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2005 Status Report-Paradox Valley Seismic Network Paradox Valley Project, Southwestern Colorado

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

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Bureau of Reclamation
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Seismotectonics and Geophysics Group

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2005 Status Report-Paradox Valley Seismic Network
Paradox Valley Unit
Southwestern Colorado

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Acknowledgements

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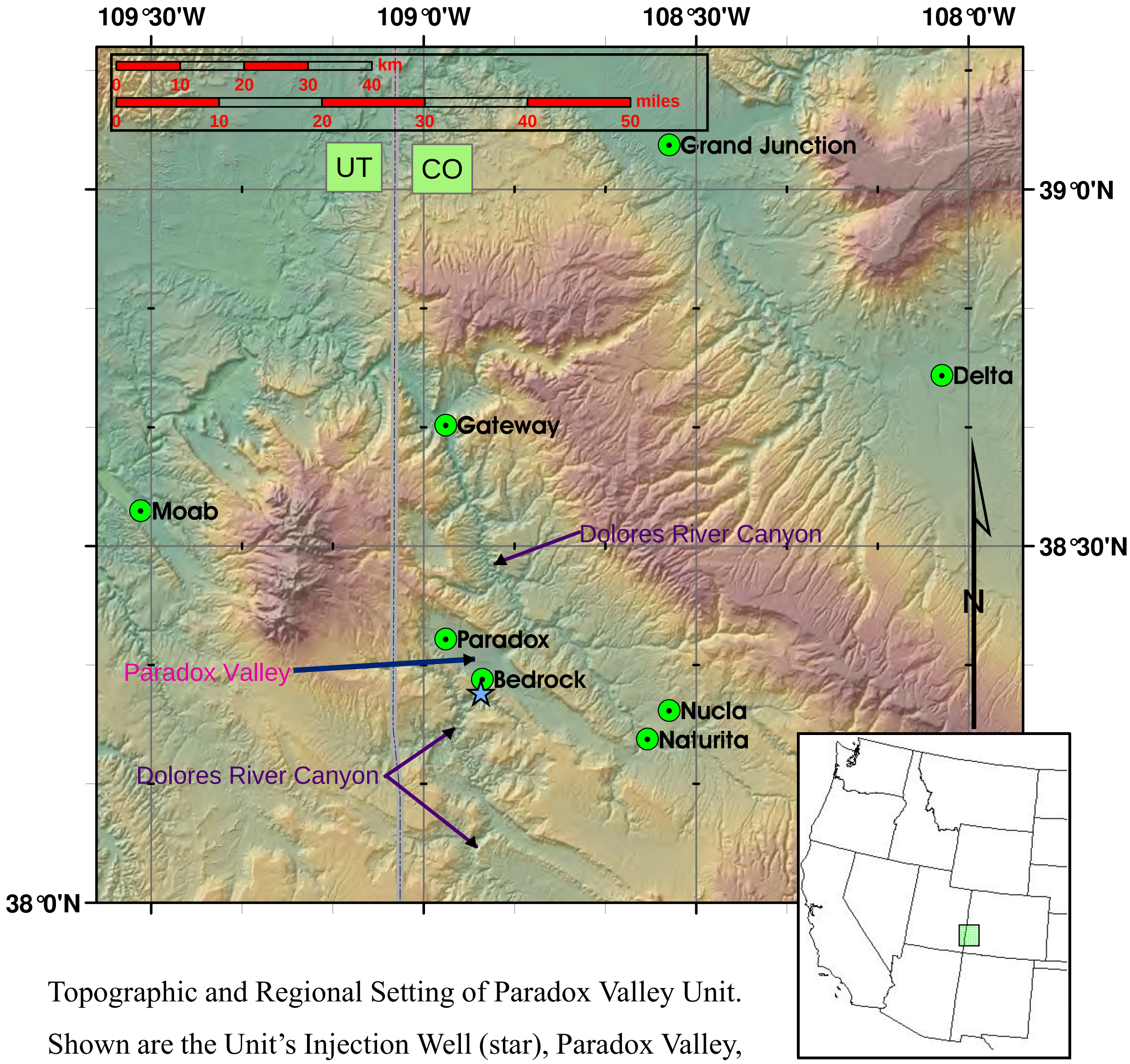
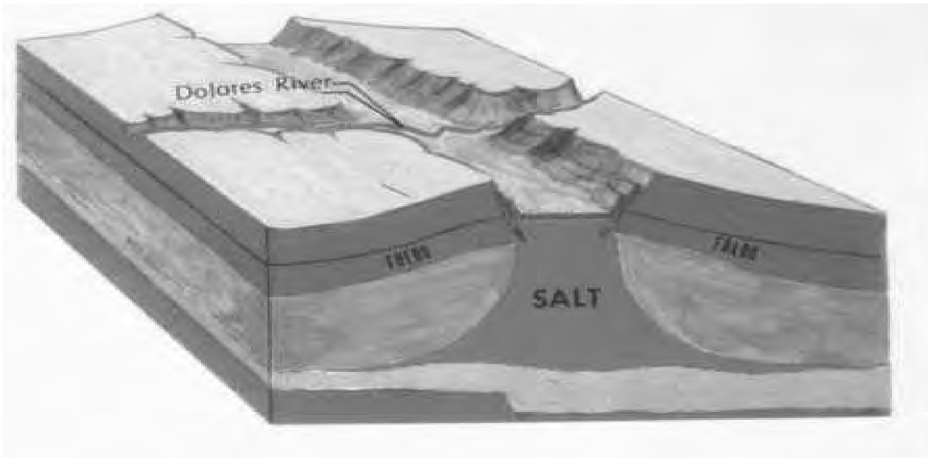


Topographic and Regional Setting of Paradox Valley Unit. Shown are the Unit's Injection Well (star), Paradox Valley, Dolores River Canyon, Local and Regional Municipalities (yellow circle with centered black dot), Colorado-Utah Border, and Geographic Location in Western US Multi-State Region (insert).



Cartoon of Dolores Canyon and River, Paradox Valley, and Regional Cross Section

Dolores Canyon and River plus Paradox Valley, Viewed to the Northeast. Paradox Valley runs left and right, across the photo near the top.

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 US Bureau of Reclamation's Paradox Valley Unit's (PVU) deep-well injection project for calendar year 2005, (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 (i.e., surface) as a function of time.

1.1 2005 - Key Activities and Findings

Described in detail in this report:

(1) In 2005 the Paradox Valley Seismic Network (PVSN) added one new seismic station and upgraded a second station. In addition, two new strong motion stations were added;

(2) In 2005, PVSN recorded 101 microearthquakes within the two seismogenic zones defined by previous years' microearthquake locations;

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

(4) As in previous years, the spatial patterns of observed seismic sources and observed seismic source mechanics seem to follow the Wray Mesa fault and fracture system and are consistent with relevant tectonic stress characteristics.

(5) No large (magnitude **M**3.0 or great) events occurred during 2005; the largest event in 2005 was a magnitude **M**2.6.

(6) Injection controls (i.e., reduced injection rate and biannual 20-day shut downs) were continued during 2005 and the rate of seismic event production remains very low compared to the early years of continuous pumping.

1.2 Cumulative Findings

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 induced seismicity at Paradox illuminates an extensive, non-symmetric, connected network of fractures, faults, joints, etc.

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.

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 secondary seismogenic zone lies along the trend of the local fault system, the Wray Mesa system, from the primary seismogenic zone. The primary seismogenic zone covers a reservoir volume of between 20 and 30 cubic kilometers

Based on extrapolation of the PVSN data and comparison with data from injection sites that were monitored with *in situ* instruments, our best estimate indicates PVU has induced ~3 million events with magnitudes **M**-3.0 or greater. The smallest events probably include both shear and tensile (i.e., crack-opening) events. Being a surface array with its closest instrument ~4 km from the downhole injection interval, PVSN's sensitivity limit is approximately **M**0.0. Thus, PVSN probably only records ~0.1% of the events PVU induces.

More than 99.9% of the over 4,200 surface-recorded events induced at the Paradox Valley injection since 1991 have magnitudes less than **M**2.0. (Human detection threshold ~ **M**2.5); ~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 injecting.

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.

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 occasional swarms; swarms can occur over hours to days in a single location.

The subclass of seismic swarms at Paradox associated with one, large event sometimes show some smaller foreshocks and a few smaller aftershocks or one large event followed by after-shocks.

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

The seismicity occurs within the interior and on the border of the existing seismogenic zones; since about mid-1999, the expansion of the seismogenic zones is evident but minor.

By the end of 2005, PVU has injected ~0.004 cubic kilometers 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.

Seismic event are vertically contained between ~2.5 km and ~6 km below the wellhead.

