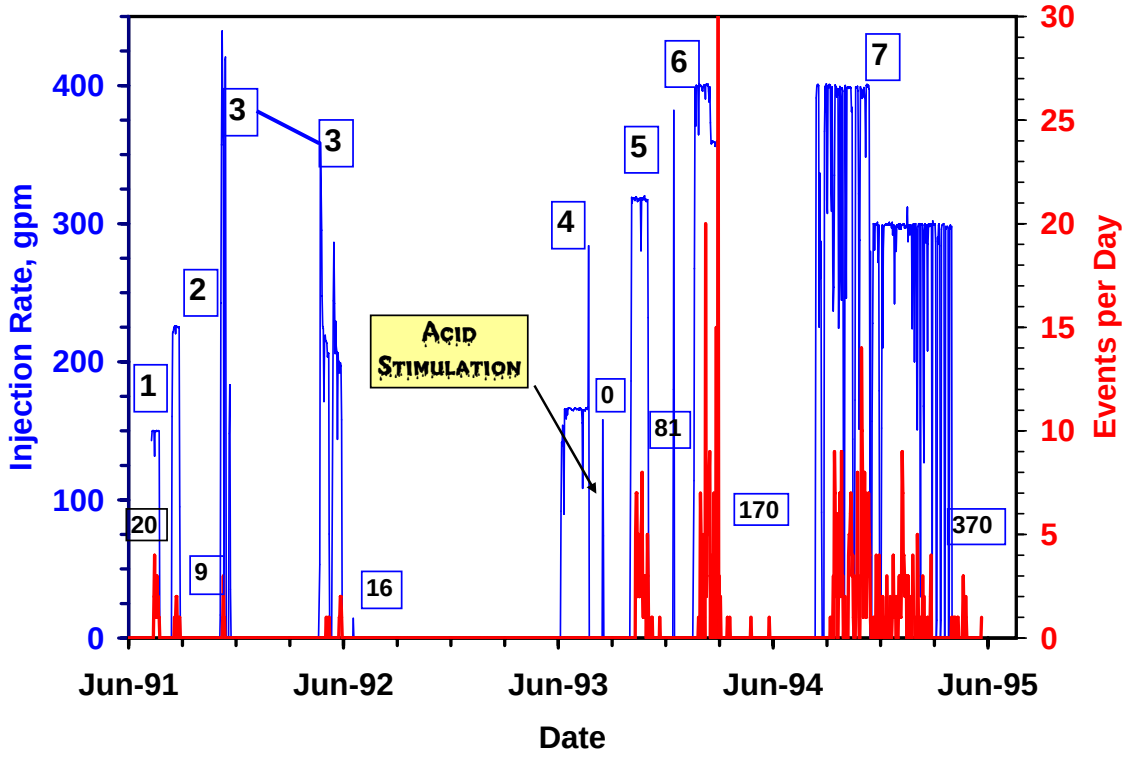


Figure 9-2 Injection Rate (blue lines) and daily number of Injection-Induced Seismic Events (red lines) for Tests. The boxed numbers at the top of the figure identify the tests; the boxed numbers at the bottom of the figure are the number of seismic events recorded during and immediately following the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

corp, 1995). **Figure 9-3** shows the cumulative epicenters induced by the injection tests. The locations in **Figure 9-3** were calculated (in early 2008) using the most recent velocity model and current processing methods.

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

Table 9-2 gives a year-by-year listing of event production since the start of continuous injection. Because of variations in the detection threshold of PVSN over it's operational history, the lowest-magnitude events are not consistently detected for all years. For this reason, only events with magnitudes **M**0 or greater are considered in **Table 9-2** (and in many of the subsequent figures and tables). 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. In addition, because of poor PVSN performance during 2007, the seismicity rate for 2007 was computed for only that portion of the year for which the seismic network was judged to be sufficiently operational (June 11 to Dec. 31; see section 4 for details). As discussed in section 4, the seismic network was almost certainly experiencing performance problems during 2006 also. However, the network performance for 2006 has not yet been evaluated sufficiently to compute a corrected seismicity rate. Hence, the seismicity rate for 2006 listed in **Table 9-2** is very likely underestimated. Ignoring the questionable seismicity rate for 2006 and the initial low seismicity rate for 1996 when continuous injection began (since it took nearly 4 months for the reservoir to

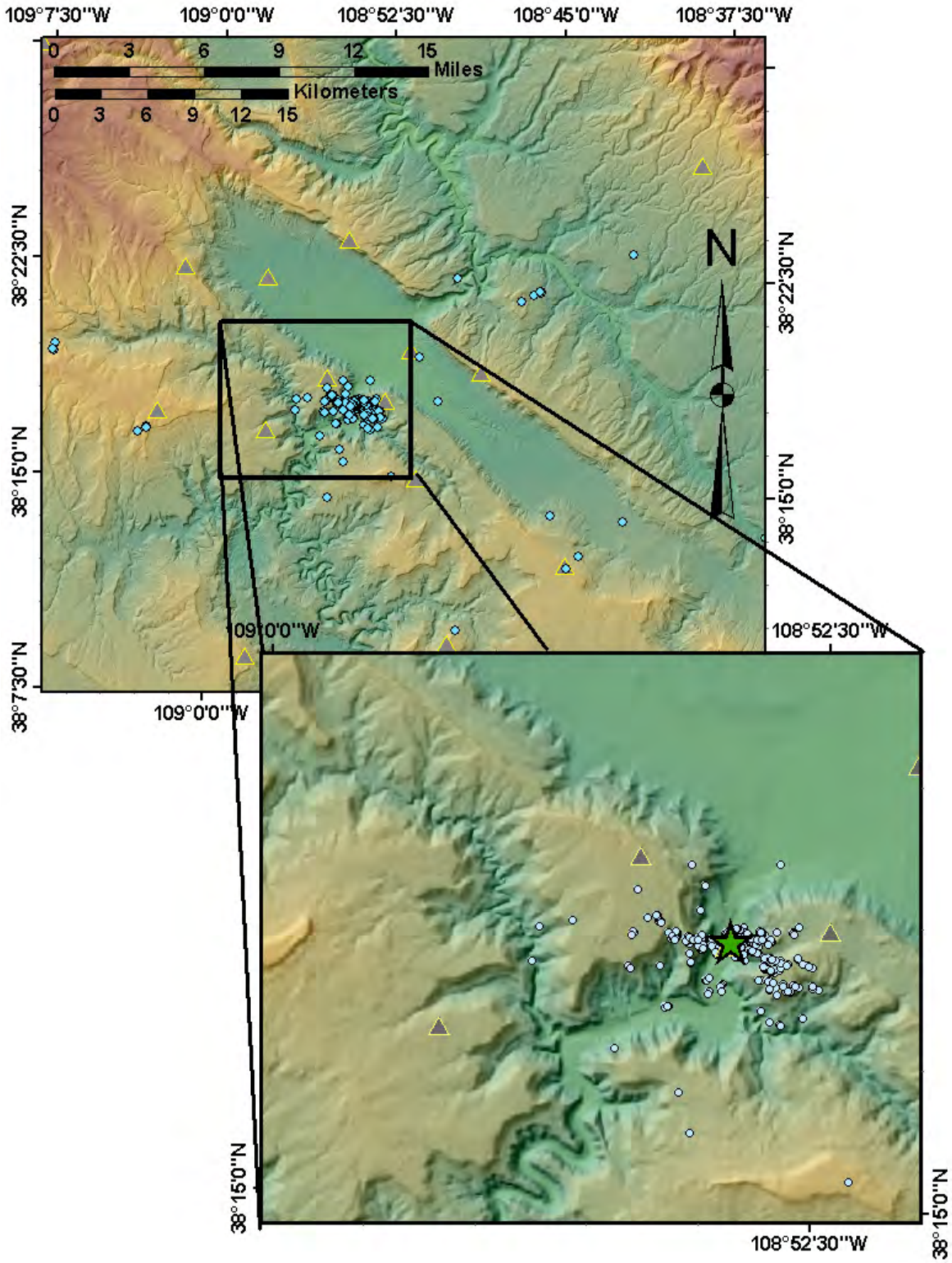


Figure 9-3 Epicenters of Seismic Events Recorded During Injection Tests, 1991-1995. Triangles show the current local stations of PVSN and star is the injection well. Note that many of the events occurring at large distances from the injection well are likely explosions that have not been properly flagged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

Table 9-2 Yearly Event Production for M >= 0

Year	No. of Days of Seismic Monitoring[5]	No. of Induced Events (M >= 0)	Average Events Per Day
1996[1]	224	9	0.04
1997[2]	365	508	1.39
1998	365	1108	3.04
1999	365	1070	2.93
2000	342	282	0.82
2001	365	81	0.22
2002	360	58	0.16
2003	350.5	134	0.38
2004	350	106	0.30
2005	331	101	0.31
2006[3]	318	25	0.08
2007[4]	178	22	0.12

[1] The rate for 1996 was computed for a partial year, starting on May 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 is believed to be biased low, because of poor network performance during part of the year; see section 4 for details.
[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 section 4 for details.
[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 2002-2007 (as listed in Table 6-3). 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.

re-pressurize and start inducing seismicity), the seismicity rate for 2007 is the lowest rate observed during continuous injection operations at PVU.

Table 9-3 presents the seismicity rate data by PVU injection phase (see section 7 for a description

Table 9-3 Event Production by Injection Phase for M >= 0

Phase	Dates	Duration	No. of Days of Seismic Monitoring[1]	No. of Induced Events (M >= 0)	Avg. Events per Day	Injected Volume
		Days				Mgal
I	5/22/96 - 7/26/99	1161	1161	2453	2.11	427
II	7/27/99 - 6/22/00	332	320	398	1.24	118
III	6/23/00 - 1/7/02	564	552	207	0.38	156
IV [2]	1/8/02 - 12/31/07	2184	1880.5	446	0.24	593

[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 2002-2007 (as listed in Table 6-3), as well as for the five months of poor network performance during 2007 (see 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.

[2] The number of days of seismic monitoring and corresponding seismicity rate for *phase IV* has not been corrected for the suspected poor network performance in 2006. Therefore, the average daily rate of seismicity may be slightly underestimated.

of the injection phases). **Table 9-3** indicates that injection well shut-downs and reduced injection rate have reduced event production. The number of induced events per day dropped 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 production (for **M** >= 0) 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). **Figure 9-5** and **Figure 9-6** show events per day for PVU operation since 1996 (i.e., continuous pumping) plus average daily injection rate and average daily downhole pressure, respectively.

Figure 9-7 shows the ratio of the cumulative number of induced seismic events to cumulative injection volume (red), a histogram of the events/day (black), and a plot of the average daily downhole injection pressure (blue), each as a function of time since continuous injection began in 1996. The pressure and events/day data are included for reference. The important element of the figure is the ratio, number of events to cumulative volume. From 1996 through mid-1999 the ratio generally increased. (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 decreases through the present.

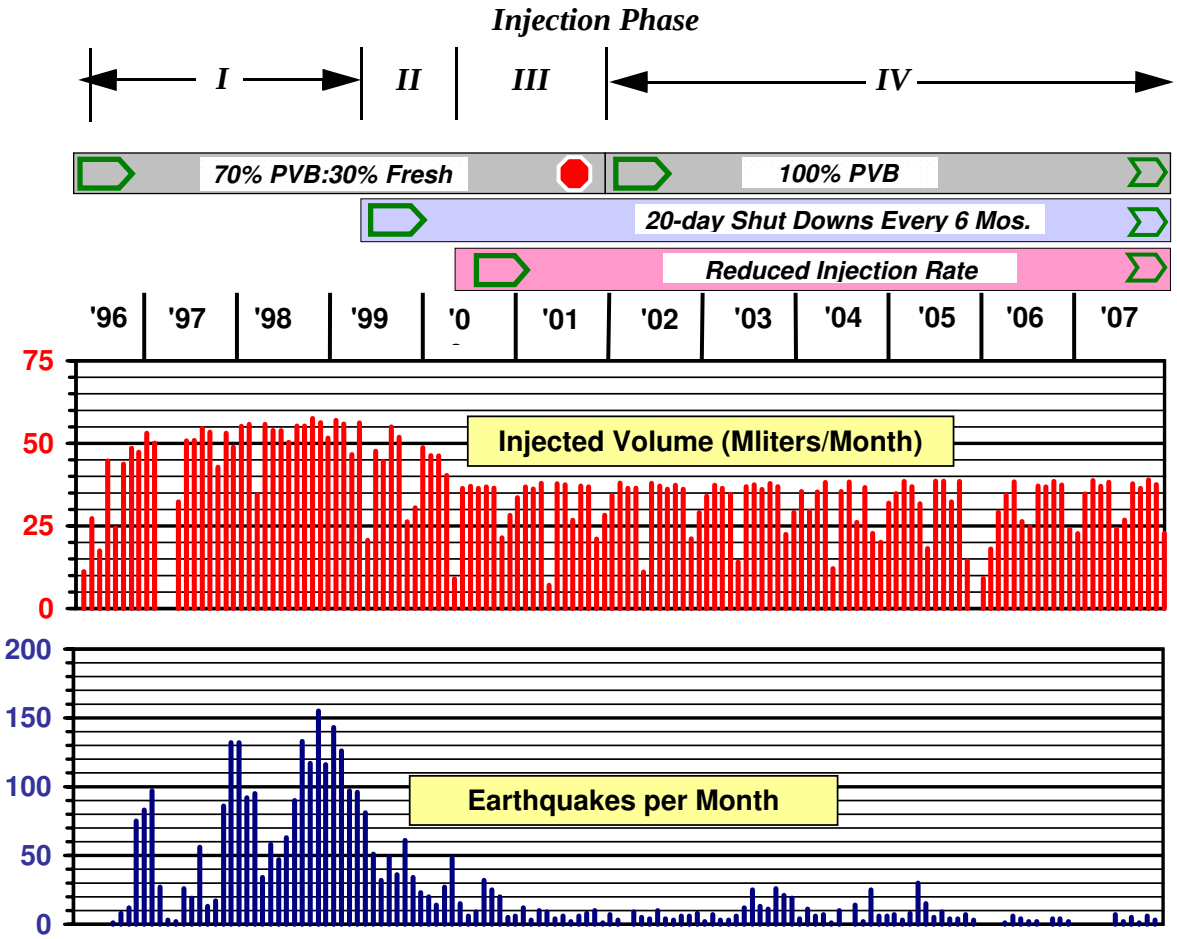


*Figure 9-4 Injection Volume and Monthly Earthquake Production (**M** >= 0) at PVU for Years Since Continuous Injection Began in 1996. At the top note the injection phases and corresponding time bars. From top down the time bars are (1) the change in injectate ratio, (2) the implementation of bi-annual, 20-day shut-downs and, (3) the reduced injection rate.*

Note that the time the ratio peaks correlates with the onset of the bi-annual 20-day 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 function of injection volume.

Figure 9-8 and **Figure 9-9** show events per year and cumulative seismic energy per year, respectively, as functions of the indicated injection parameters. Note that in each figure, there are two groupings of the data, one at the top right and the other at the bottom left. The two data points at the top right are for years 1998 and 1999, the years of maximum injection. The other data points are for years 2000 through 2007. In some cases these data groupings show linear trends. To a limited extent, these linear trends may potentially be used as predictors of future behavior. However, in any figure, the closer these groupings lie directly above and below each other, the weaker the correlation (i.e., predictability) between the abscissa (i.e. X-axis) and ordinate (i.e., Y-axis) variables; the more laterally displaced these two groups, the better the correlation (i.e., predictability).

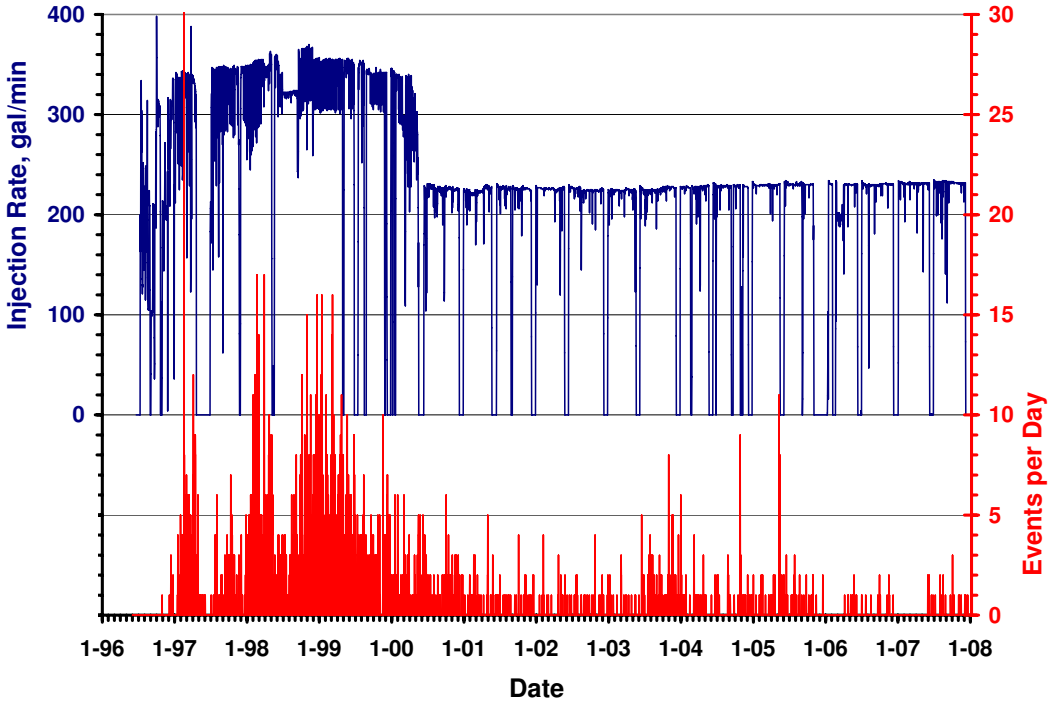


*Figure 9-5 Number of Events per Day (with **M** >= 0; red) and Average Daily Injection Rate (blue) Versus Time.*

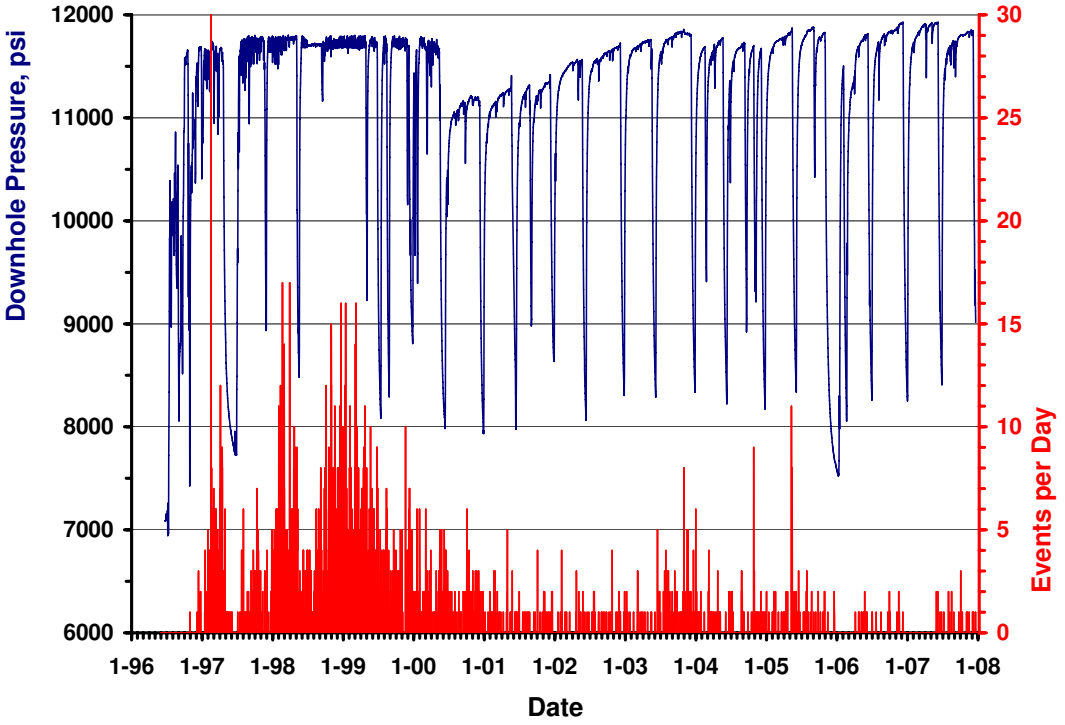


*Figure 9-6 Number of Events per Day (with **M** >= 0; red) and Downhole Injection Pressure (blue) Versus Time. Downhole pressure is calculated for the depth 4.3 km (14,080 ft) below the wellhead.*

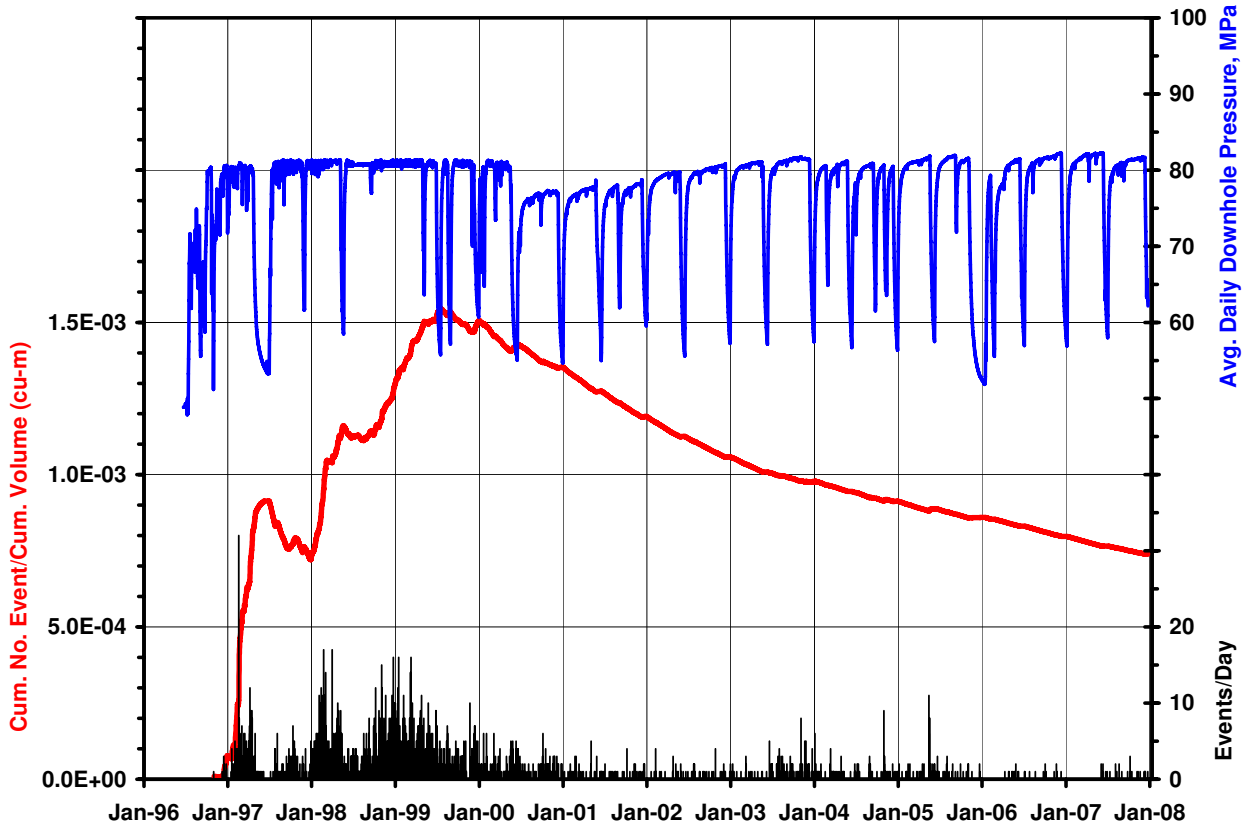


Figure 9-7 Ratio of Cumulative Number of Seismic Events to Cumulative Injection Volume (red line) Versus Time with Additional Curves of Events/Day (black histogram) and Average Daily (Calculated) Downhole Pressure (blue), both Versus Time.

Specifically, in **Figure 9-8**, the best correlations are with figures (b) and (d), the annualized injection volume and the annualized injection energy, respectively. In **Figure 9-9**, the best correlations of seismic energy are, again, with the annualized injection volume and the annualized injection energy. (Note, the injection energy is called "averaged" since it is proportional to the product of the injection pressure and injection volume; both pressure and volume are reported to us as an averaged value per day.)

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 km and a smaller secondary zone, located 6 to 8 km northwest of the injection well (**Figure 9-10**). 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 second-

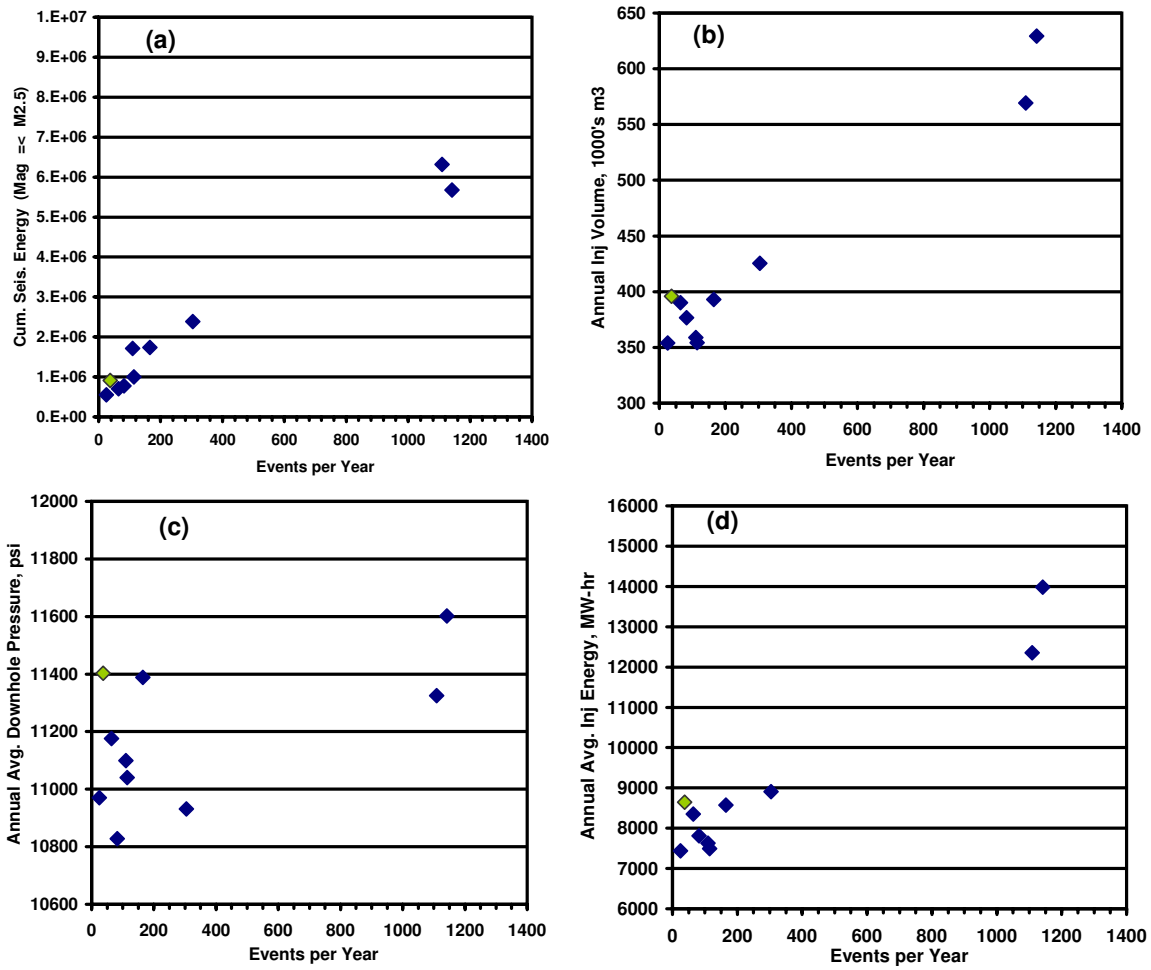


*Figure 9-8 (a) Cumulative Seismic Energy for All Events **M**2.5 and smaller; (b) Annual Daily-Averaged Injection Volume in 1000's of cubic meters; (c) Annualized Daily-Averaged Downhole Pressure in psi; and (d) Annualized Daily-Averaged Injection Energy in megaWatt-hour as a function of Total Number of Injection-Induced Seismic Events per Year for Each Year, 1998 Through 2007. In each figure, the lime-colored diamond is for 2007; the two events at the top right are years 1998 and 1999.*

ary 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 9-11** to **9-22**. 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 9-10**) 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

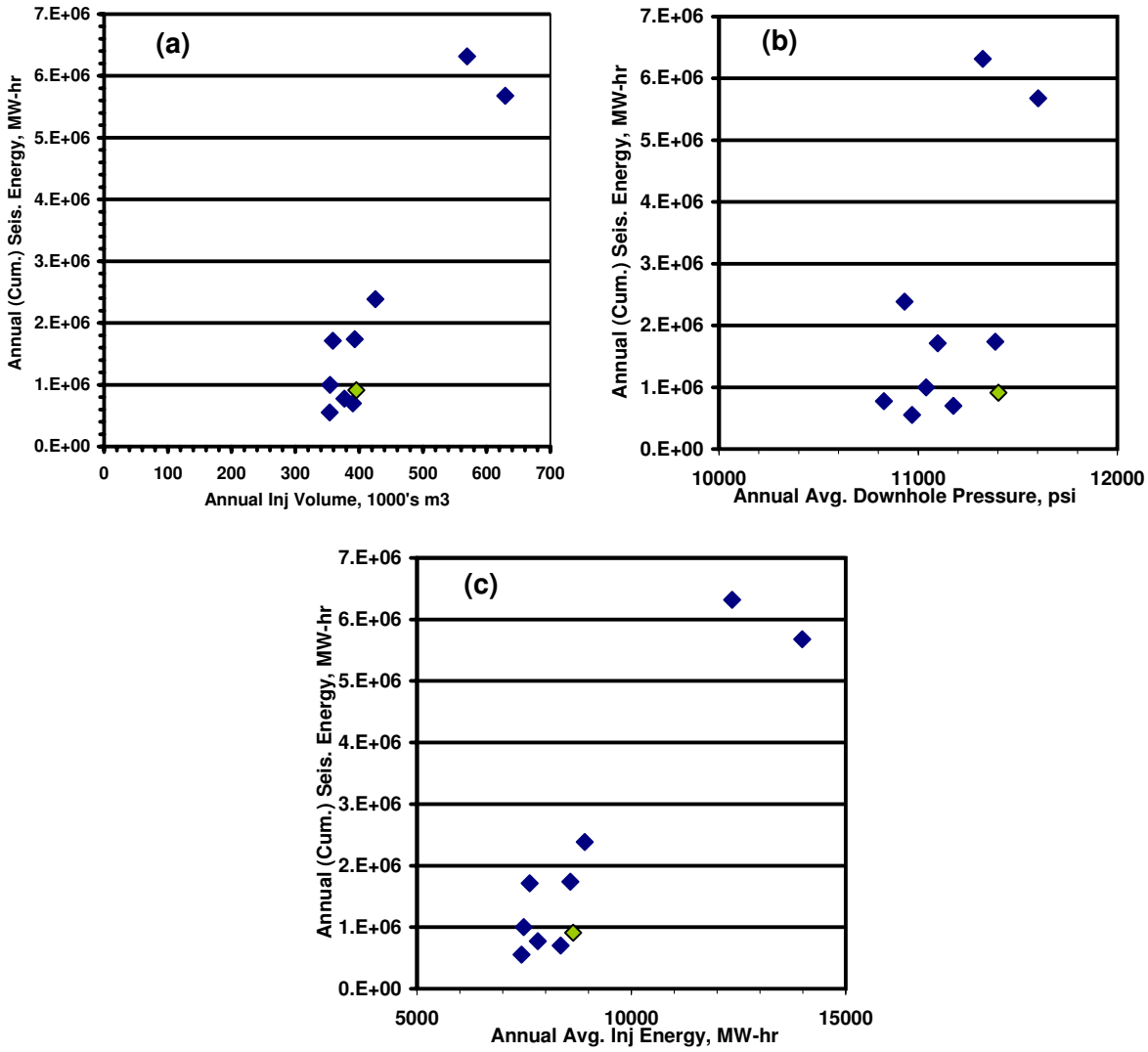


*Figure 9-9 Cumulative Annual Seismic Energy for Events with Magnitude **M**2.5 and smaller from Years 1998 Through 2007 as a function of (a) Annual Daily-Averaged Injection Volume in 1000's of cubic meters; (b) Annual Daily-Averaged Downhole Pressure in psi; and (c) (Cumulative) Annual Daily-Averaged Injection Energy in megaWatt-hour. In each figure the lime event is for 2007; the two points at the top right are for years 1998 and 1999.*