The epicenters group into linear features that illustrate the secondary fracture and fault network of the Wray Mesa. The alignments of the epicenter lineations imply the locations of the major, through-going faults of the Wray Mesa system.

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 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.

The 20-day shut down periods relax the *in situ* stress state, resulting in a reduced procliv-ity for large events.

In 2002, PVU increased the percentage of Paradox Valley Brine in the injectate. 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 bottomhole pressure prior to 2002.

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.

2.0 PVSN - PROJECT OVERVIEW

2.1 Mandate

From the project inception and based on other deep-well injection projects, including the Denver Arsenal, CO in the 1960's and Rangley, CO in the later 1960's and early 1970's, the U.S. Bureau of Reclamation (Reclamation) recognized and planned for monitoring the small earthquakes that were likely to be induced by the PVU injection. In 1985, six years before the first injection at PVU, Reclamation began recording and compiling a catalog of natural/background seismicity in the Paradox Valley region. Recording, archiving, analyzing, and interpreting local seismicity were, and still are, the mandate of the PVSN and its staff. Specifically, PVSN operations (1) gather continuous ground motion data originating in and around Paradox Valley and the surrounding region; (2) electronically collate and transmit these data to the Denver Federal Center (DFC) in Lakewood, CO; (3) identify, isolate, evaluate, and catalog local, injection-induced seismic events within these data; (4) locate the source (i.e., origin location) and source time of each seismic event; (5) determine cumulative and individual characteristics of the events, when feasible; (6) identify and evaluate relationships between seismicity, geology, tectonics, subsurface brine and connate water/pressure movements and locations, and injection parameters; (7) maintain a database of both events and injection parameters; (8) and report findings both internally and to the scientific community.

2.2 Background

Since 1985, Reclamation has operated PVSN -- its local, surface-based, (now) 16-station seismometer network -- as part of the PVU, a member of the Colorado River Basin Salinity Control family of projects. PVU collects unwanted Paradox Valley brine (PVB) prior to it entering the Dolores River, a tributary of the Colorado River. PVU then injects the brine in the world's deepest disposal well, the US-EPA Class V PVU Salinity Control Well No. 1, ~4.3 km below the Earth's surface into the Mississippian-aged Leadville Limestone and surrounding formations. Since 1991, the project has disposed more than 4 billion liters of PVB-rich injectate (~600 million+ kg of salts). Between 1991 and 1995 injection was a punctuated sequence of 7 injection tests and an acid stimulation demonstrating well and reservoir integrity to qualify for a Class V, EPA permit for deep disposal. With the granting of the permit, injection became round-the-clock in 1996. The exceptions to round-the-clock injection were and are as-needed maintenance shut downs and, beginning in 2000, a scheduled, 20-day shut down every 6 months.

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 a 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. The injection has induced an estimated 3+ million microseisms (i.e., seismic events with magnitudes equal to or greater than **M**-3.0) and a largest induced event of magnitude **M**4.3. By the end of December 2005, PVSN had recorded over 4,200 of the largest of these events, specifically those with magnitudes ~**M**0.0 or greater. The recorded data radiate from two, spatially-separated, seismic source ("seismogenic") zones: a principal zone - asymmetric and E-W elongated surrounding the injection well and containing more than 90% of the events - and a secondary zone - also asymmetric but centered ~8 km northwest of the injection well. As a point to note, from the western boundary of the principal zone, the secondary seismogenic zone lies along the direction of the local major fault trend, the Wray Mesa Fault system.

Although the injection pressure 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 recorded by any PVSN station; the closest PVSN station is 3 to 4 km from a seismogenic zone. Instead the recorded events are shear failures along preexisting planes of weakness (e.g., faults, old fractures, etc.). These shear sources are not uniformly or randomly distributed in the 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 their anticipated principal shear stress directions. One very significant finding from these 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 has allowed, and continues to allow, the injectate time to diffuse from the injected (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-2002, these changes have substantially reduced seismic event production and seem to have reduced the proclivity to produce felt events.

3.0 PVSN ACTIVITIES IN 2005

3.1 New Instrumentation Installed

During 2005 our staff finished installing a new PVSN site (PV17), reoutfitted an existing single-motion component PVSN site into a 3-component site (PV12), and installed a new, third strong motion sensor site. A complete discussion of network instrumentation, including the new sites, is given in later in this report

3.2 Seismicity and High-Sample Rate Pressure Data

One PVSN mandate has been to relate the induce-seismicity to the injection parameters. On a long-time scale we have been moderately successful which has resulted in reduced levels of seismicity (e.g., Mahrer et al., 2004; Mahrer et al., 2003) Unfortunately we have not been able to relate individual seismicity 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 3-1** shows PVU wellhead pressure recorded at one-minute sampling ("high-sample rate" data) and daily averaged pressure (horizontal, dashed lines). Also shown in the figure are the occurrence times of 3 microseismic events. The lack of specific injection information resulting from averaging is quite obvious: 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; daily average is one value. To date very little work has been completed relating injection data recorded at a high-sample rate and the microseismic data of PVSN. Presently we are trying to acquire high sample rate data; this has required some contractual renegotiations with the site contractors. In the future we hope to rectify this and use high-sample rate date to investigate if a relationship or relationships exist between the microseismic events and variation or anomalies in PVU operations (e.g., wellhead pressure, injection volume, and/or injection energy) on a comparable time scale.

3.3 Event/Injection Ratio

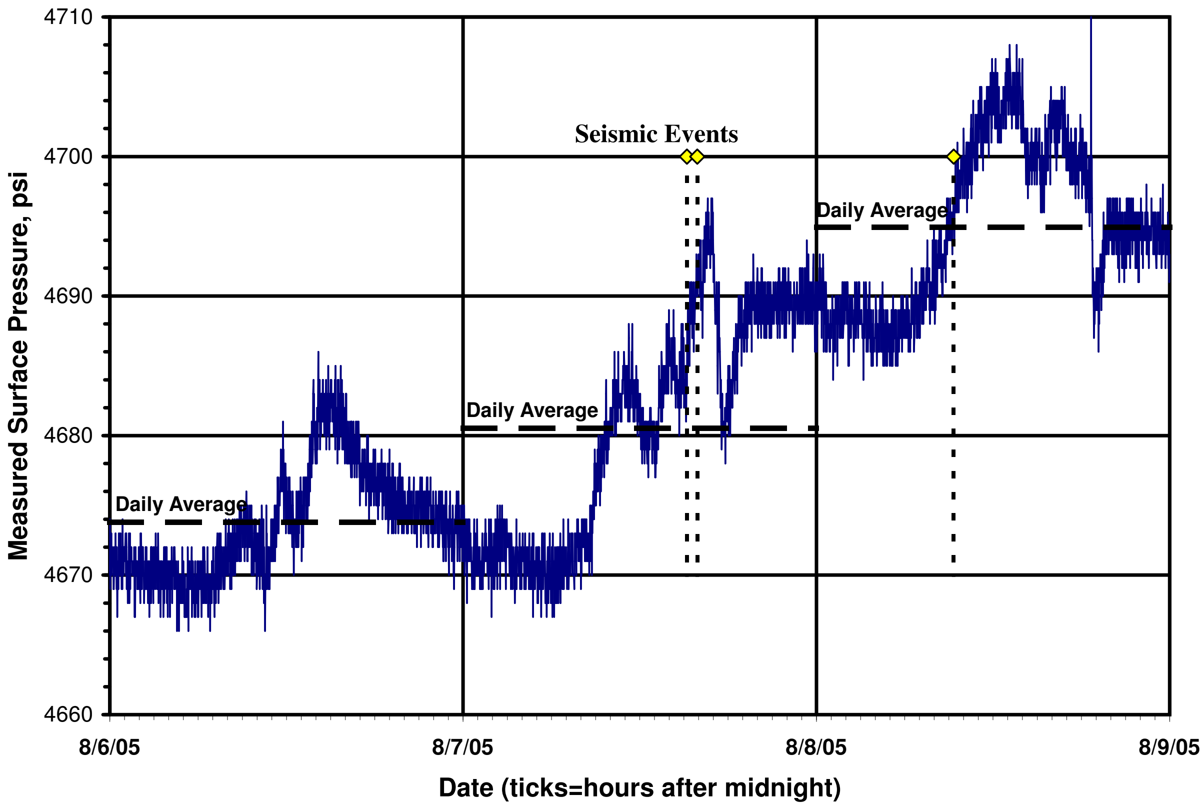


Figure 3-1 Comparison of 1-Second Sampled Pressure (blue) and Daily Averaged Pressure (dashed) and Occurrences of 3 Seismic Events (diamonds).