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 ~N55ºW. 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 9-10** suggests communication through conduits in a ~N55ºW direction. We believe this behavior suggests that fluid is being preferentially carried

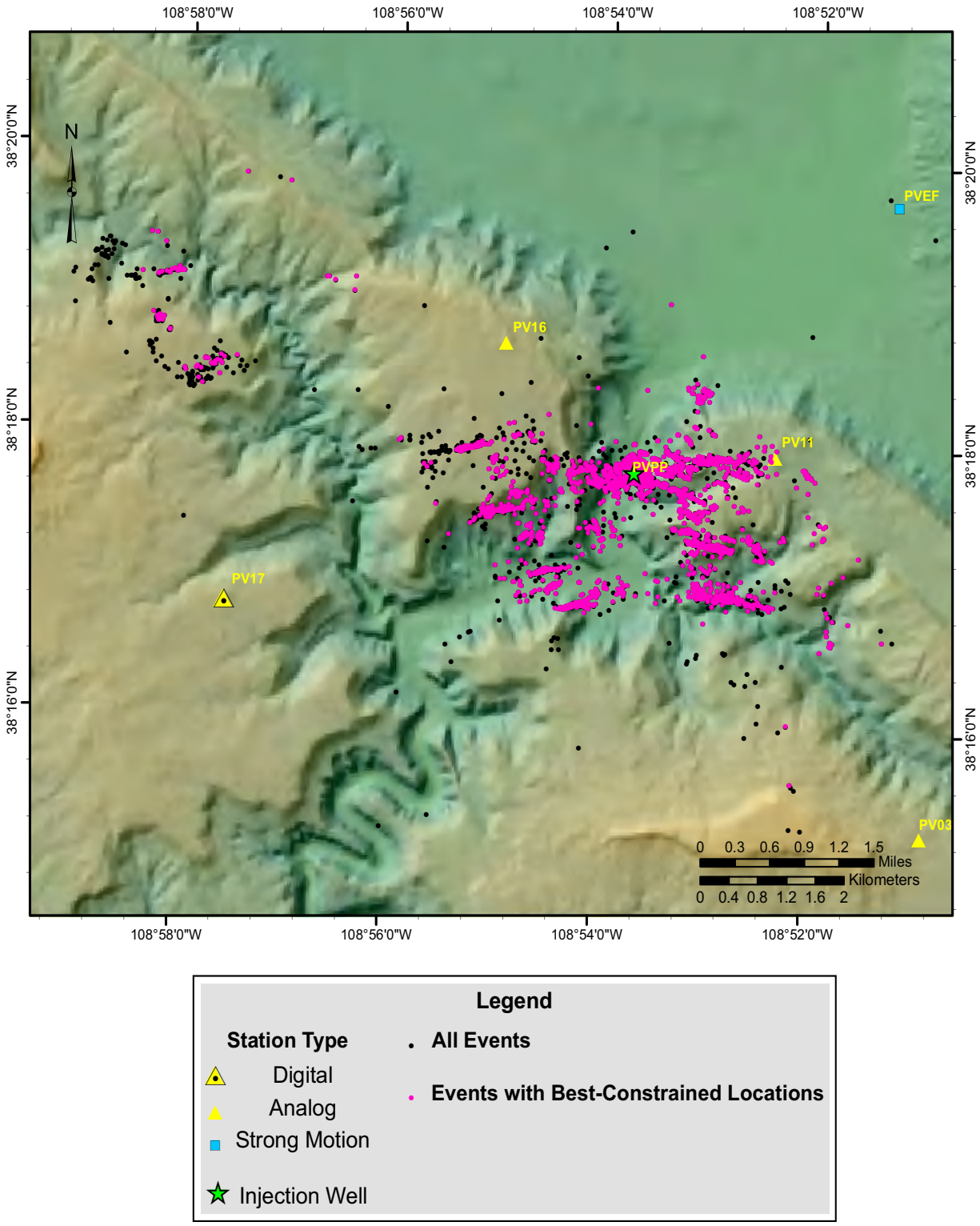


Figure 9-10 Epicenters of earthquakes recorded from 1991 through 2007.

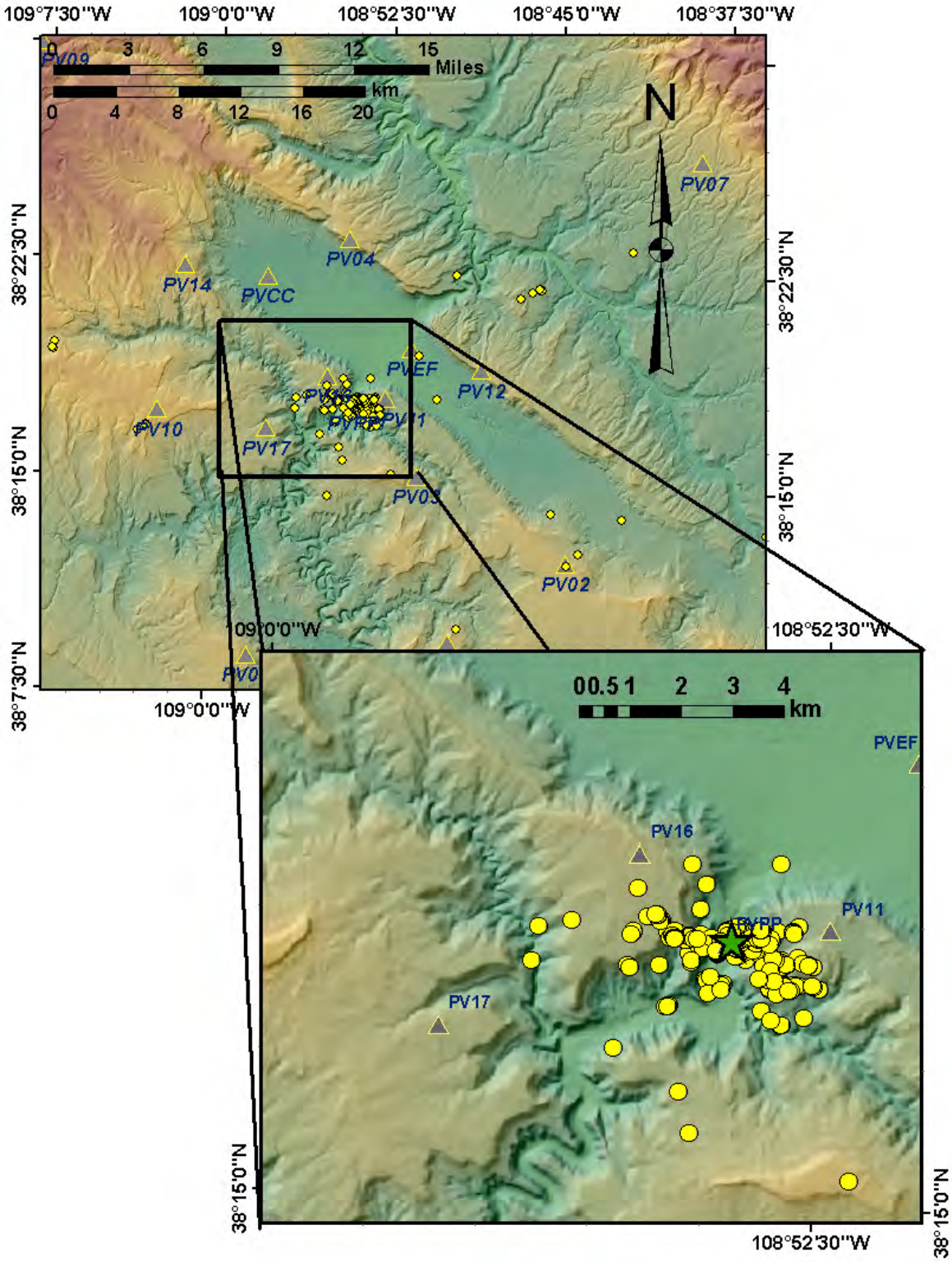


Figure 9-11 1991-1995 Epicenters. Star is injection wellhead.

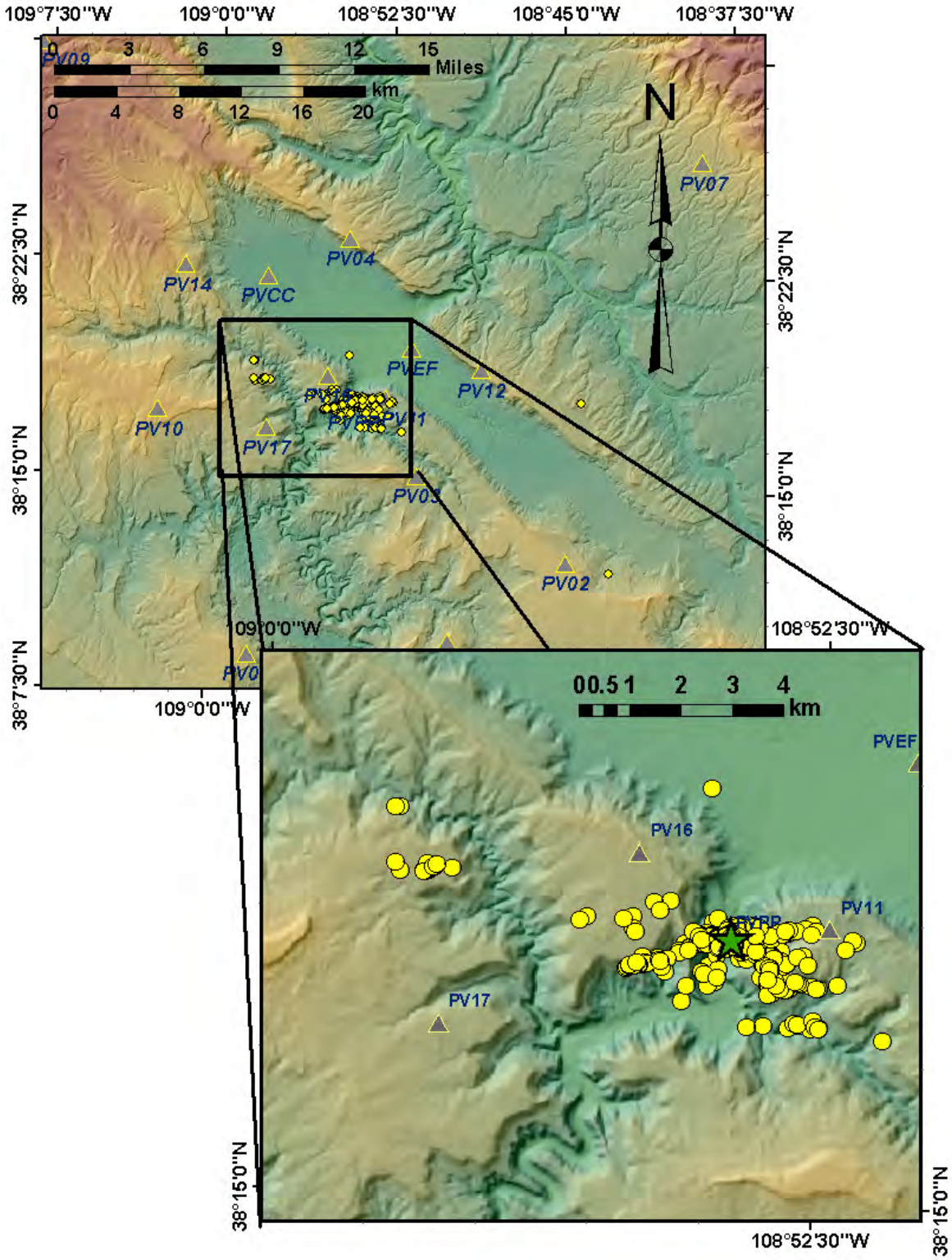


Figure 9-12 1996-1997 Epicenters. Star is injection wellhead.

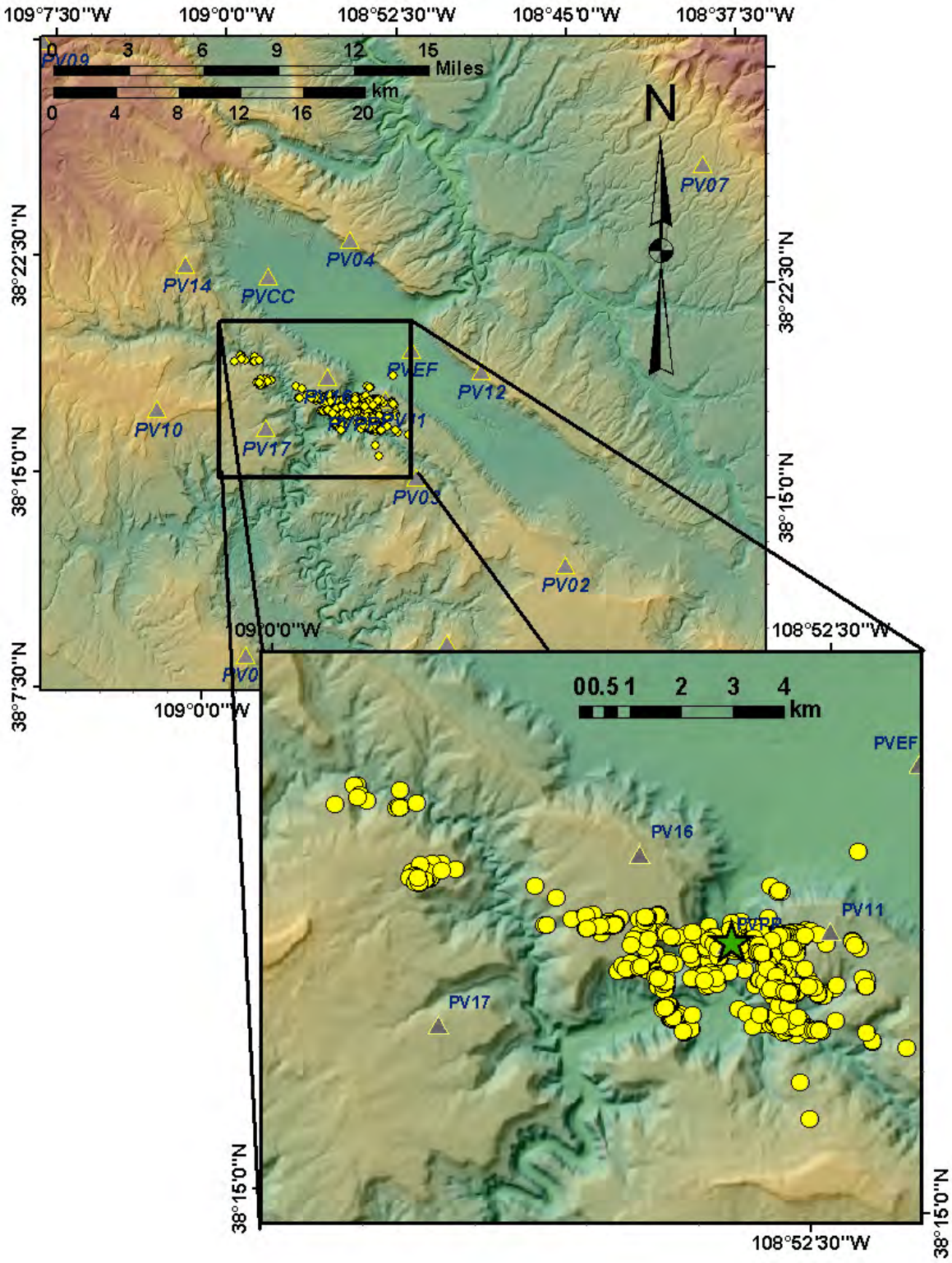


Figure 9-13 1998 Epicenters. Star is injection wellhead.

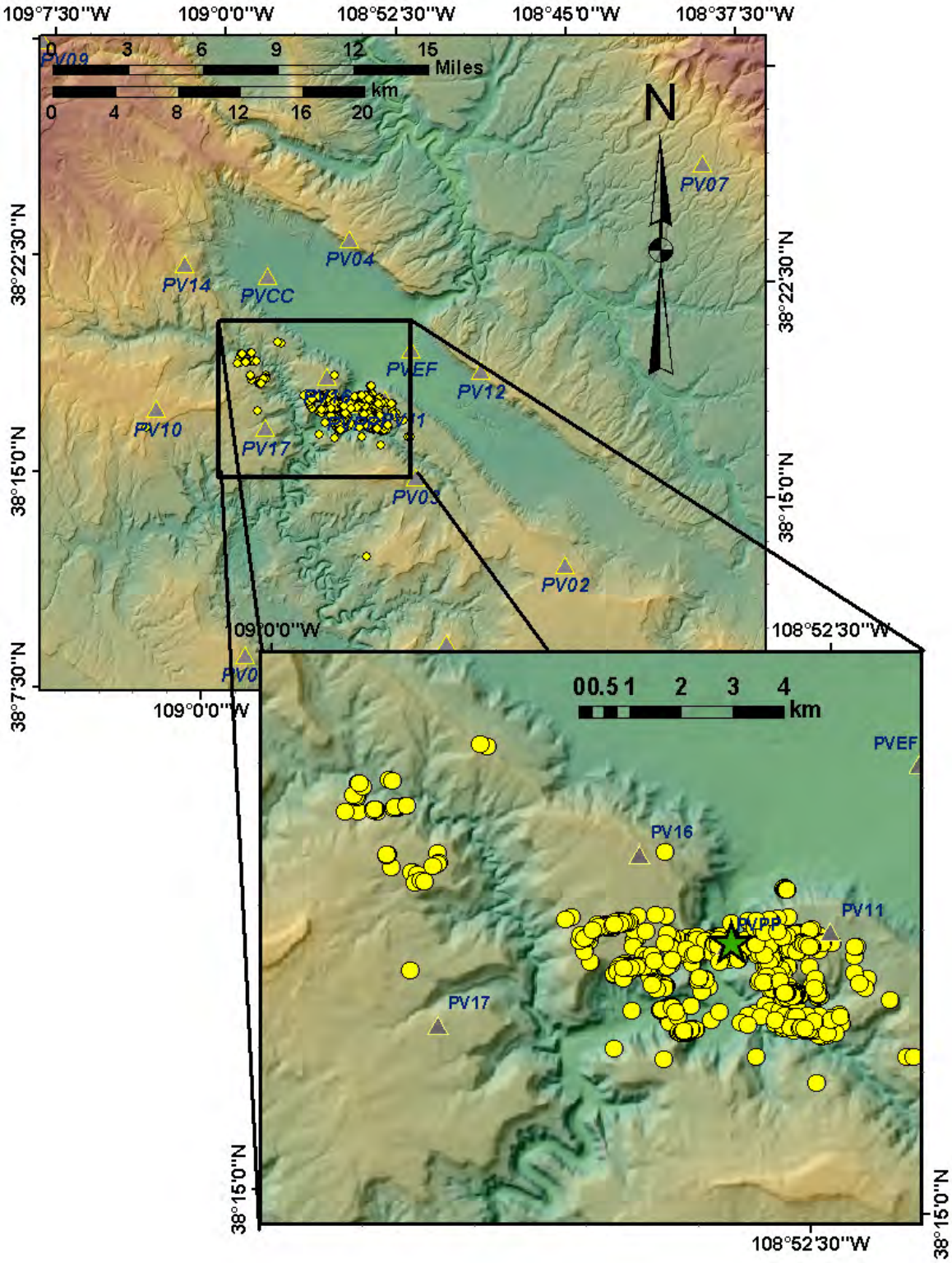


Figure 9-14 1999 Epicenters. Star is injection wellhead.

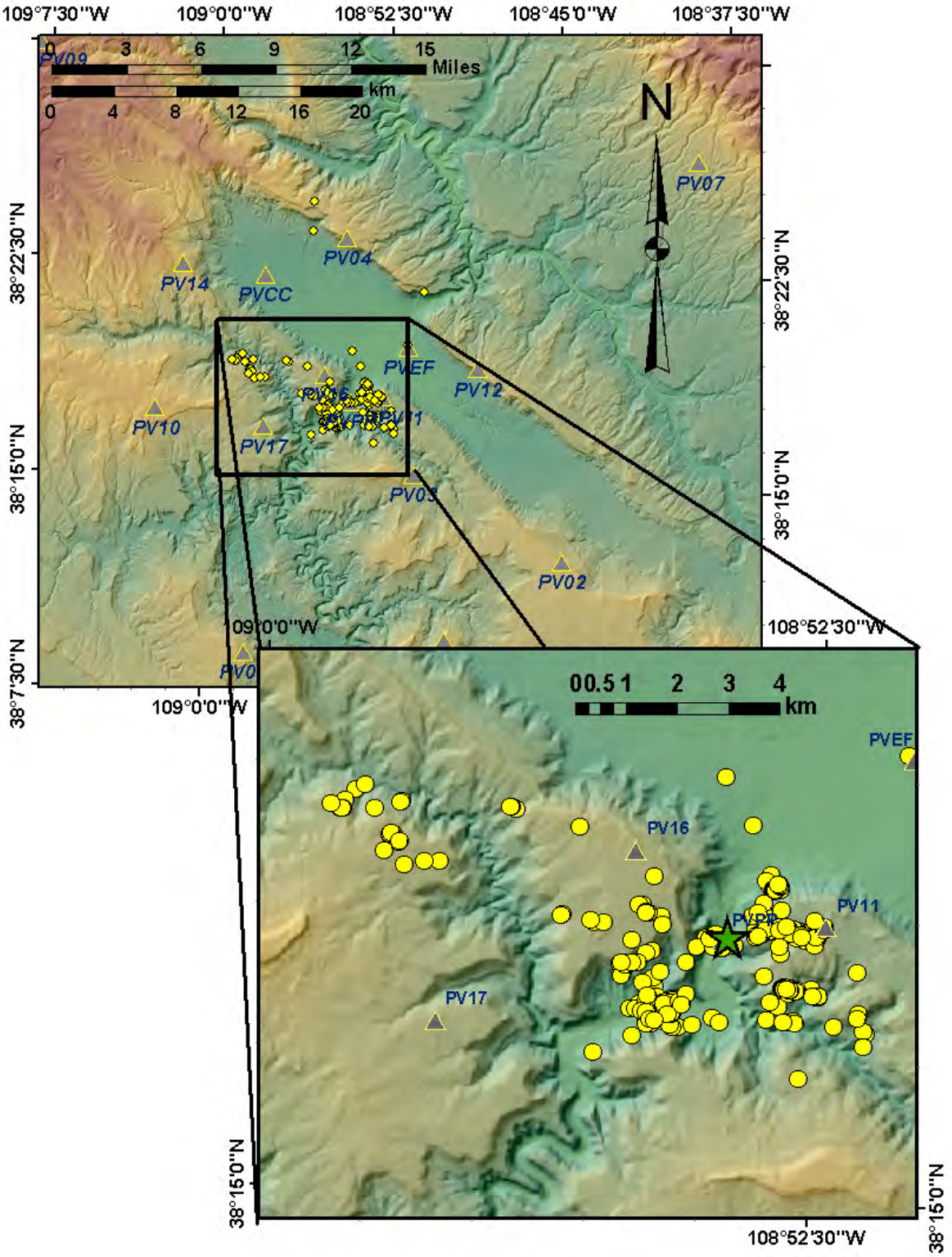


Figure 9-15 2000 Epicenters. Star is injection wellhead.

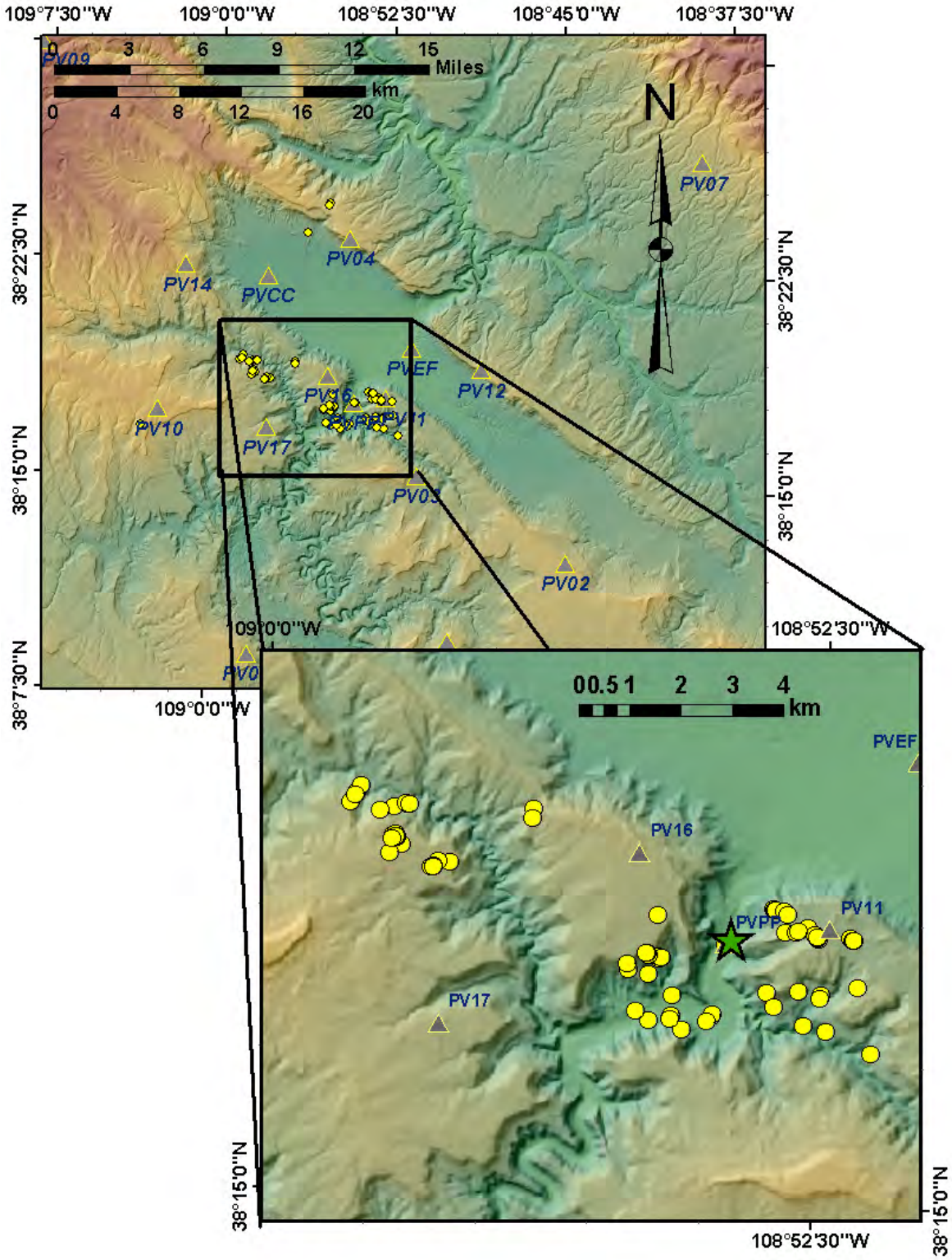


Figure 9-16 2001 Epicenters. Star is injection wellhead.

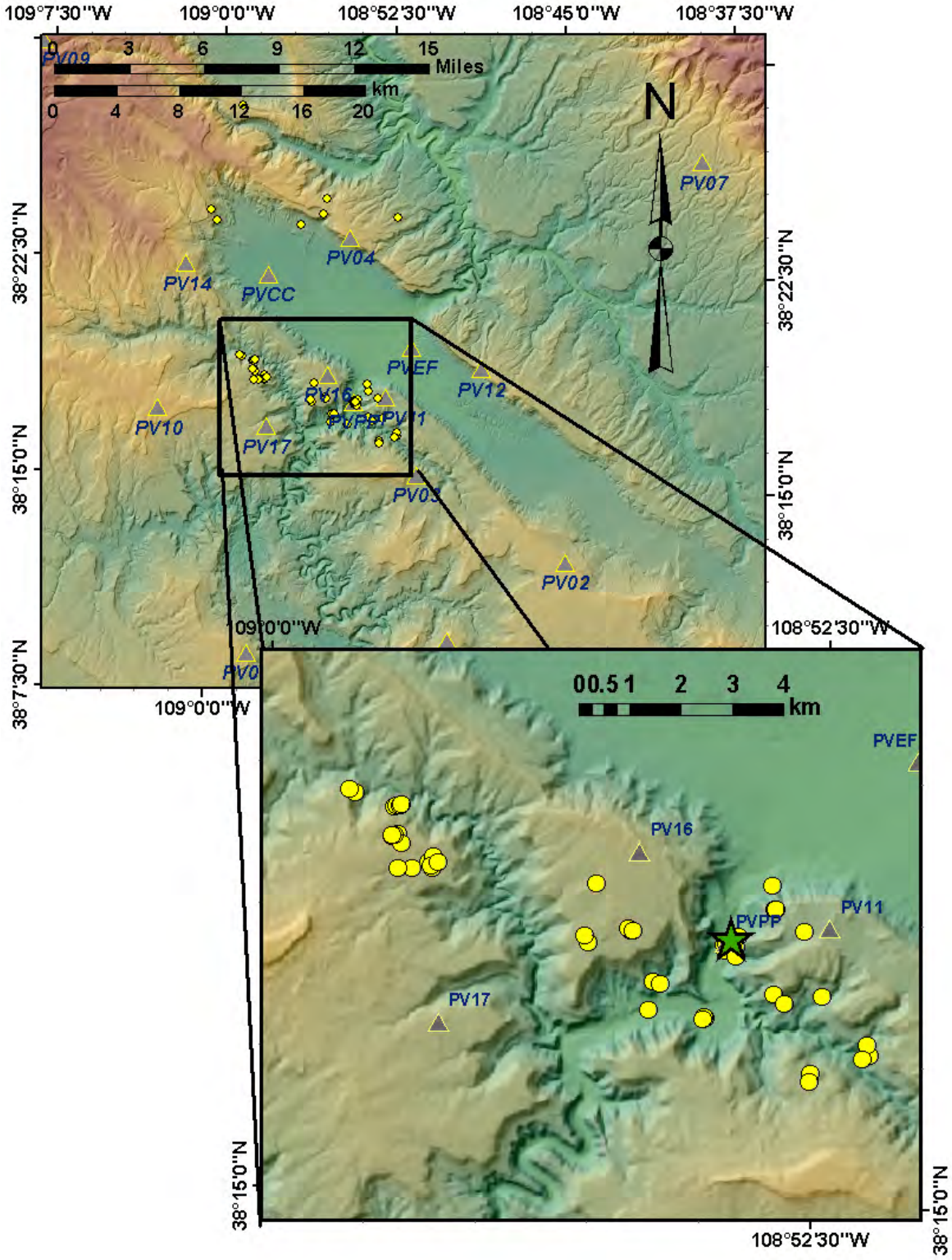


Figure 9-17 2002 Epicenters. Star is injection wellhead.