Figure 3-2 is a plot of the ratio of cumulative number of seismic events to cumulative injection volume, the events/day, and the average daily downhole injection pressure, 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. We feel, the decrease in the ratio for the later half of 1997 is suspect; as noted in this and previous reports, the completeness of 1997 data is not trusted. However, in the figure, the ratio peaks in mid-1999 and then continues to decrease at a decreasing rate through to the present. The time the ratio peaks seems to correlate with the onset of regular shut downs, both scheduled and non-scheduled. The importance of the peaking and subsequent decrease seems to quantify a decrease in the proclivity to generate microseisms. This approach, combining the seismic and injection data and examining the ratio as a function of time, is new and will be studied in the future.

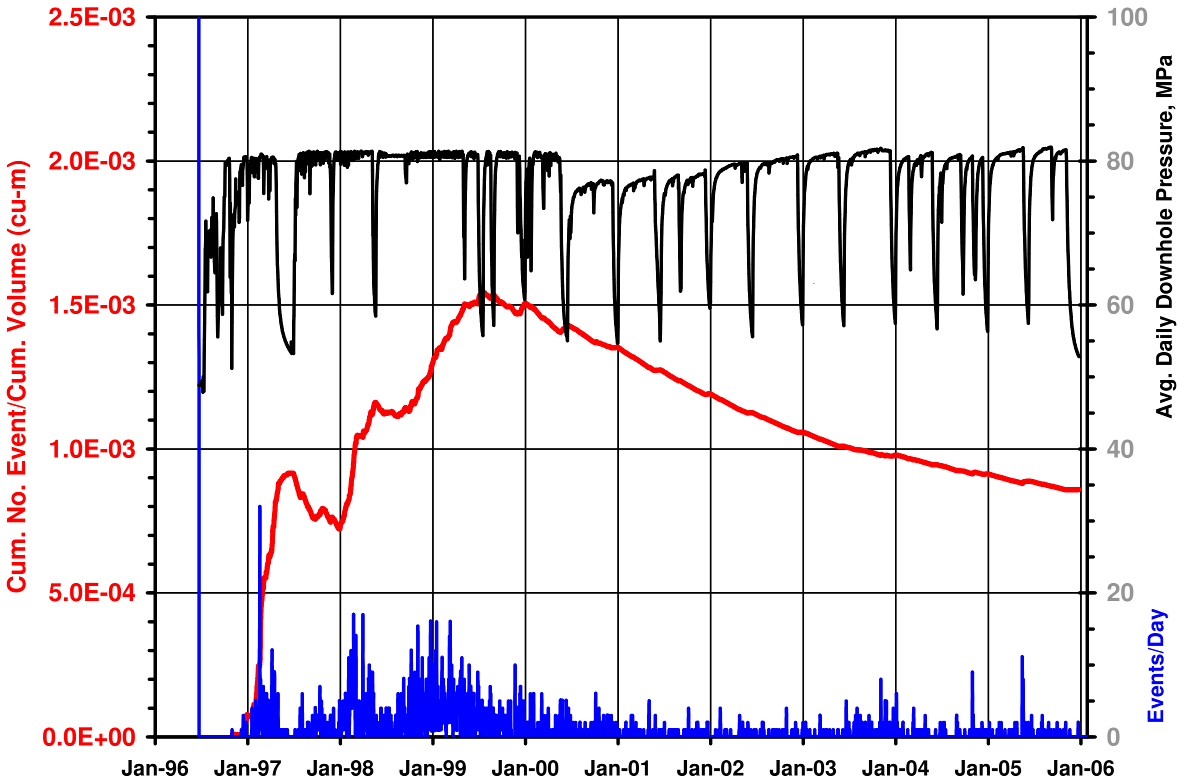


Figure 3-2 Ratio of Cumulative Number of Seismic Events to Cumulative Injection Volume (red line) Versus Time with Additional Curves of Events/Day (blue) and Average Daily Downhole Pressure (black), both Versus Time.

3.4 Seismic Event Relocation Methods

As described later (**Chapter 7.0**), calculating the origin locations of the injection-induced seismicity (i.e., the hypocenters), is a two-phased procedure. During the year we analyze the incoming data daily and determine a preliminary location using a quick and elementary procedure involving a simple, one-dimension (1-D) model. The preliminary locations are good, but not the best that can be done. At the end of the year we apply the second phase of the location procedure: we use a much more advanced and computationally-intensive computer code to relocate the hypocenters. Since 2000 we have used the same or a slightly-revised relocation code and its associated sensitivity criteria. In 2005 we relocated all of the events (1991 through 2005) using a revised procedure and criteria. The details of the new relocated procedure are beyond the scope of this report; however, we give a heuristic description of the procedure in the next paragraph.

The hypocenter relocation procedure consists of two steps. First, we locate the events in a three-dimensional (3-D) regional velocity model using absolute arrival time picks for the P- and S-waves in the recorded waveform signals. The P's are picked on all signals with suitable signal-to-noise ratios and S's are picked on a subgroup of signals from stations suitable for accurately identifying S-waves (i.e., 3-component stations, see **Chapter 5.0**). Second, precise relative event locations are computed using arrival time differences between pairs of seismic events recorded at the same station. The time differences are computed from cross-correlation of the signals (i.e., waveforms) from the two different events. In the new procedure, we updated and improved both steps of the earthquake location procedure. We developed a new P-wave and S-wave regional velocity model using data from additional earthquakes and mine blasts that have occurred since the velocity model was last revised in early 2000. These additional events provide more raypath coverage for constraining the velocity model. Also, for the first time, we incorporated into the velocity (inversion) scheme, data from station PV16. Using both P-wave and S-wave arrival times from this three-component station we constrained the velocity model. We improved the second step of the earthquake relocation procedure by greatly increasing the number of waveform cross-correlations. This resulted in many earthquakes being better-constrained in their relative relocations than they were previously. Approximately 86% of all injection-related events are now well-constrained in the earthquake relative relocation, compared to about 70% that were well-constrained using the previous method. **Figure 3-3**, **Figure 3-4**, and **Figure 3-5** show the preliminary one-dimensional epicenters, the pre-2005 epicenters (i.e., data from 1991-2004 using the previous method) and the 1991-2005 epicenters using the new method, respectively.

3.5 May '05 Seismic Event Swarm

Between May 22nd and May 27th, 2005, PVSN recorded a 28-event swarm located north and slightly west of the injection wellhead and at depths between 3.8 and 4.3 km (average = 4.16 km: standard deviation = 0.10 km) below the wellhead. The largest events in the swarm were a magnitude **M**2.4 on May 26th and an **M**2.1 on the 22nd. The May-22nd event marked the beginning of this swarm. In 2005, PVSN recorded about 100 events and nearly 1/3 of the 2005 events occurred during this 6-day period.

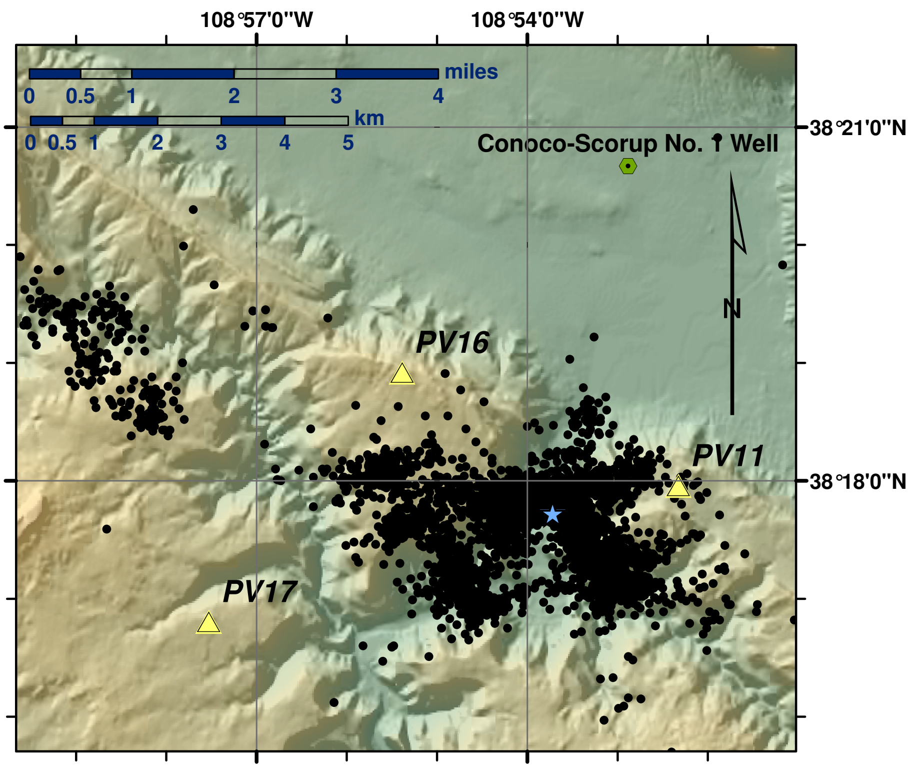


Figure 3-3 Paradox Preliminary Epicenters Based on One-Dimensional Velocity Model. Events are from 1991-2005.

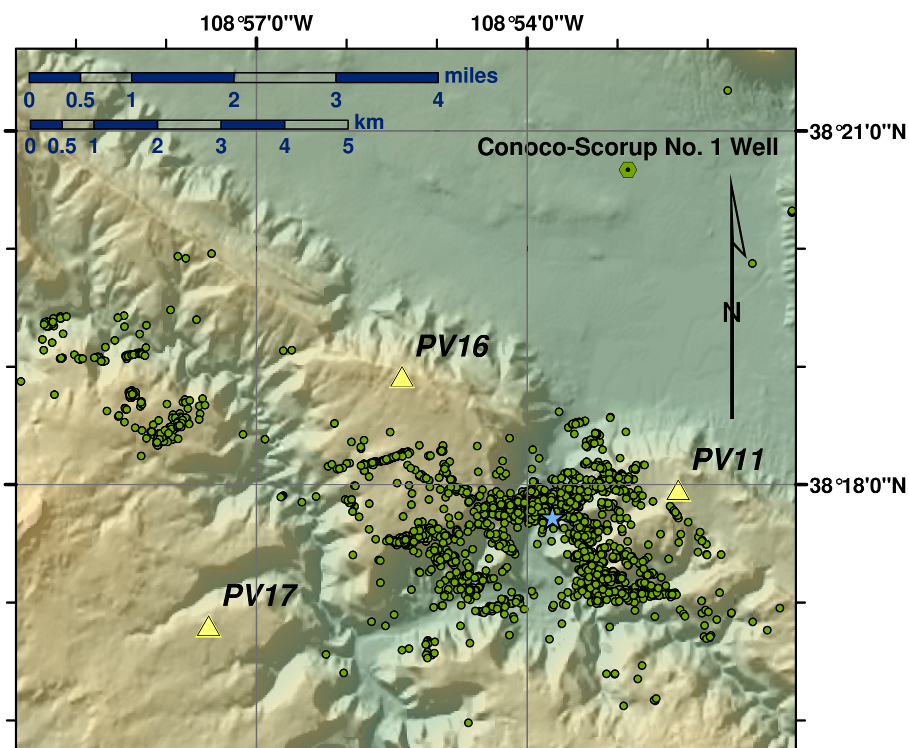


Figure 3-4 Relative Relocation of Paradox Epicenters Using Pre-2005 Inversion Methods Data are from 1991-2004.

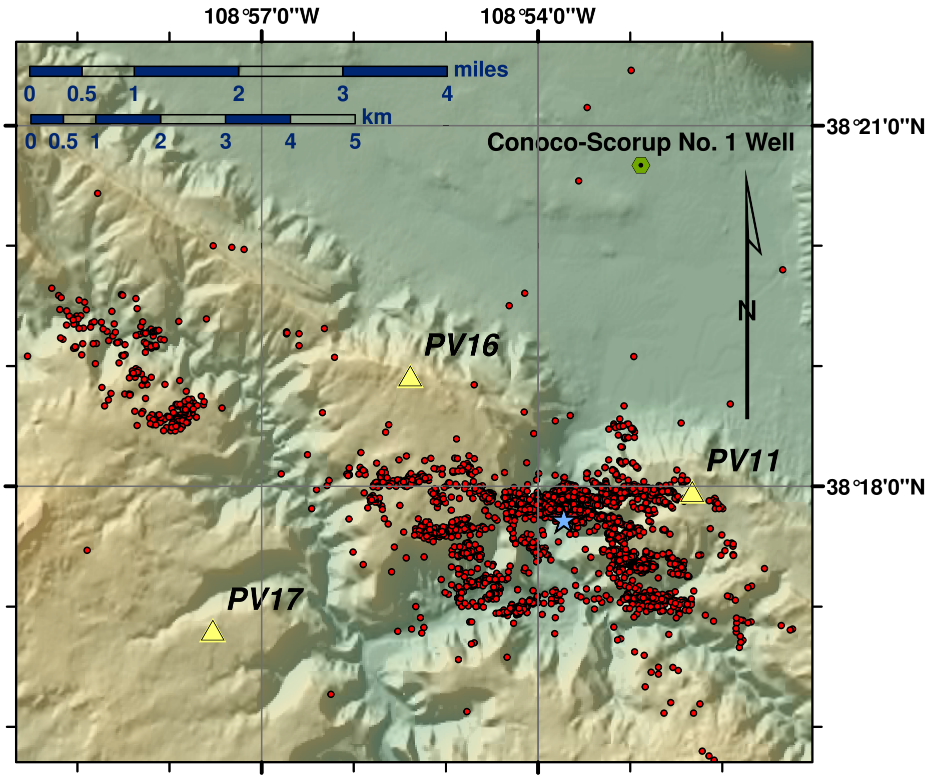


Figure 3-5 Relative Relocation of Paradox Epicenters Using New, 2005 Inversion Methods. Data are from 1991-2005.

3.5.1 Subswarms Versus Pressure

Figure 3-6 shows the occurrences of the May '05 swarm on a plot of high-sample rate wellhead (measured) pressure data for the 6-day period. These data show 4 subswarms or 4 tight-time groupings of events, as noted in **Figure 3-6**. Each of the subswarms also had one largest event followed by aftershocks with the exception of subswarm 4 that had a couple of small events (foreshocks?) followed by the **M**2.4, the largest event of the swarm.

3.5.2 Subswarms Versus Epicentral Locations

In conjunction with the subswarm groupings of **Figure 3-6** we present **Figure 3-7**, the epicenters of the May '05 swarm plotted by day of occurrence. Note that the epicenters generally form a straight line and that the epicenters appear to migrate from the southwest to a northeast. We have

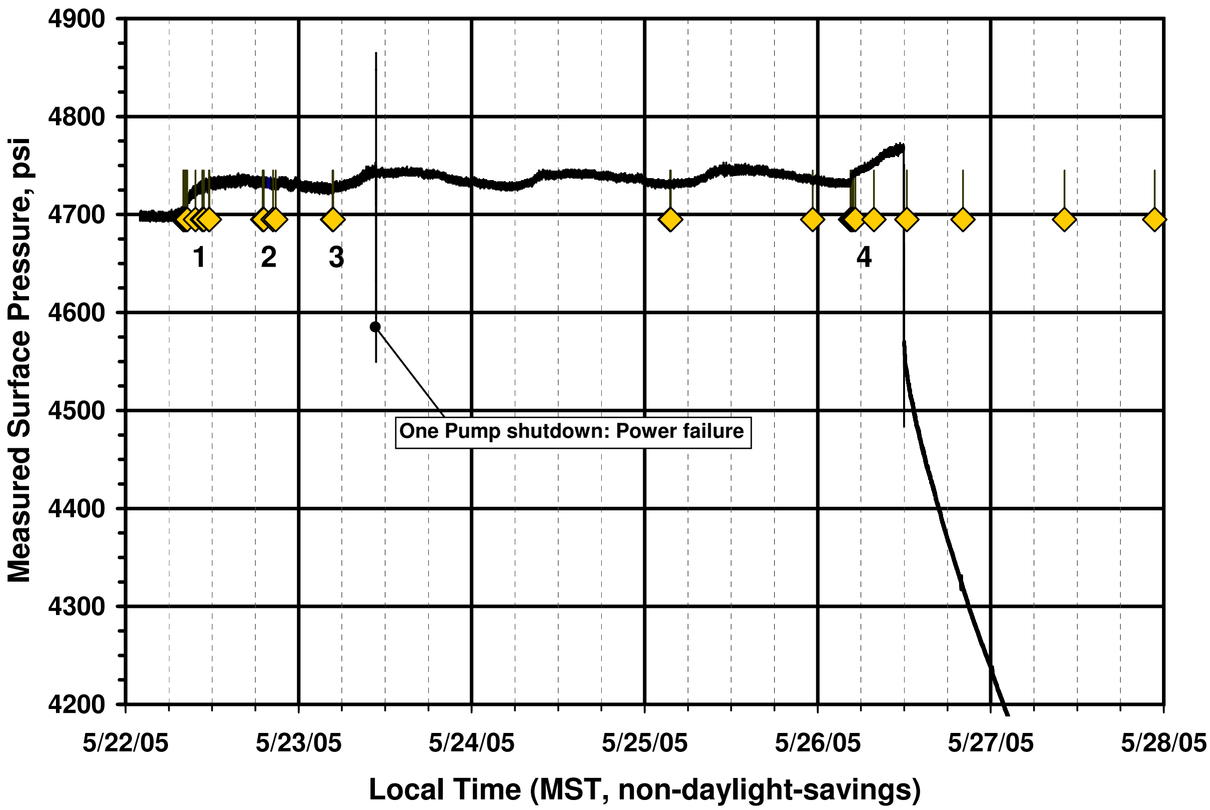


Figure 3-6 High-Sample Rate Pressure (black line) and Occurrence of Seismic Events (diamonds) for May 22nd through May 28th, 2005. Seismicity occurred in a swarm of which 4 subswarms are noted and identified by number in the figure.

not noted migratory behavior like this before, but are now aware of the possibility of swarm-epicenter migration and will be looking for it in the future. We also intend to reexamine previously-recorded data for such behavior.