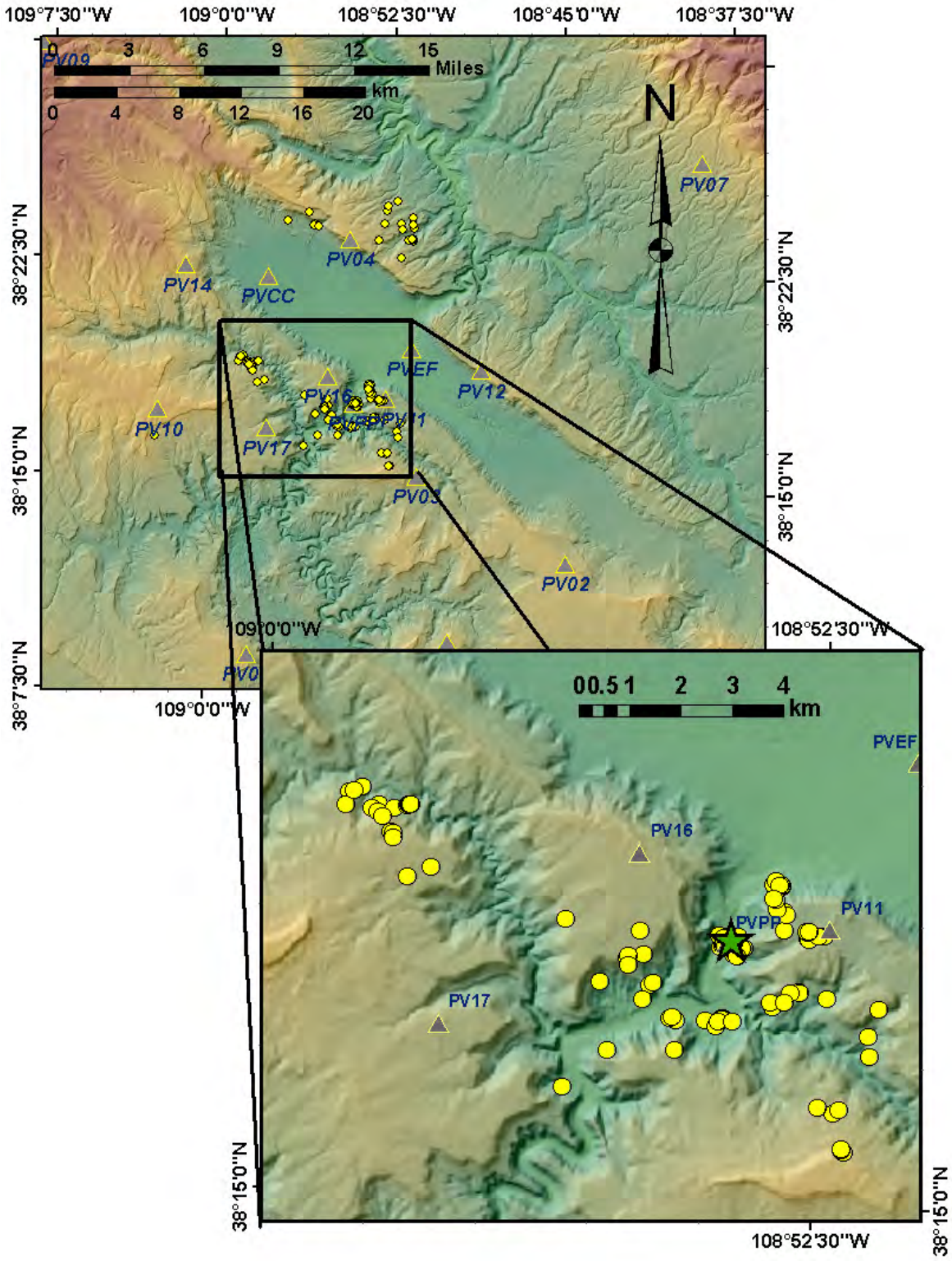


Figure 9-18 2003 Epicenters. Star is injection wellhead.

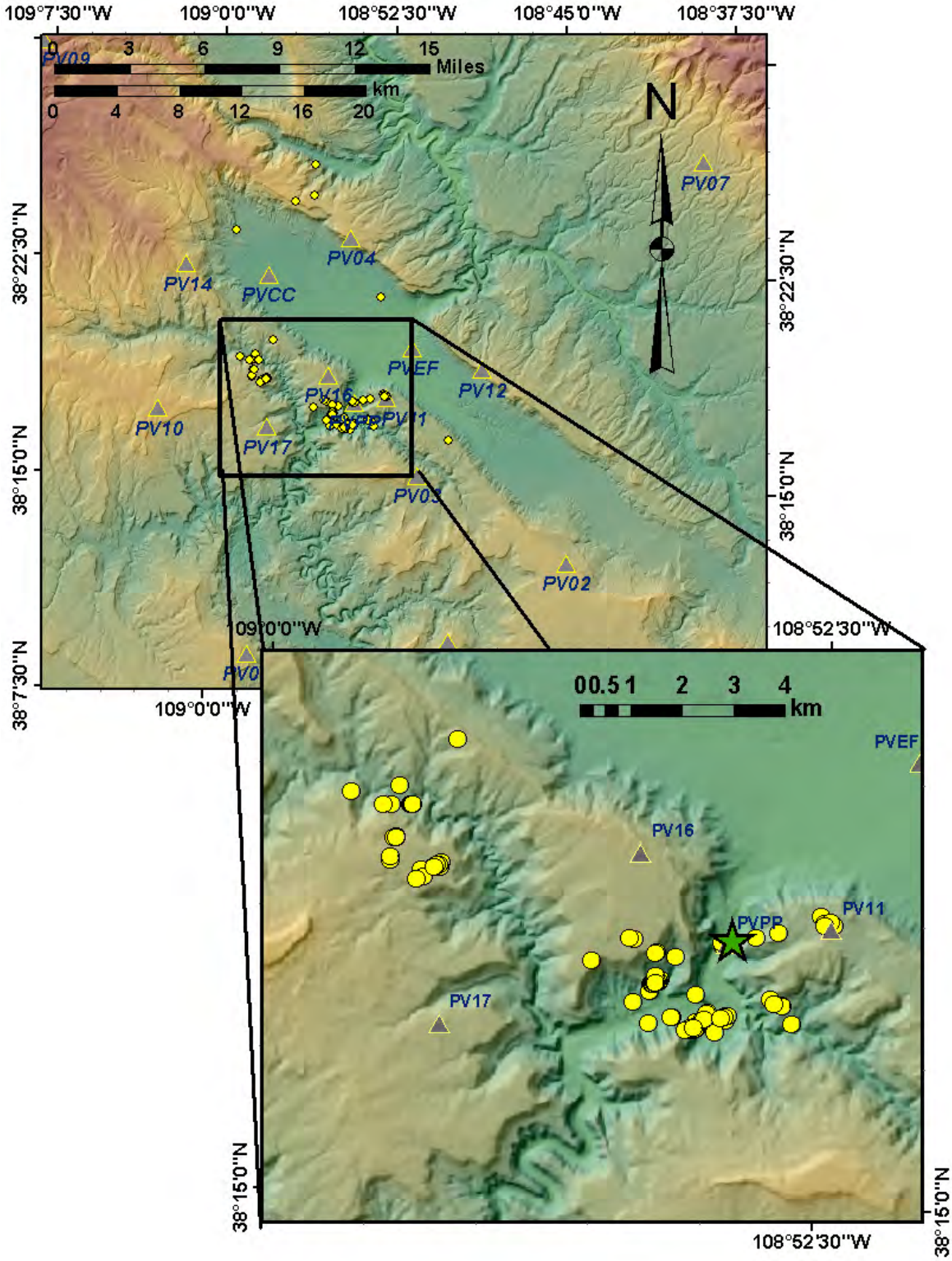


Figure 9-19 2004 Epicenters. Star is injection wellhead.