3.6 June-November '05 Seismic Event Locations

In conjunction with the May '05 swarm we plotted subsequent epicenters to look for tight or geometrically-significant swarming**. Figure 3-8** shows the epicenteral locations for all Paradox seismic events from June through November, 2005, inclusive. During these 6 months, PVSN recorded 44 events. Although these events did not show the migration pattern seen in the May swarm, these 44 events did occur predominantly in two, geometrically-separated and significant regions: one, in the region near the injection well and the May '05 swarm, and the other to the southwest overlaying the swarm of the November '04 **M**3.9 event (Mahrer et al., 2005). The rest

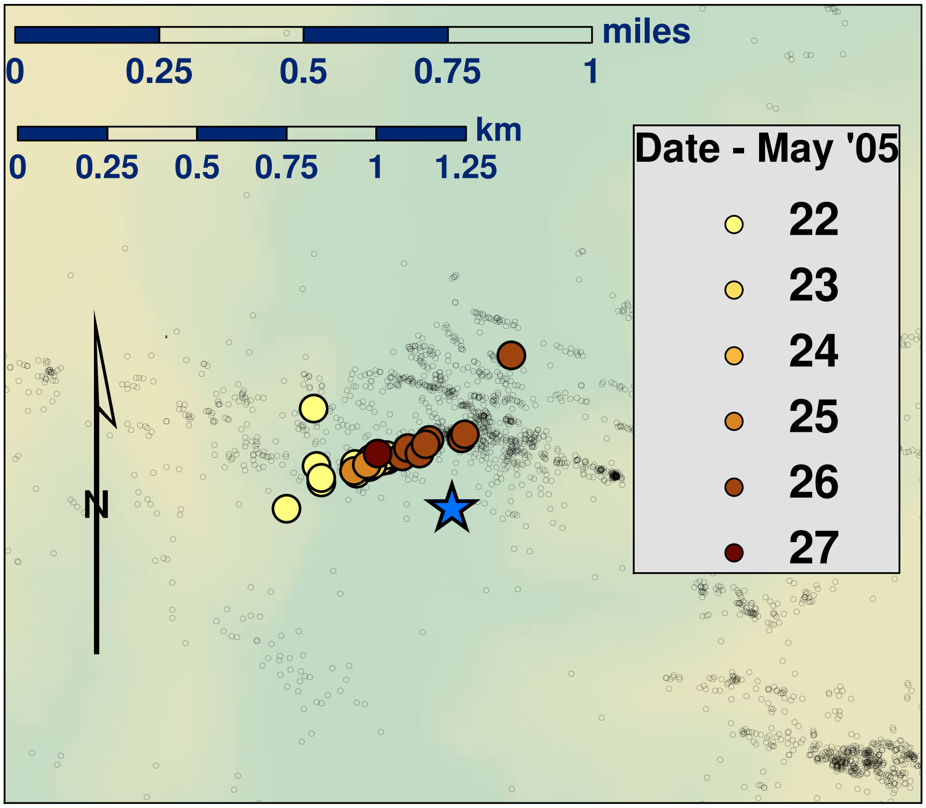


Figure 3-7 Epicenteral Locations of May '05 Microseismic (Swarm) Events Versus Date of Occurrence. Star is injection wellhead and small black circles are the near-wellbore, injection-induced epicenters from '91 through the end of '05.

of the region, for this six-month period, was aseismic, with the exception of two events. Both of these events located about 2 km from the wellhead, one approximately due east and the other approximately due west, and both occurred in November.

3.7 Annualized Data Comparison

Since PVSN has a complete and reliable data set dating to 1998, we decided to try a different approach in analyzing these data. The approach is shown in **Figure 3-9** and **Figure 3-10**; these figures show events per year and cumulative seismic energy per year, respectively, as functions of the indicated injection parameters.

Note in each figure, there are two groupings of the data, one at the top right and the other at the

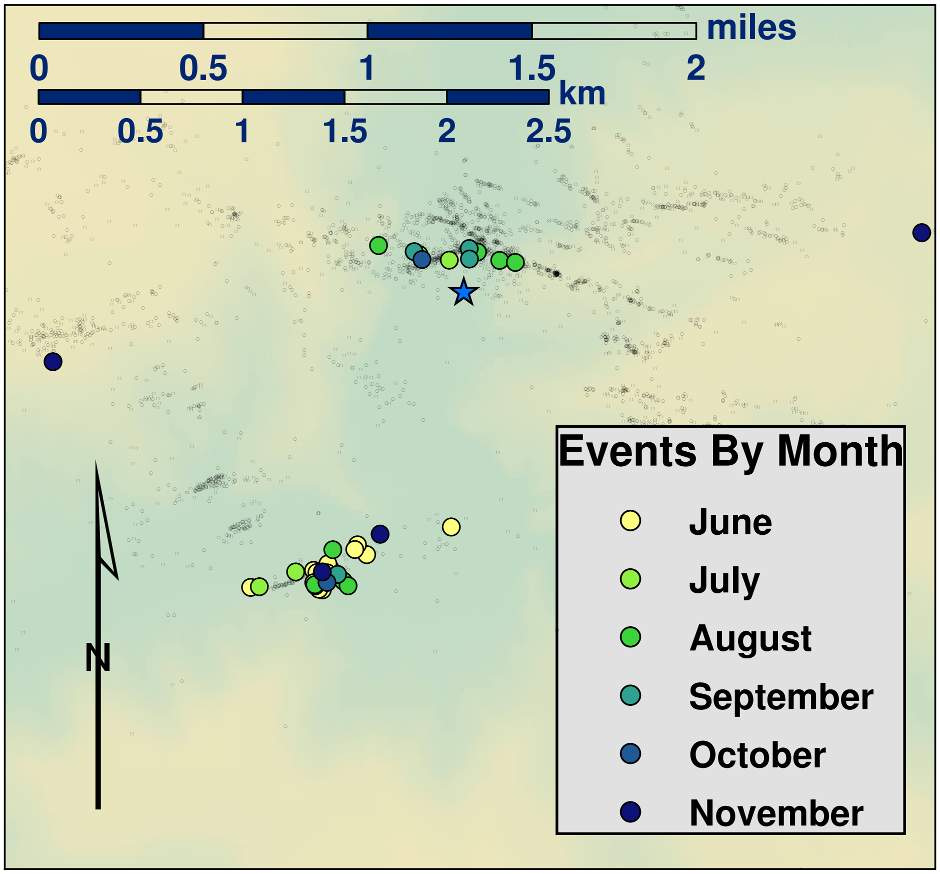


Figure 3-8 Epicenters of Injection-Induced Seismic Events in June Through November, 2005. Star is PVU injection wellhead.

bottom left. The two data points at the top right are for years 1998 and 1999, the years of maximum injection. The other grouping are for years 2000 through 2005. In some cases these data groupings show linear trends. These linear trends are interesting, because they can be used, with a guarded degree of reliability, 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). Specifically, in **Figure 3-9**, the best correlations are with figures (b) and (d), the annualized injection volume and the annualized injection energy, respectively. In **Figure 3-10**, 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