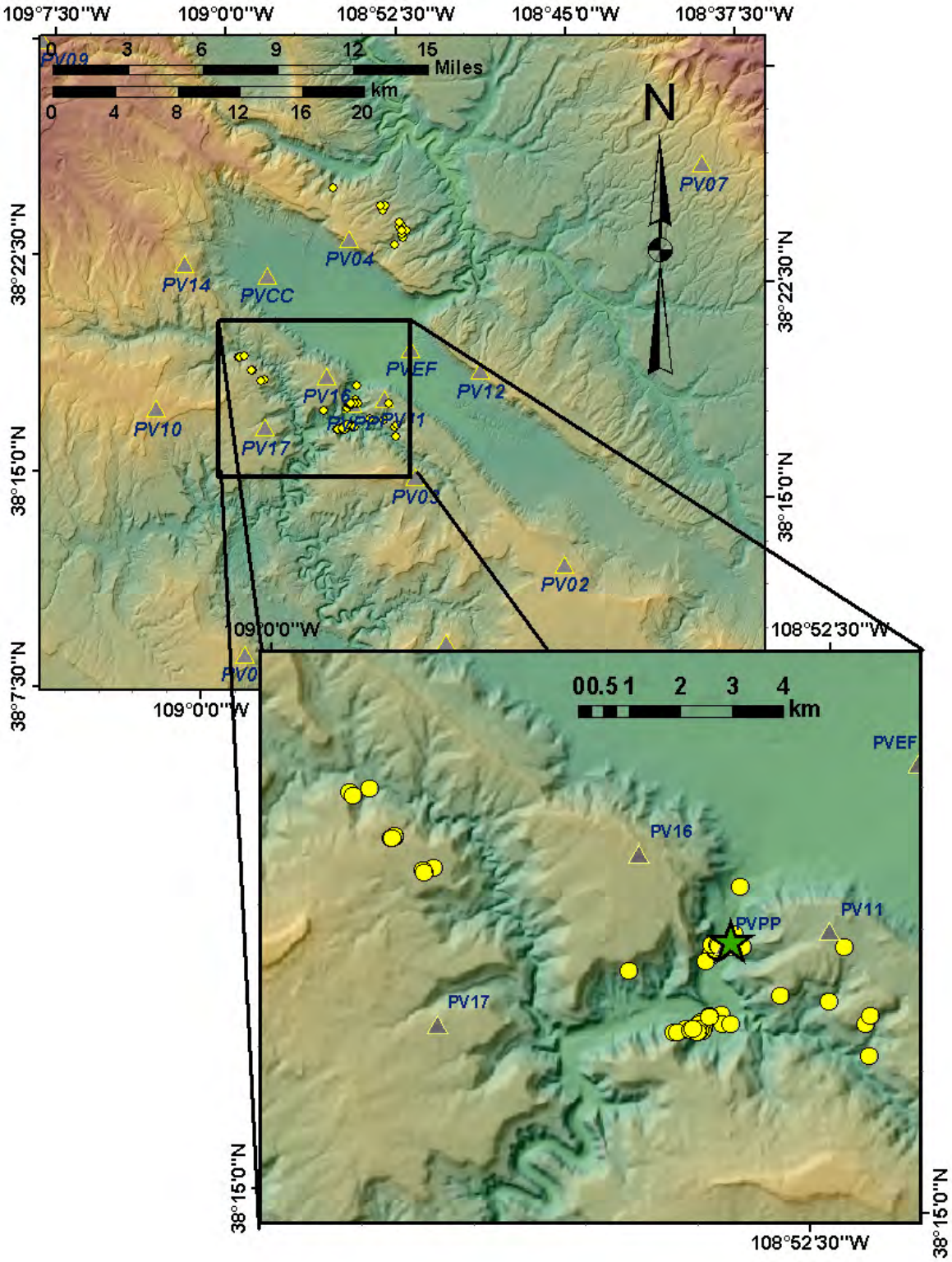


Figure 9-20 2005 Epicenters. Star is injection wellhead

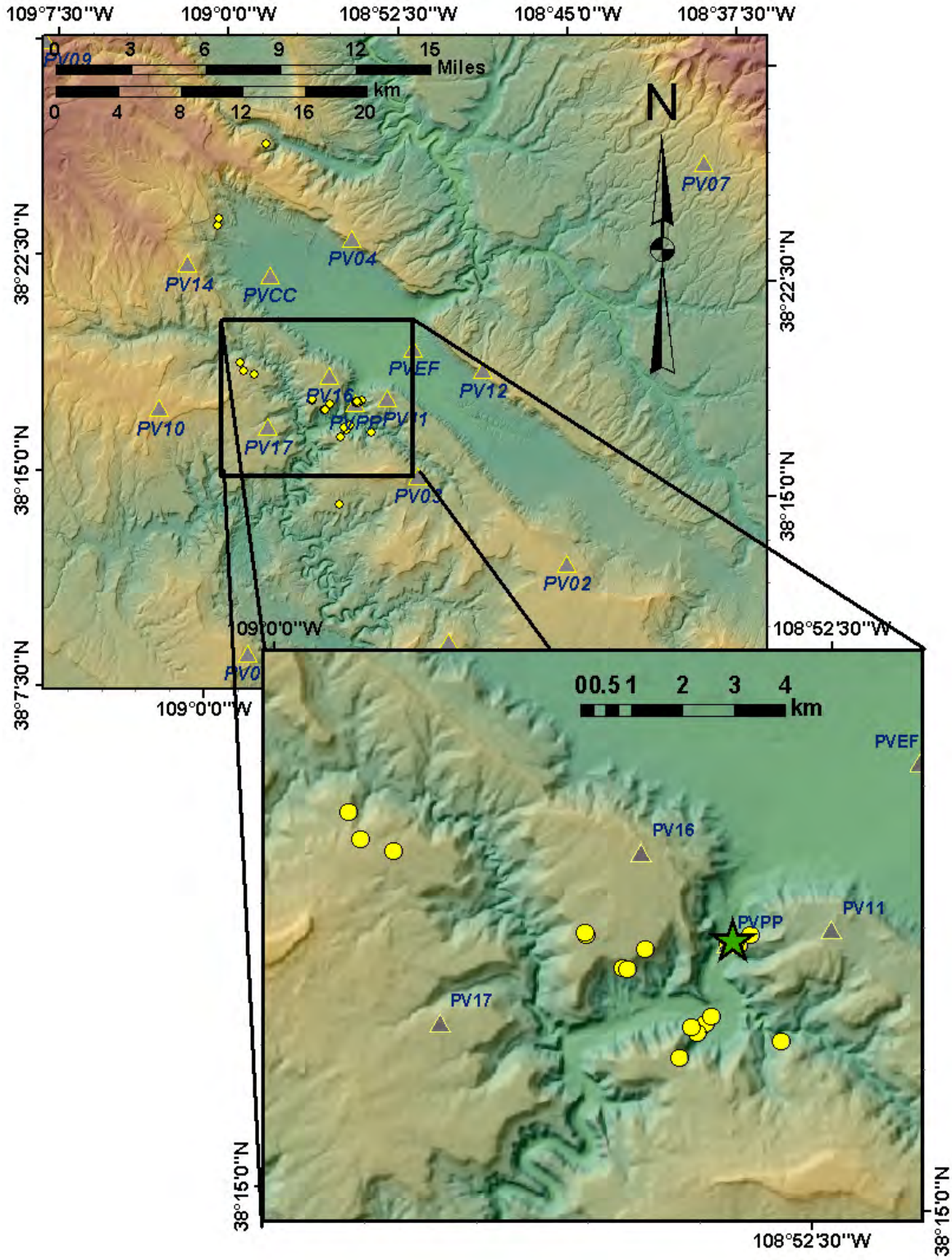


Figure 9-21 2006 Epicenters. Star is injection wellhead

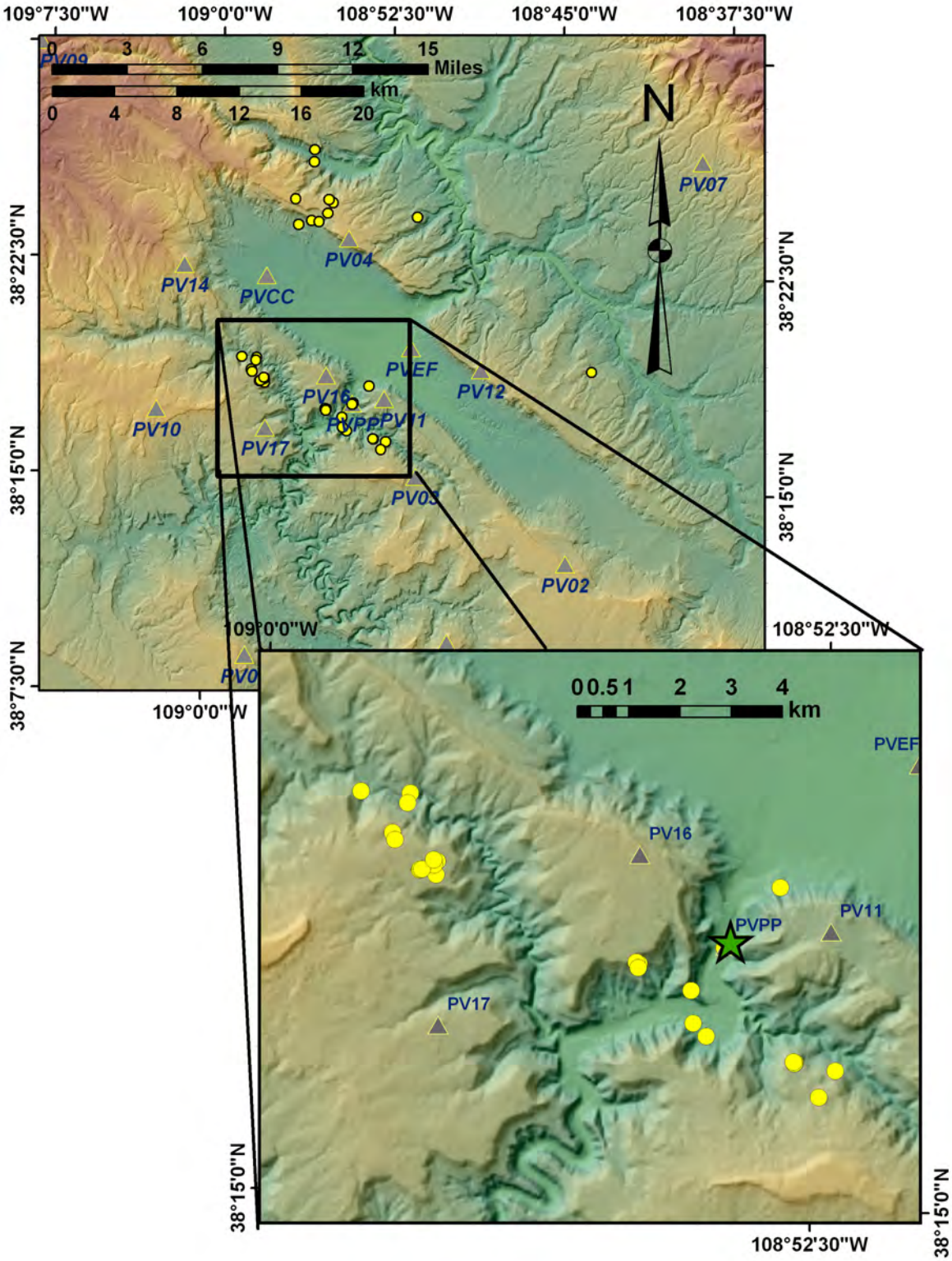


Figure 9-22 2007 Epicenters. Star is injection wellhead

along steep planes of the Wray Mesa fault with a northwest strike (i.e., the through-going elements of the Wray Mesa system and the fault that define the fault block of this region). 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.

Figure 9-23 shows the Paradox epicenters color-coded by depth in kilometers (km) relative to the wellhead. Note that these data show a shallowing of the event depths to the west-southwest, which is consistent with the local geology. This indicates that the seismicity follows both the stratigraphic shallowing and the fault-fracture structure of the Wray Mesa system.

Figure 9-24 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 Harr's (1988) original interpretation and speculation. 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 9-24** shows a number of features. First it shows two vertical groupings of events: one in the Precambrian near the injection well and one starting in the Leadville and rising through the salt about 1.5 km southwest of well. Most likely the second grouping is the actual location of the fault Bremkamp and Harr (1988) speculated to lie about 1.5 km west of the well. **Figure 9-24** 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 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 9-24 shows that a significant number of earthquakes occur below the bottom of the well in the Precambrian basement rocks. In 1998 approximately 18% of the events had depths greater than 4.8 km relative to the wellhead, the depth to the top of the Precambrian at the well. During 1999, 24% were below this depth horizon. In 2000, before the May 27th event, 30% of the events were below this depth horizon. After pumping resumed at a reduced injection rate in June, 16% were below this depth. In 2001, 35% were below 4.8. In 2002, about 34 of the 59 (relocated) events or 58% were 4.8 km or deeper. In 2003, 38 of the 138 (relocated) events or 28% were 4.8 km or deeper. In 2004, 11 of the 106 (relocated) events or 10% were 4.8 km or deeper; in 2005, 9 of the 101 (relocated) events or 9% were 4.8 km or deeper; in 2007, 4 of the 25 (relocated) events or 16% were 4.8 km or deeper. Note that since the Precambrian shallows to the west, these numbers represent a minimum number of events in the Precambrian.

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 mecha-

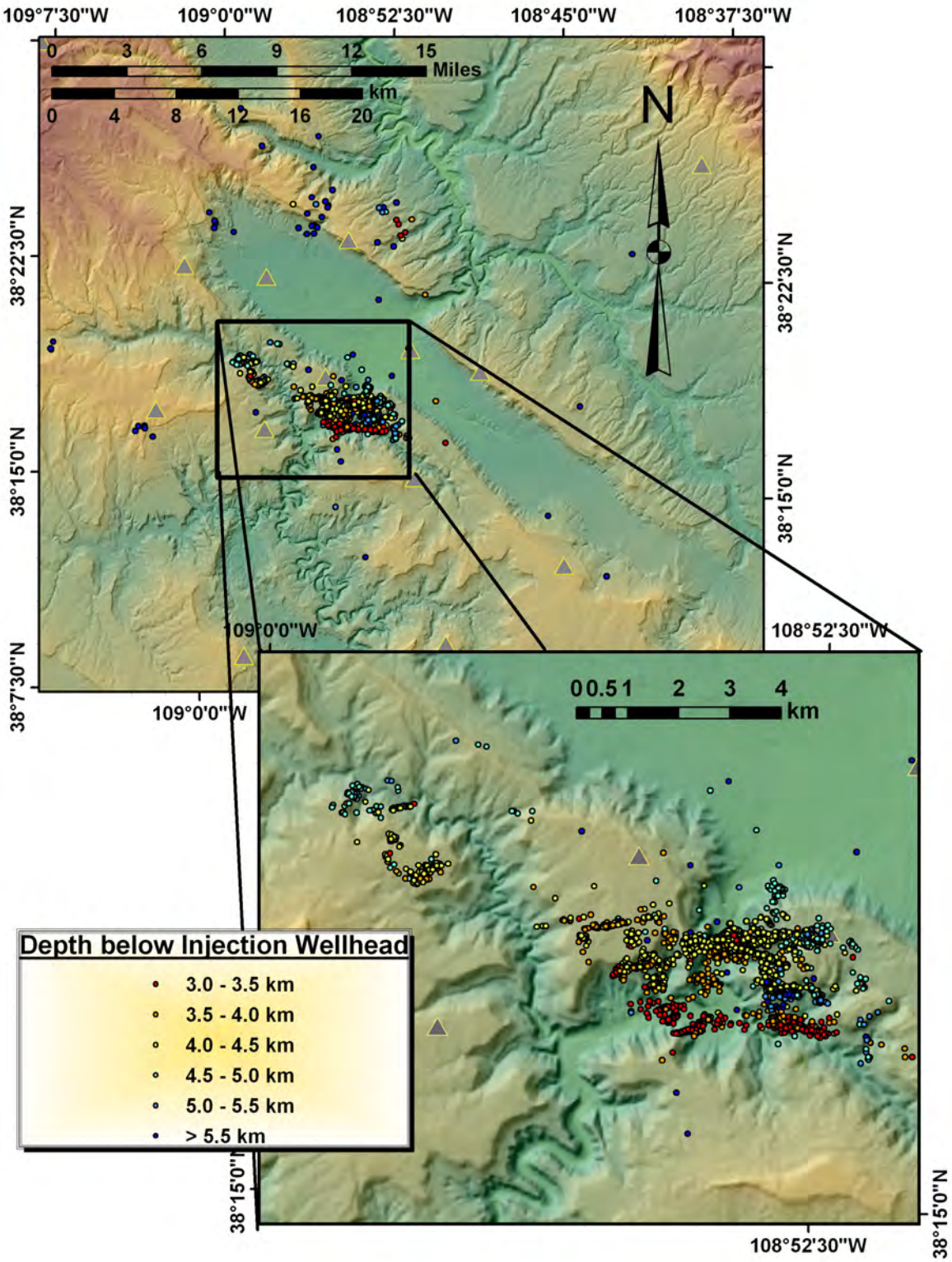


Figure 9-23 1991-2007 Epicenters Color-Coded by Depth, in Kilometers, Relative to Ground Surface [i.e., Injection Wellhead (star)].

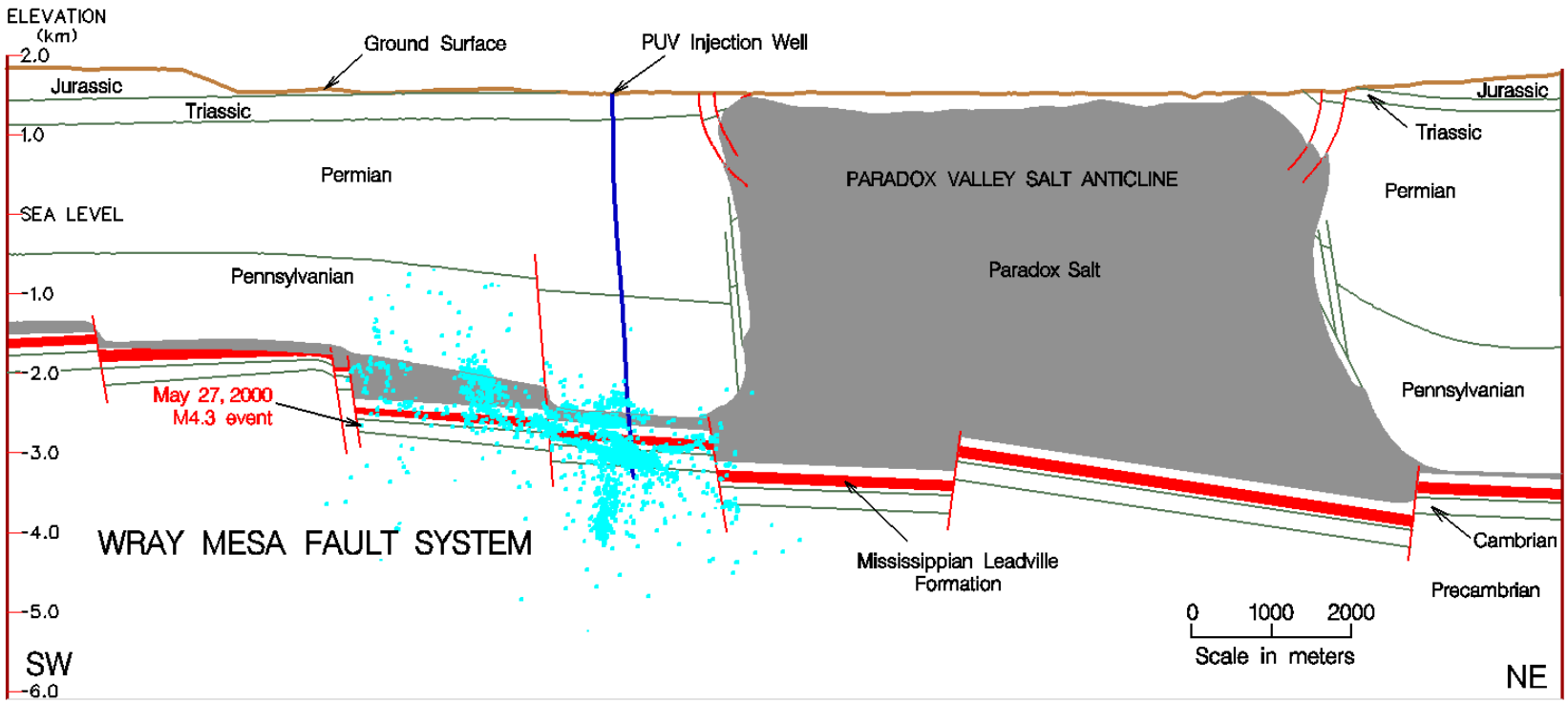


Figure 9-24 Bremkamp and Harr (1988) Cross Section Interpretation of Paradox Valley and Bordering Stratigraphy. Section passes through PVU injection well and runs normal to strike of the valley. Projected on to cross section are seismic events (1991-2002) within 1.5 km of the viewed plane.

nisms 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., standard deviation = 19 deg.) and 311 degrees (mean = 311 deg., 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 9-10**). 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

The larger-magnitude induced seismic events are not uniformly distributed throughout the two seismic source zones, but preferentially occur on some fault segments. **Figure 9-25**, **Figure 9-26,** and **Figure 9-27** show all events with magnitudes **M**1.7 and greater plotted against a background of all the events. **Figure 9-25** is a plan view and **Figure 9-26** and **Figure 9-27** are depth cross sections looking north and west, respectively. (The depth sections indicate horizontal stratigraphic bedding. The bedding is not horizontal at Paradox; these beds are drawn based on depths of the stratigraphic layers as measured at the wellbore.) 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 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 yet 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 Felt Events

By the end of 2007, PVSN recorded more than 4,300 seismic events attributed to the PVU injection. Of these, more than 99.5% were imperceptible (i.e., magnitude < **M**2.4) to people at the surface. From 1991 to 1996 no events were reported felt. Between August, 1997 (i.e., the first reported felt event) and the end of 2007, about 20 felt events were reported.

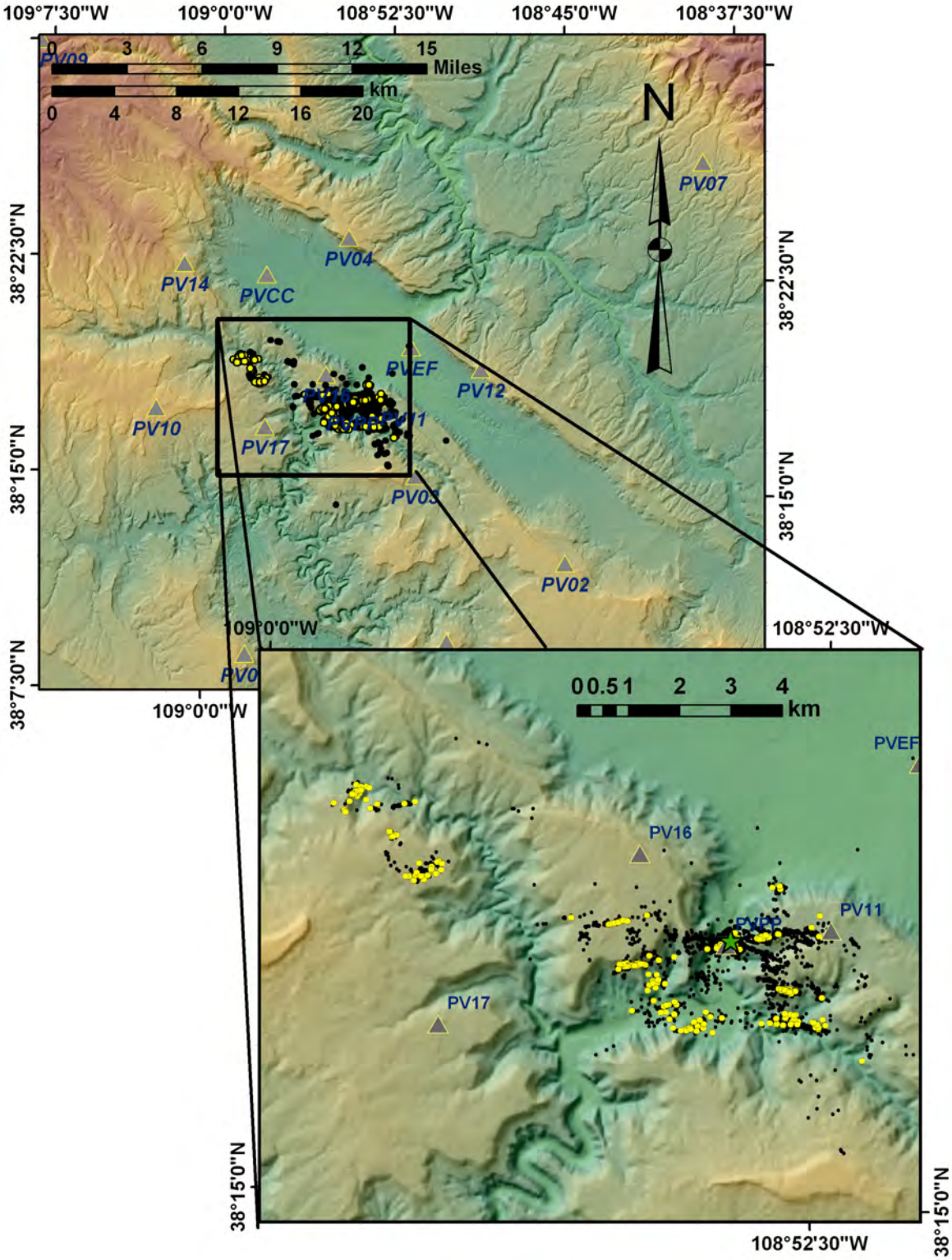


*Figure 9-25 PVU Epicenter Map of Events with Magnitude **M**1.7 and Greater (yellow circles) Superimposed on All of the Seismicity (small black dots) 1991-2007.*

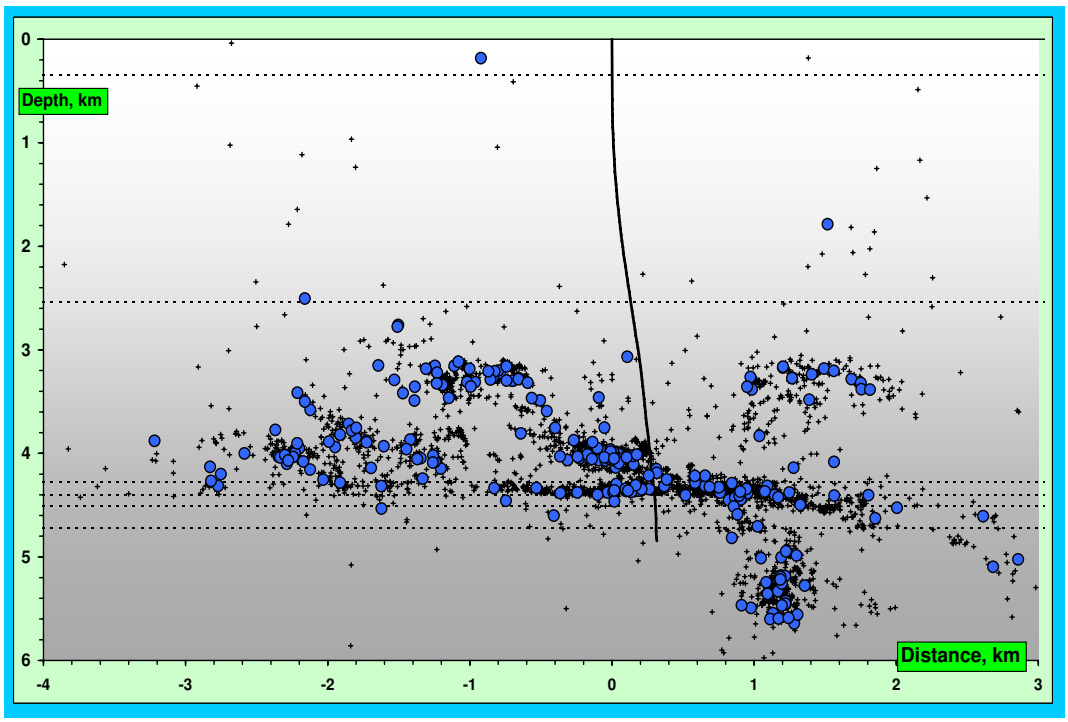


*Figure 9-26 Depth Cross Section of Event Locations Superimposed on an East-West Plane, i.e., Viewer is Looking North. Blue dots are events of magnitude **M**1.7 and larger. Dark line from top and bending to the right is wellbore profile*

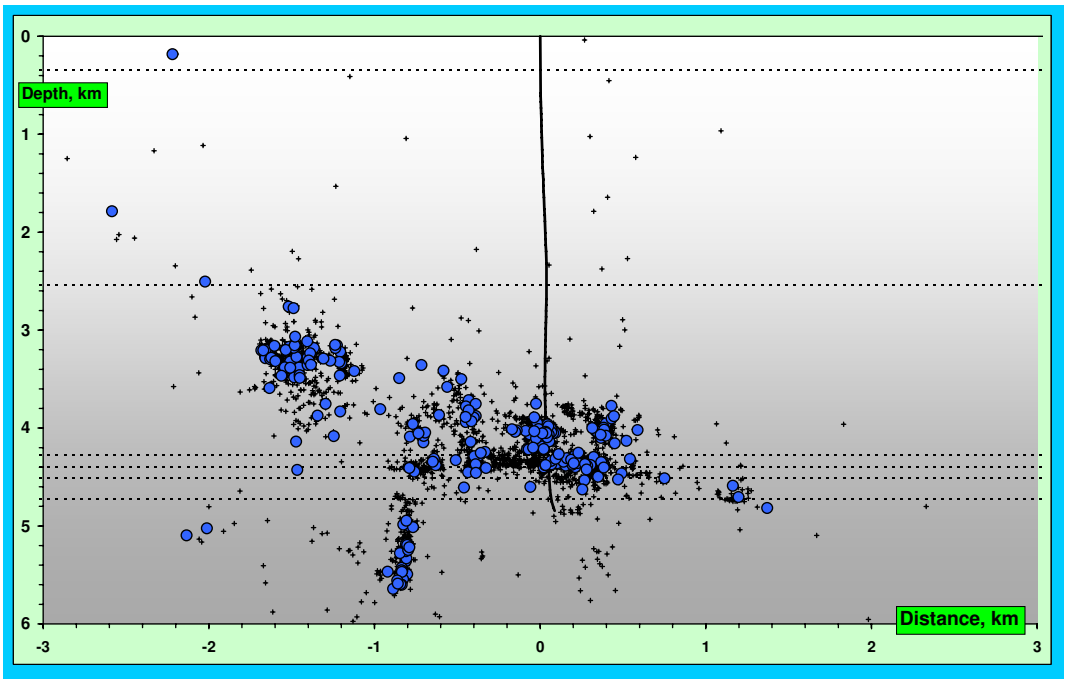


*Figure 9-27 Depth Cross Section of Event Locations Superimposed on a North-South Plane, i.e., Viewer is Looking West. Blue dots are events of magnitude **M**1.7 and larger. Vertical line in middle is wellbore profile.*

9.8 Northern Valley Events

Recurring seismicity located at the northern end of Paradox Valley is shown in **Figure 9-28**, 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 major improvements to PVSN data acquisition systems in 2000 improved it's detection capabilities for this area.

Based on the current set of data and computed earthquake locations, the earthquakes appear to occur in three distinct areas:

1. Events located about 3 km east 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) and Oct. 1-3, 2005 (10 events).

2. Events located northwest of station PV04. Several events in this area have been recorded each year since 2000.

3. A smaller group of events located approximately 3 to 4 km northeast of station PV14.

Due to marginal ray coverage and a lack of nearby 3-component stations to provide S-wave arrival times, the computed depths of most of these earthquakes are very poorly constrained. 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. These changes have improved the depth estimates for events occurring in this area. As discussed in section 4, the four events with well-constrained locations that were detected in this region in late 2007 range in depth from 5 to 8 km, with a median depth of 6.1 km.

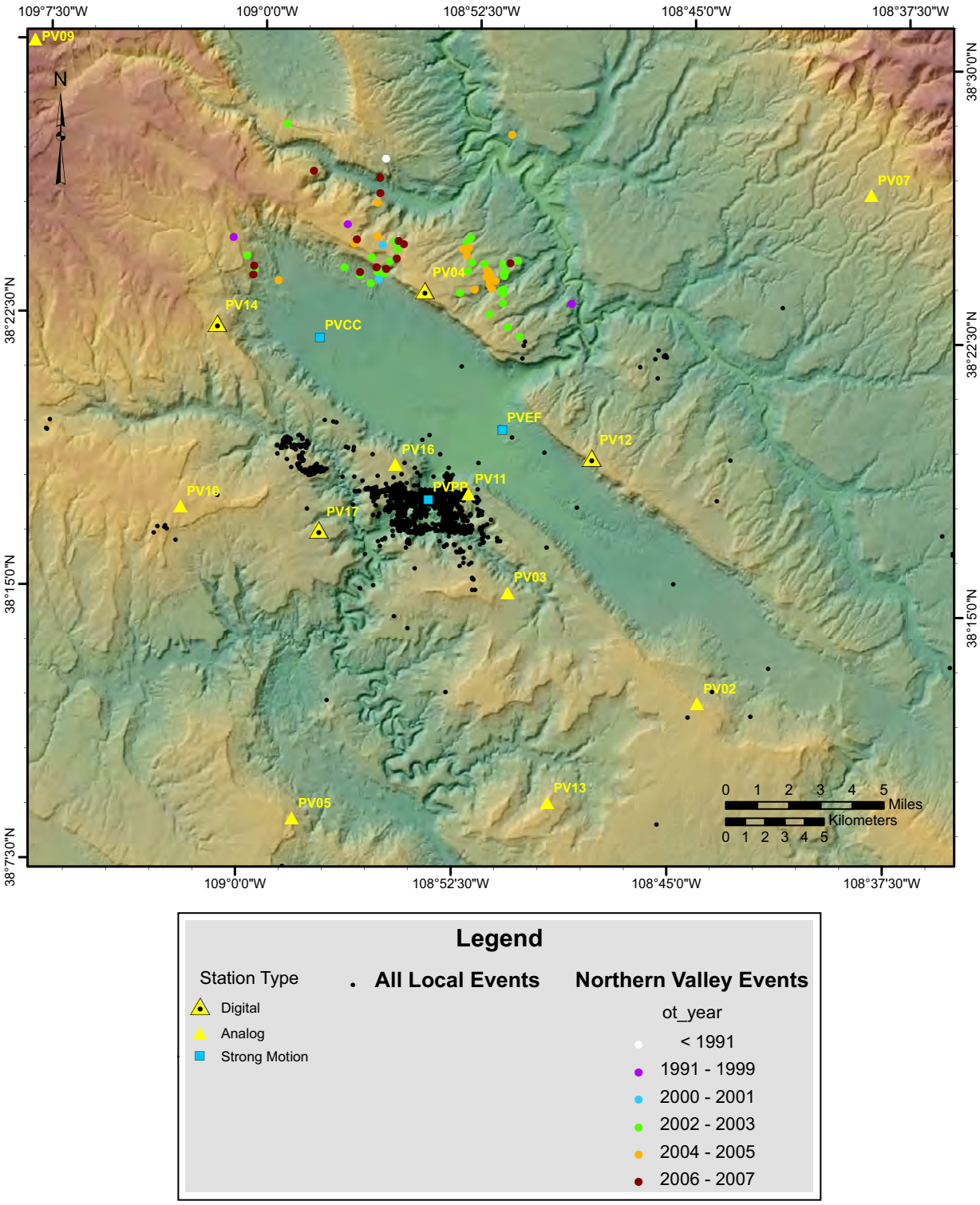


Figure 9-28 Seismicity occurring at the northern end of Paradox Valley, color-coded by year of occurrence.

10.0 CONCLUSIONS

Observations from seismic data recorded in 2007 include:

(1) The 27 induced microearthquakes recorded in 2007 locate within the two seismogenic zones defined by previous years' microearthquake locations. Hence, the reservoir does not appear to be expanding.

(2) Induced earthquakes continue to occur ~8 km northwest of the injection well with an aseismic gap between those events and the event zone surrounding the injection well.

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

(4) The microseismic activity does not indicate upward migration of the injected fluid.

(5) No large (magnitude **M**3.0 or greater) induced events occurred during 2007. The largest induced event recorded in 2007 had a magnitude of **M**2.3.

(6) Injection controls (i.e., reduced injection rate and biannual 20-day shut-downs) were continued during 2007, and the rate of seismic event production remains very low compared to the early years of continuous pumping.

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APPENDIX A

2007 SITE VISIT REPORTS

Paradox Valley Seismic Network
Site Visit No. PVSN-07-1

Dates of visit: May 6 – 12, 2007

Personnel: Matt Jones (TSC), Dave Copeland (TSC), and Denis Bourdeau (Matrix-5 Technologies, Inc.)

Objectives of Site Visit:

1. Determine and document vehicle and foot access to each station; survey GPS tracks to stations for future access
2. Survey the precise GPS coordinates of each station and the injection well-head
3. Inventory the specific components each station is composed of
4. Measure where each station's radio telemetry is directed
5. Conduct a site radio survey needed for station upgrades
6. Make repairs and upgrades to three stations with known access and configuration

Summary of Accomplishments:

Station	GPS track to station completed	GPS coordinates of station surveyed	Station components inventoried
PV01	X	X	X
PV02	X	X	X
PV03	X	X	X
PV04	X	X	X
PV05			
PV06	X	X	N/A (station removed; replaced by PV15)
PV07			
PV08			
PV09			
PV10	X	X	
PV11	X	X	X
PV12	X	X	X
PV13	X	X	X
PV14	X	X	X
PV15	X	X	X
PV16	X	X	
PV17	X	X	X
Strong-motion station PVPP	N/A	X	N/A
Strong-motion	N/A	X	N/A

station PVEF			
Strong-motion station PVCC	N/A	X	N/A
Injection wellhead	N/A	X	N/A

The current telemetry for the radio transmissions was determined for the entire network.