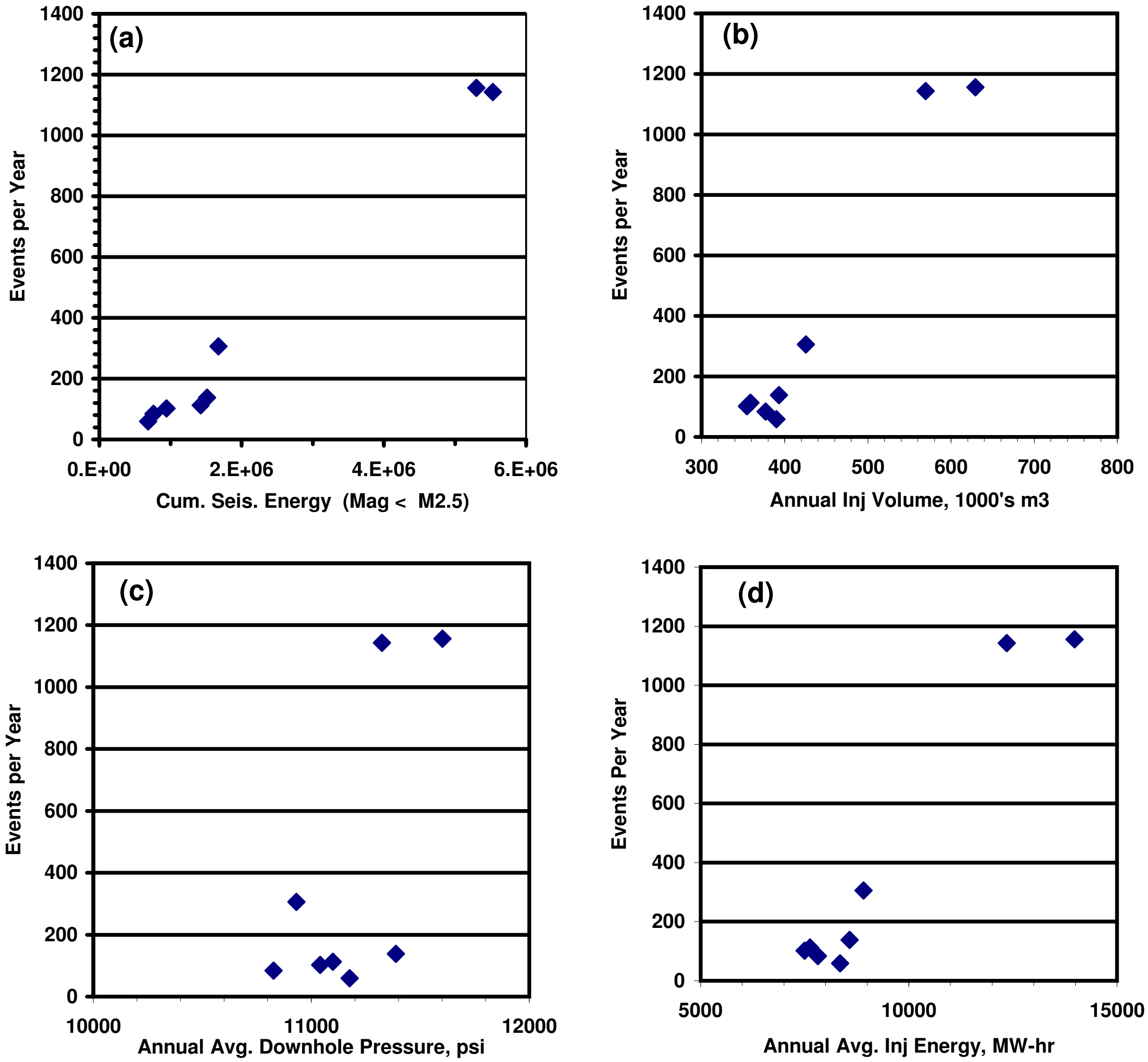


Figure 3-9 Total Number of Injection-Induced Seismic Events per Year for Each Year, 1998 Through 2005, as a Function of (a) Cumulative Seismic Energy for All Events M2.4 and smaller; (b) Annual Injection Volume; (c) Annualized Average Downhole Pressure; and (d) Annualized Average Injection Energy. In each figure, the two events at the top right are years 1998 and 1999.

day.) We mentioned using these figures for prediction because we foresee these plots as being beneficial if and when the maximum surface injection pressure (MSIP) at PVU is increased, as presently expected.

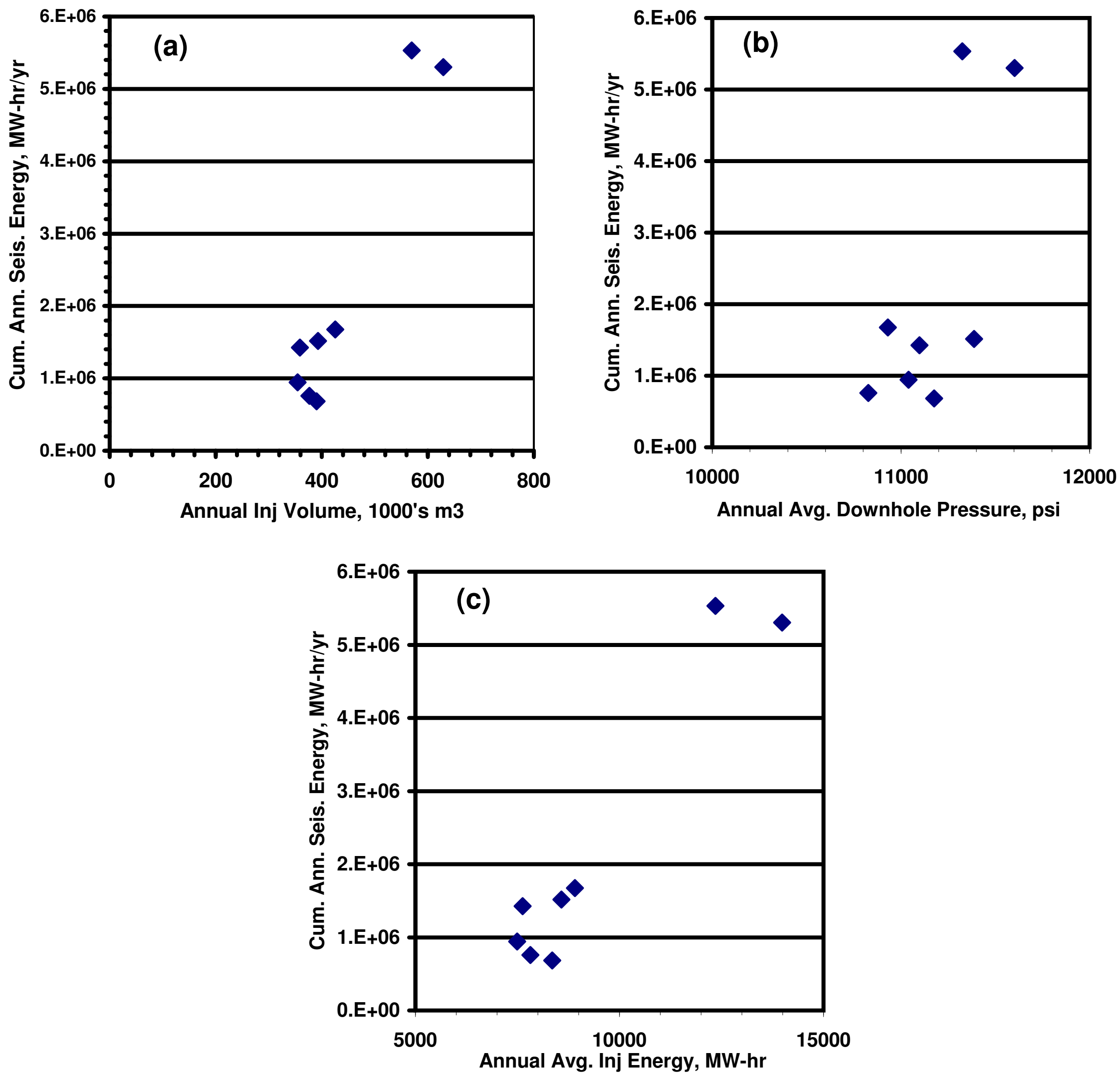


*Figure 3-10 Cumulative Annual Seismic Energy for Events with Magnitude < **M**2.5 from Years 1998 Through 2005 as a function of (a) Annual Injection Volume; (b) Annual Average Downhole Pressure; and (c) (Cumulative) Annual Average Injection Energy. In each figure, the two points at the top right are for years 1998 and 1999.*

4.0 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 4-1**, **Figure 4-2** & **Figure 4-3**). 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.

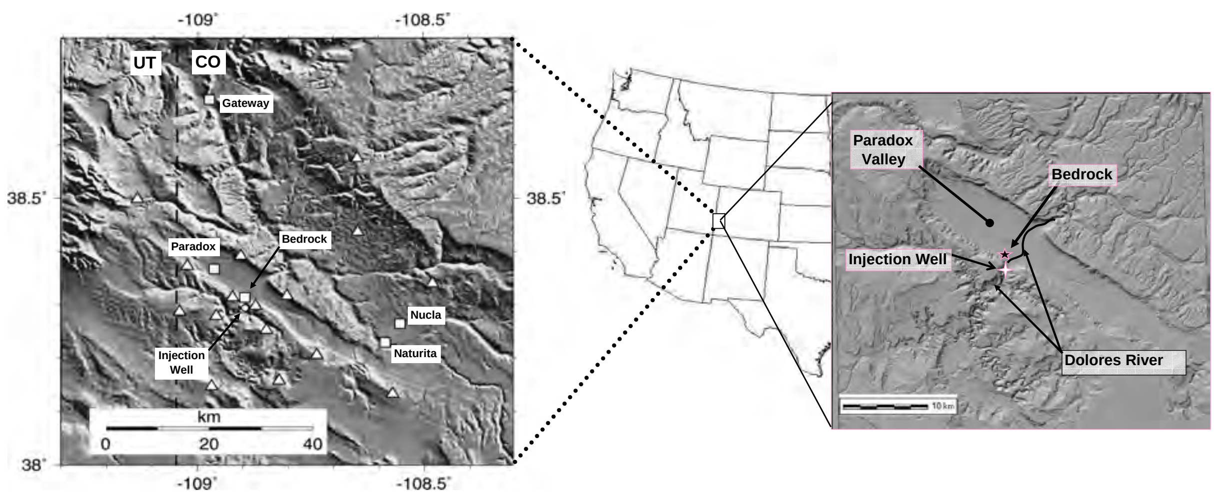


Figure 4-1 Location Map of Paradox Valley Unit, Dolores River, and Local Topography. See Figure 4-2 for expanded version of map.

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 Par-

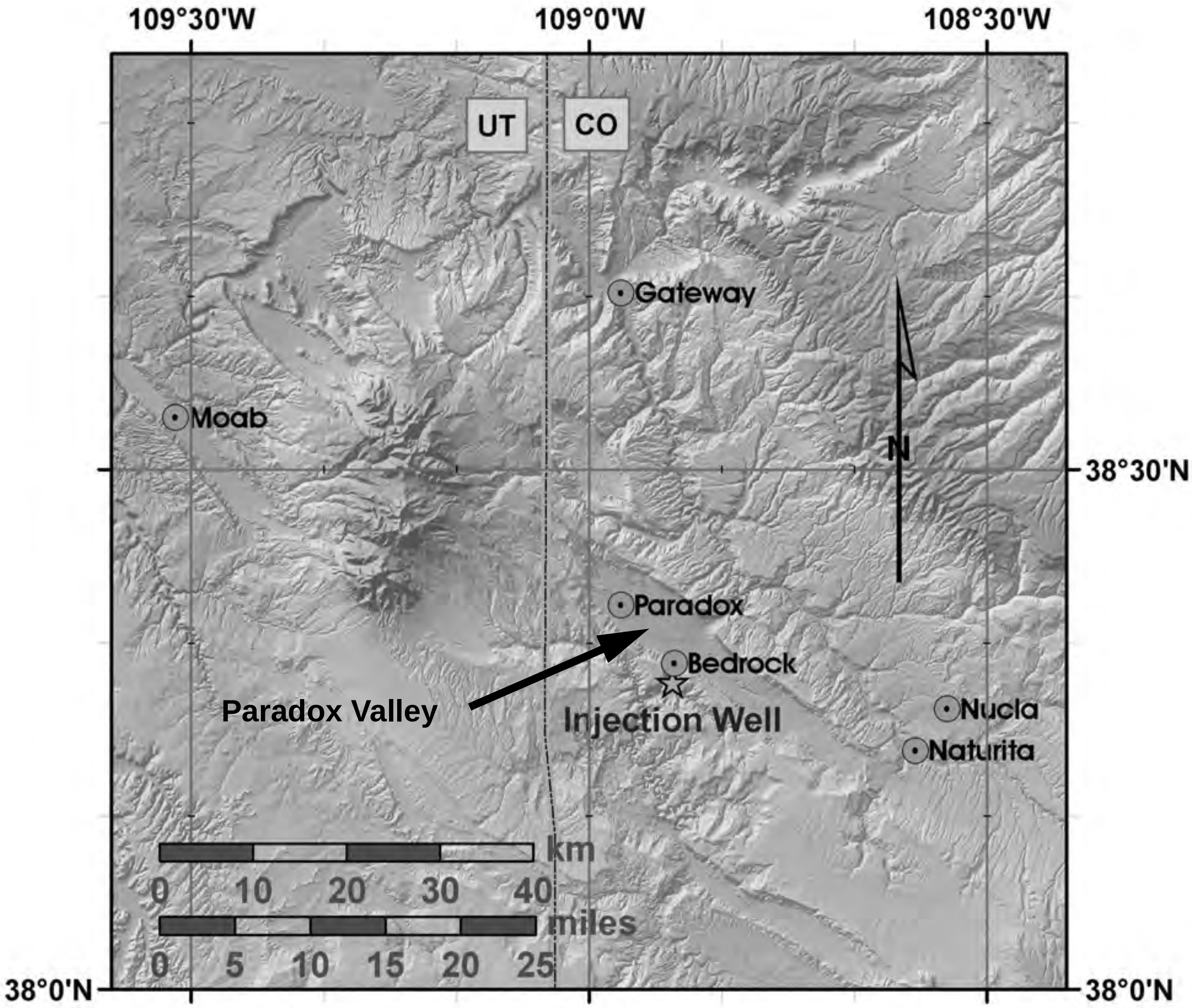


Figure 4-2 Local Topographic Setting of PVU Injection Well, Paradox Valley, Local and Regional Municipalities, and the La Sal Mountains between Paradox and Moab.

adox Valley. Currently, the Dolores River flows across the strike (i.e., axis) of the valley near Bedrock, CO (**Figure 4-2** and **Figure 4-3**).

The Dolores River originates in the San Juan Mountains southwest 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. Small tributaries in the unit 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

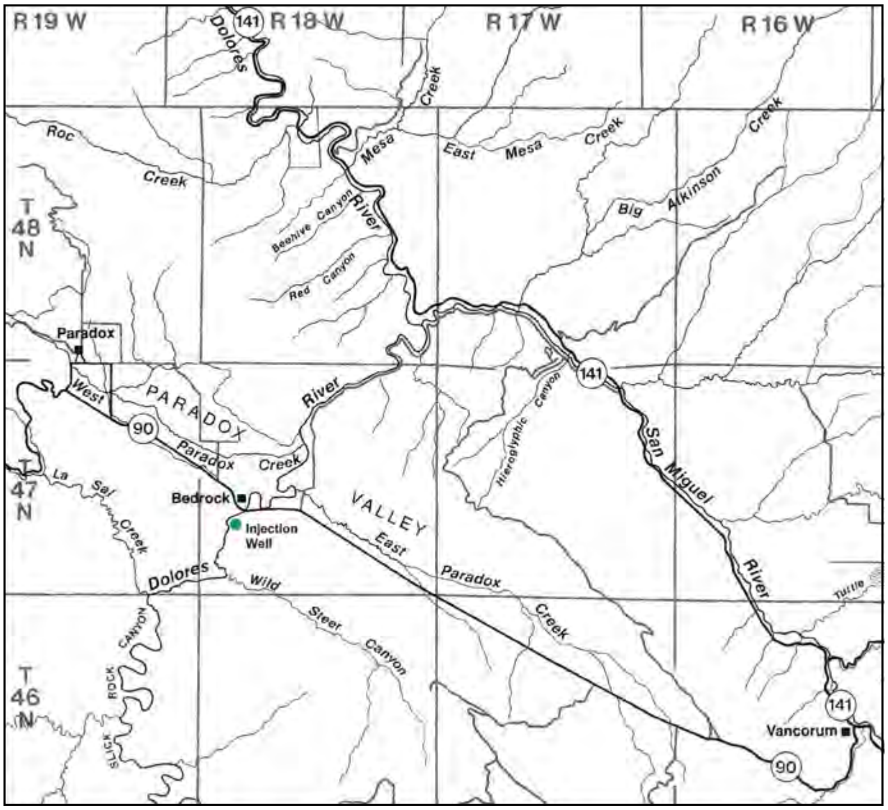


Figure 4-3 Paradox Valley Unit Injection Well and Local Geography. Figure is adapted from Parker (1992). Each square is approximately 10 km by 10 km.

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 the 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 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.