The site radio survey (needed for digital station upgrades) was partially completed (approximately 15-20% complete).

The following station upgrades and repairs were made:

1. PV04 was converted from a single-component short-period vertical station to a 3-component broadband digital station. It was also brought back online, having previously been down.
2. The cables at stations PV12 and PV17 were converted to low-noise wiring.
3. Station PV17 was brought back online.

Paradox Valley Seismic Network
Site Visit No. PVSN-07-2

Dates of visit: June 4 – 10, 2007

Personnel: Matt Jones (TSC) (June 4-8), and Chris Wood (TSC)(June 5-10)

Objectives of Site Visit:

1. Finish the GPS station surveys and tracks not completed during trip PVSN-07-1.
2. Make repairs at analog stations PV03, PV07, and PV13 and bring them back online.
3. Perform critical maintenance at station PV02.
4. Install a digital station at PV14.

Summary of Accomplishments:

Matt Jones completed the surveying of the remaining PVSN seismic stations (PV01, PV05, PV07, PV08, and PV09). All stations have now been surveyed, and GPS tracks obtained to document access from major roads to each site.

Chris Wood upgraded PV14 to digital broadband three-component, and installed a digital repeater at PV04. Analog stations PV02, PV03, PV07, and PV13 were visited and repaired, including replacing batteries, solar panels, voltage regulators, and instrumentation. All stations are operational, however the repeater site PV02 needs additional work to relay the signal from PV07 back to the base station at Hopkins Field.

All PVSN seismic stations are now online except for PV07.

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: PVSN-2007-3 **Departure Date:** 7/30/2007 **Return Date:** 8/4/2007

Purpose: USGS coordination; Perform initial site infrastructure upgrades (seismometer vaults, antenna masts, and steel conduit) at four existing stations closest to injection well, and/or required as new telecommunications hubs.

Work Summary: Coordinated with USGS personnel on PVSN operations, including evaluation of sites to install USGS-provided seismometer to be used for cooperative NEIC operations. Performed initial site infrastructure upgrades at PV02 (new hub), PV03, PV10, and PV11.

Action Items:

1	Need to install air conditioning in Hopkins Field equipment room ASAP. Router, micro-switch, and seria device servers (MSS-100s) are overheating, which may lead to total loss of network operations.
2	Complete station upgrades at these four sites by installing towers, new enclosures, new solar panels, new cabling, digital radios, and digital seismometers (requires approx. one day field work for two people, per site). Station enclosures and other ancillary equipment will need to be procurred (requires approximately 6 weeks lead time), so this work is planned for FY2008.

Personnel:

	Name	Organization
1	Chris Wood	Reclamation, Seismotectonics & Geophysics, 86-68330
2	Mark Meremonte	USGS, Golden
3	Jeff Fox	USGS, Golden
4	Dan Dalton	USGS, Golden
5	Ben Treseder	USGS, Golden

Work by Site:

	Site	Work Accomplished
1	PV02	Installed 3-ft Rohn tower base, poly-overpack seismometer vault, and buried 1-1/2" Sealtite conduit with pull-rope and 6-gauge solid copper ground wire.
2	PV03	Installed 3-ft Rohn tower base, poly-overpack seismometer vault, and buried 1-1/2" Sealtite conduit with pull-rope.
3	PV10	Installed poly-overpack seismometer vault, and buried 1-1/2" Sealtite conduit with pull-rope. Site already has Rohn tower.
4	PV11	Installed 3-ft Rohn tower base, poly-overpack seismometer vault, and buried 1-1/2" Sealtite conduit with pull-rope.
5	Hopkins Field	Reset Lantronix MSS-100 (NUCC-DS2). Checked station signals.

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: 2007-4 **Departure Date:** 8/20/2007 **Return Date:** 8/25/2007

Prepared By: Chris Wood, Geophysicist/Team Leader, 86-68330

Purpose: Repair and maintain seismograph stations; USGS site evaluation and coordination; Complete the station survey begun in May, and install permanent markers at survey control points; Identify potential sites for a new seismograph station to better characterize seismicity occurring along northern margin of Paradox Valley. Coordinate repairs of A/C system at Hopkins Field.

Work Summary: Power infrastructure upgrades (batteries, solar panels, regulators, etc.) were completed at seven analog stations. Stations that had been operating intermittently (or not at all) were repaired. Survey of existing stations was completed. Potential sites for a new station in the Blue Mesa area were identified, and USGS/ANSS site evaluations were made. A contractor was found to perform A/C repair work.

Post-visit Instrumentation Status: All analog stations are on-line except for PV08, which was taken off-line ca. 2003 to accommodate construction activities at the adjacent communications facility. Analog station PV07 has displayed an abnormal instrument response in recent earthquake data, and may need seismometer repairs. Digital stations PV04 and PV14 are providing high quality data; the malfunctioning seismometer at PV14 was replaced, and the vaults at both stations are now fully covered to avoid thermally-induced drift problems seen earlier. Digital stations PV12 and PV17 will continue to suffer occasional dropouts until a working CRM can be installed at PV12. The seismometer at PV12 may also have an intermittent noise-spike problem on the vertical component. Amplifier gains at five analog stations were reduced to improve event detection sensitivity and data quality (too much dynamic range was being consumed by background noise). Work is ongoing to repair the A/C at Hopkins Field (replacement parts are on order), and the contractor is scheduled to complete repairs this month. All stations have been surveyed, and the temporary control points were made permanent in anticipation of survey work needed for FY08.

Action Items:

1	Follow-up on A/C repairs.
2	Schedule servicing of PV07 seismometer - recent data indicates corroded seismometer feet or connector may be the culprit.
3	To reduce dropouts, schedule installation of a functioning CRM at PV12, with corresponding changes at PV17. The two spare (but dead) CRMs have been shipped back for factory repair.
4	Monitor vertical channel of PV12 over the next few weeks to see if spikes are recurring, and schedule seismometer replacement if so.
5	Evaluate bringing PV08 back on line (as an analog station) this fall, and collecting data over the winter. Pros: (1) Provide some constraints on earthquakes occurring on north side of net until an optimally-situated station can be installed; (2) Collect current noise data to help assess whether or not PV08 is sufficiently quiet to warrant upgrading to digital. Cons: (1) Cost of 1-2 days of field work.
6	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.
7	Planning for next maintenance trip. Tentative dates: October 22-27, 2007.
8	Plan how to complete the digital upgrade of the four sites where new vaults and tower bases were installed this summer.

Personnel:

	Name	Organization
1	Matt Jones	Reclamation, Seismotectonics & Geophysics, 86-68330
2	Chris Wood	Reclamation, Seismotectonics & Geophysics, 86-68330
3	Mark Meremonte	USGS, Golden

Work by Site:

	Site	Work Accomplished
1	PV01	Installed new batteries, solar panel, regulators, wiring, and shelf. Performed analog maintenance. Old battery was dead, so station was functioning properly only during daylight hours. Quiet site on bedrock.
2	PV02	Replaced dead mux board and adjusted signal levels. Adjusted transmitter and measured parameters. Dried and sealed new seismometer vault. Repairing this repeater site brought PV07 and PV15 back on line.

Work by Site:

	Site	Work Accomplished
3	PV03	Dried and sealed new seismometer vault.
4	PV04	Replaced temporary serial cables. Re-oriented seismometer to true north (was mis-oriented to N28W). Built earthworks over exposed seismometer vault for thermal insulation.
5	PV05	Installed new batteries, regulators, and wiring. Performed analog maintenance. Reduced gain from 78 to 66 dB (seismic noise with breeze was consuming 20% of full-scale range).
6	PV09	Installed new batteries, regulators, and wiring. Performed analog maintenance. Reduced gain from 78 to 66 dB (seismic noise with light breeze was consuming 10% of full-scale range). Noisy site on alluvium.
7	PV10	Surveyed seismometer vault. Installed new batteries, solar panel, regulators, and wiring. Performed analog maintenance. Reduced gain from 78 to 72 dB (seismic noise with breeze was consuming 7% of full-scale range).
8	PV11	Installed new batteries, regulators, and wiring. Performed analog maintenance. Dried and sealed new seismometer vault. Reduced gain on vertical channel from 72 to 66 dB (seismic noise with no wind was consuming 2% of full-scale range).
9	PV14	Replaced bad digital broadband seismometer. Built earthworks over exposed seismometer vault for improved thermal insulation.
10	PV15	Installed new batteries, regulators, and wiring. Performed analog maintenance. Reduced gain from 78 to 66 dB (seismic noise with breeze was consuming 10% of full-scale range).
11	PV16	Installed new batteries, regulators, and wiring. Performed analog maintenance. Removed rodent nest and repaired damage. Old battery was dead, so station was functioning properly only during daylight hours..
12	Hopkins Field	Evaluated signal quality and levels pre- and post-maintenance. Adjusted analog levels.

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: 2007-5 **Departure Date:** 9/23/2007 **Return Date:** 9/27/2007

Prepared By: Chris Wood, Geophysicist/Team Leader, 86-68330

Purpose: Emergency repairs of damaged equipment at Hopkins Field. Repair of strong-motion instrument at injection well.

Work Summary: Hopkins Field experienced a lightning strike on September 16, 2007. The surge damaged numerous electronics components including analog and digital radios, a GPS antenna, analog discriminators, power supplies, LAN equipment, and a modem. Equipment failures were diagnosed and all identified damaged equipment was replaced. Wiring and cabling was traced out and labeled. Numerous photographs were made of the equipment and wiring to provide a detailed record of the equipment and configuration. Additional surge protection devices were installed. A digital radio at PV04 was replaced to match the radio replaced at Hopkins Field. The strong motion instrument at the injection well was replaced because of a bad vertical component accelerometer.

Post-visit Instrumentation Status: All equipment at Hopkins Field was restored to service by 5 PM MDT, September 25, 2007. The strong-motion instrument at the injection well is fully functional.

Action Items:

1	None.

Personnel:

	Name	Organization
1	Dave Copeland	Reclamation, Seismotectonics & Geophysics, 86-68330

Work by Site:

	Site	Work Accomplished
4	PV04	Replaced digital radio to correspond to the digital radio replaced at Hopkins Field.
5	PVPP	Replaced internal-deck Kinnemetrics model K2 digital accelerograph with bad vertical channel.
6	PVCC	Inspected strong-motion installation located at the Paradox Community Center. Phone line has intermittent induction noise.
12	Hopkins Field	Replaced analog receivers for PV01, PV02, PV03, and PV16. Replaced digital radio for PV04. Replaced discriminator rack for stations PV01, PV02, PV03, PV05, PV07 and PV15. Replaced Matrix-5 power supply. Replaced Lantronix MSS-100 serial device server, and 5-port Milan etherswitch. Replaced Guralp GPS receiver. Replaced US Robotics model Courier modem. Installed proper grounding for GPS surge protection. Installed PolyPhaser surge protectors for PV01, PV02, PV03 and PV08. labeled all cables and equipment.

Paradox Valley Seismic Network - Site Visit Summary

Site Visit Number: 2008-1 **Departure Date:** 10/23/2007 **Return Date:** 10/28/2007

Prepared By: Chris Wood, Geophysicist/Team Leader, 86-68330

Purpose: Repair and maintain seismograph stations; Reconfigure digital telemetry; USGS coordination;

Work Summary: At PV12 and PV17 the digital telemetry system was reconfigured to reduce data dropouts; other improvements included reorienting seismometers to true north (and east), battery replacement, and reorienting directional antennas using GPS-determined azimuths. Site PV08 was restored to its original configuration as a 3-component analog station, and brought online (it had been down since October 27, 2003). Repairs were made at PV07, PV16, and Hopkins Field.

Post-visit Instrumentation Status: All stations are on-line, including PV08 (which had been down since October, 2003). Data dropouts from digital stations PV17 and PV12 have been almost entirely eliminated. The east-west component of digital station PV12 is malfunctioning and the seismometer should be replaced on the next site visit (the remaining components are functioning normally). The #2 discriminator rack at Hopkins Field has intermittent dropouts for the east-west component of PV11, and should be replaced during the next site visit. The noise problem at PV07 appears to have been fixed by replacing the seismometer surge protection and connector.

Action Items:

1	Schedule and plan for Hopkins Field upgrade (new rack, field data acquisition system, etc.), likely in December 2007, or January 2008.
2	Schedule servicing of PV16 seismometer and PV04 improvements for next field maintenance trip, likely in April or May of 2008.
3	Assess utility of PV08 for future digital upgrade, including noise level of site and monitoring benefits.
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.
5	Plan completion of the digital upgrade of the four sites where new vaults and tower bases were installed last summer.

Personnel:

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

Work by Site:

	Site	Work Accomplished
1	PV07	Opened seismometer vault. Seismometer was fine, and there was only minor corrosion of the seismometer feet. Surge protection was the old-style Teledyne model, however, and the PC board was corroded. Replaced surge protection with new Matrix-5 model, including new connector. Appears to have cleared up high-frequency noise initially observed in amplifier-output spectrum.
2	PV08	Restored station as a 3-component analog site, and brought on-line. Added top of mast. Installed new solar panel and regulator, new instrumentation voltage regulator, new batteries, new seismometer cable, new horizontal seismometers (2), new seismometer surge protection and connectors for all components, new seismometer cable, new antenna cable and jumper, and new PolyPhaser. Installed used antenna, used 3-component field package, and used VHF radio. Cleaned out and did rehab of existing seismometer vaults. Re-used existing PVC conduit (GOOD FOR 1-2 YEARS MAX). Did rehab of electronics enclosure, including new shelf. Re-used vertical-component seismometer. Removed old single-component field package. Tuned and adjusted signal levels.

Work by Site:

	Site	Work Accomplished
3	PV12	Reconfigured digital telemetry: Changed PV17 radio to point-to-point master; added CRM-6 and configured to multiplex PV17 and PV12 packets, sending output to PV17 radio; changed data logger baud rate to 9600. Reoriented seismometer to true north (north component had been mis-oriented to about S10E). Reoriented PV17 and Hopkins Field directional antennas using GPS-determined azimuths (HF antenna had been mis-oriented 30 degrees north of azimuth). Removed extraneous wiring, BOBs, omni antenna, and cables. Began removal of old analog site (top half of mast, solar panel, antenna, and battery).
4	PV16	Completed rodent cleanup: disinfected enclosure and equipment with bleach solution; added wire mesh screen to conduits; replaced louver filters; added new shelves. Discovered and replaced intermittently bad signal cable to radio. Thinned trees and brush from helicopter landing zone to better meet OAS suggested clearances; cleared path to location of proposed new seismometer vault.
5	PV17	Reconfigured digital telemetry: Changed radio to point-to-point slave; changed data logger baud rates to 9600; reoriented directional antenna using GPS-determined azimuth; repositioned antenna to top of mast. Installed new batteries. Removed extraneous wiring and cables. Reoriented seismometer to true north (north component had been mis-oriented to about N10W).
12	Hopkins Field	Replaced PV08 receiver (old one from ca. 2003 was bad). Configured discriminator rack #3 for PV08 3-component, and rewired receiver. Replaced discriminator rack #2 to begin trouble-shooting intermittent 5-10 Hz noise observed from PV11. Evaluated signal quality and levels pre- and post-maintenance. Adjusted analog levels.

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 contemporaneous (average) PVU injection data

(2) PDF files of the PVSN annual status reports for 2000 to 2007