4.1 PVU Salinity Control Well No. 1

The PVU Salinity Control Well No. 1 (**Figure 4-4)** was completed in 1987 at a total depth (t.d.) of

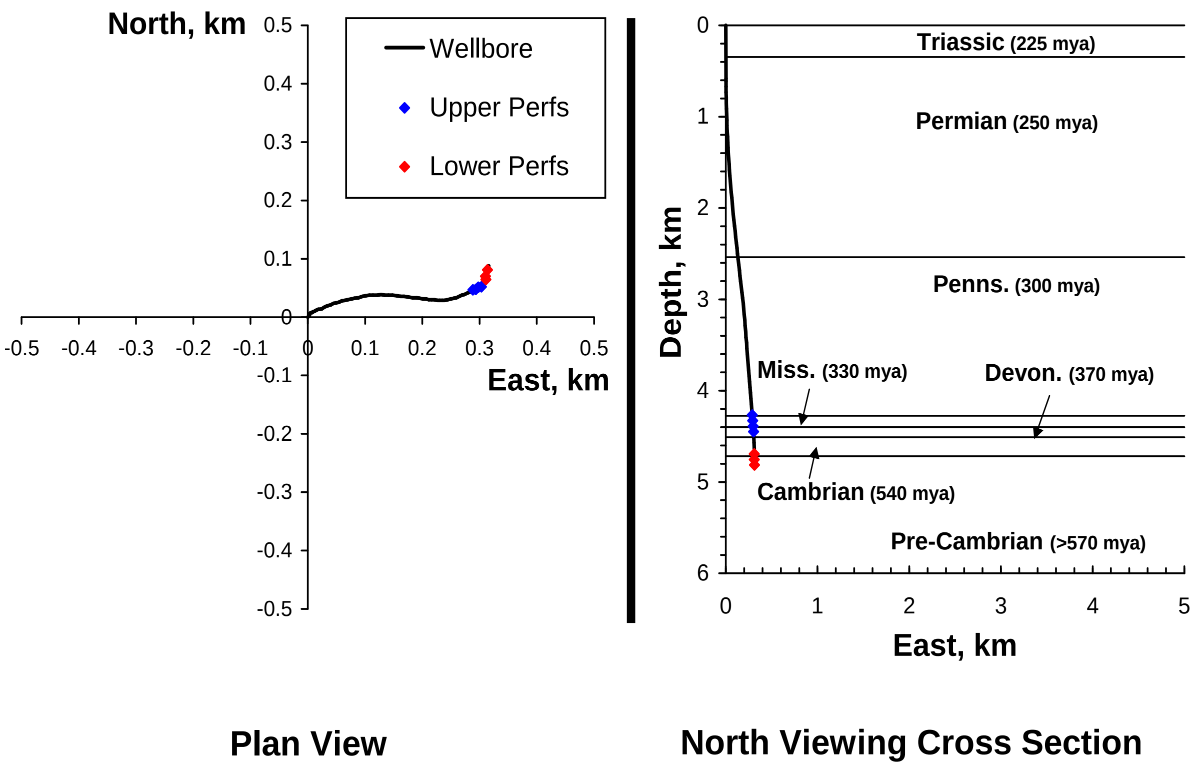


Figure 4-4 Plan View (left) and North-Viewing Cross Section (right) of PVU Injection Well: Salinity Control Well No. 1. Figures include the near-wellbore stratigraphic column, based on well logging of Salinity Control Well No. 1, and locations of casing perforations.

4.88 km (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 is located in SW SE section 30, township 47N, range 18 W Paradox Valley, Montrose County, CO. Its latitude and longitude are 38^{o} 17’ 43. 62” N (38.29545^{o} N) and 108^{o} 53’ 43.32” W (108.89537^{o} W), respectively. The wellhead elevation (i.e., ground surface) is

1.523 km (4,996 ft) above mean sea level. The Kelly bushing of the well, an elevation marker frequently used by drillers and well loggers, is listed at 9.8 m (32 ft) above ground surface.

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. Well-log-based, near-wellbore stratigraphy, the perforation intervals, and a plan view of the well are shown in **Figure 4-4**. 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.

4.2 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 4-2**). In their 1988 report, Bremkamp and Harr predicted that the 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 4-5** 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 4-5** west of the salt anticline (i.e., Paradox Valley) appears to be at the same level as the valley. However, the actual surface west of the valley shows a sharp elevation increase to plateaus (**Figure 4-1** and **Figure 4-2**). 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.]

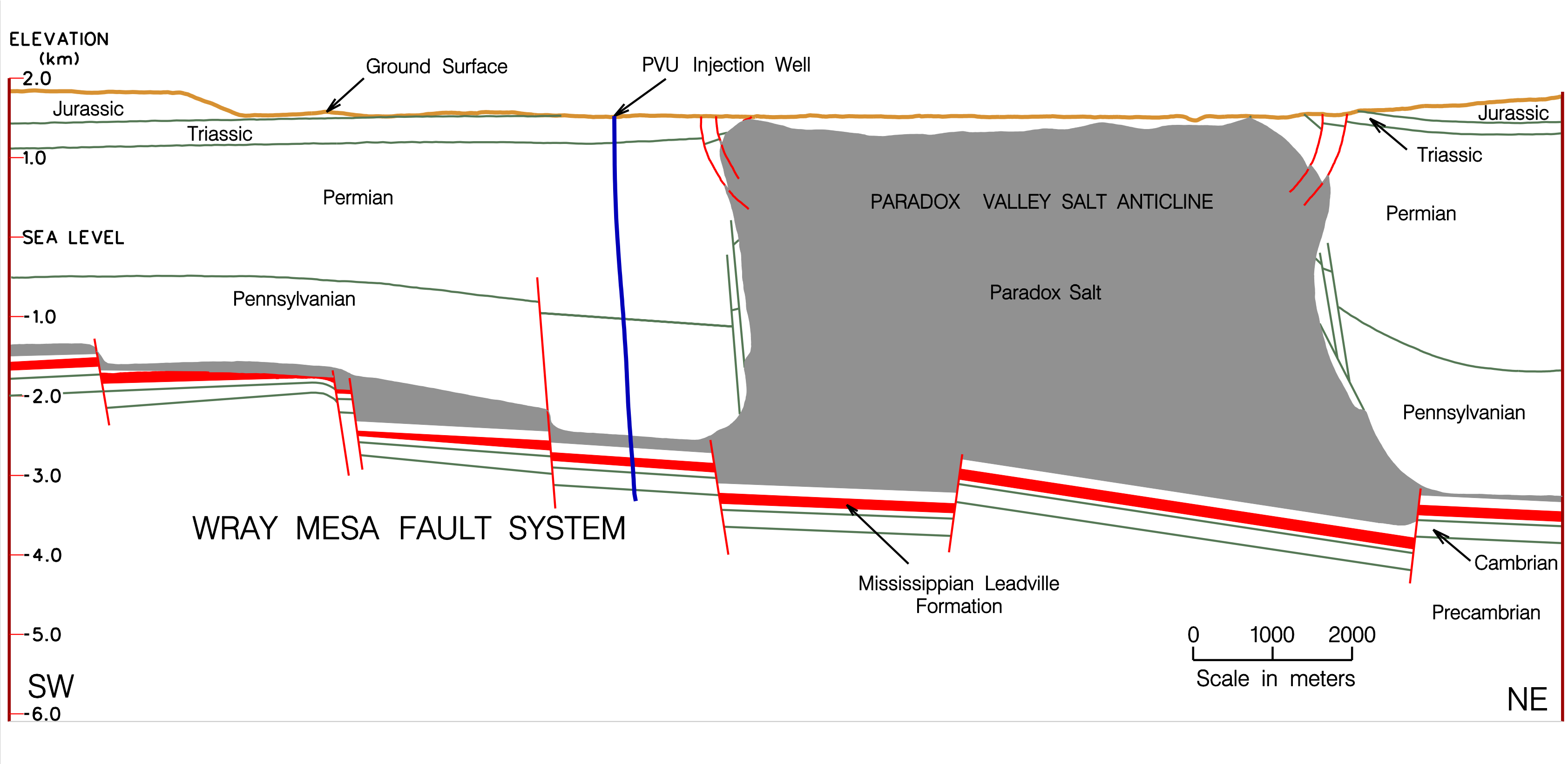


Figure 4-5 Bremkamp and Harr's (1988) Northeast-Southwest Cross Section Through Paradox Valley and its Bordering Region. Cross Section runs through the injection well and surface topography reflects surveyors path up the canyon of the Dolores River and not the local mesa topography.

5.0 PARADOX VALLEY SEISMIC NETWORK

5.1 Paradox Valley Seismic Network

The Paradox Valley Seismic Network (PVSN) is operated by the Bureau of Reclamation, Seismotectonics Group out of the Denver Federal Center and provides seismograph coverage for roughly 5500 km^2 of the Colorado Plateau centered on the intersection of the Dolores River and the west side of Paradox Valley (**Figure 5-1**). The first stations of PVSN were installed in late 1983 and the

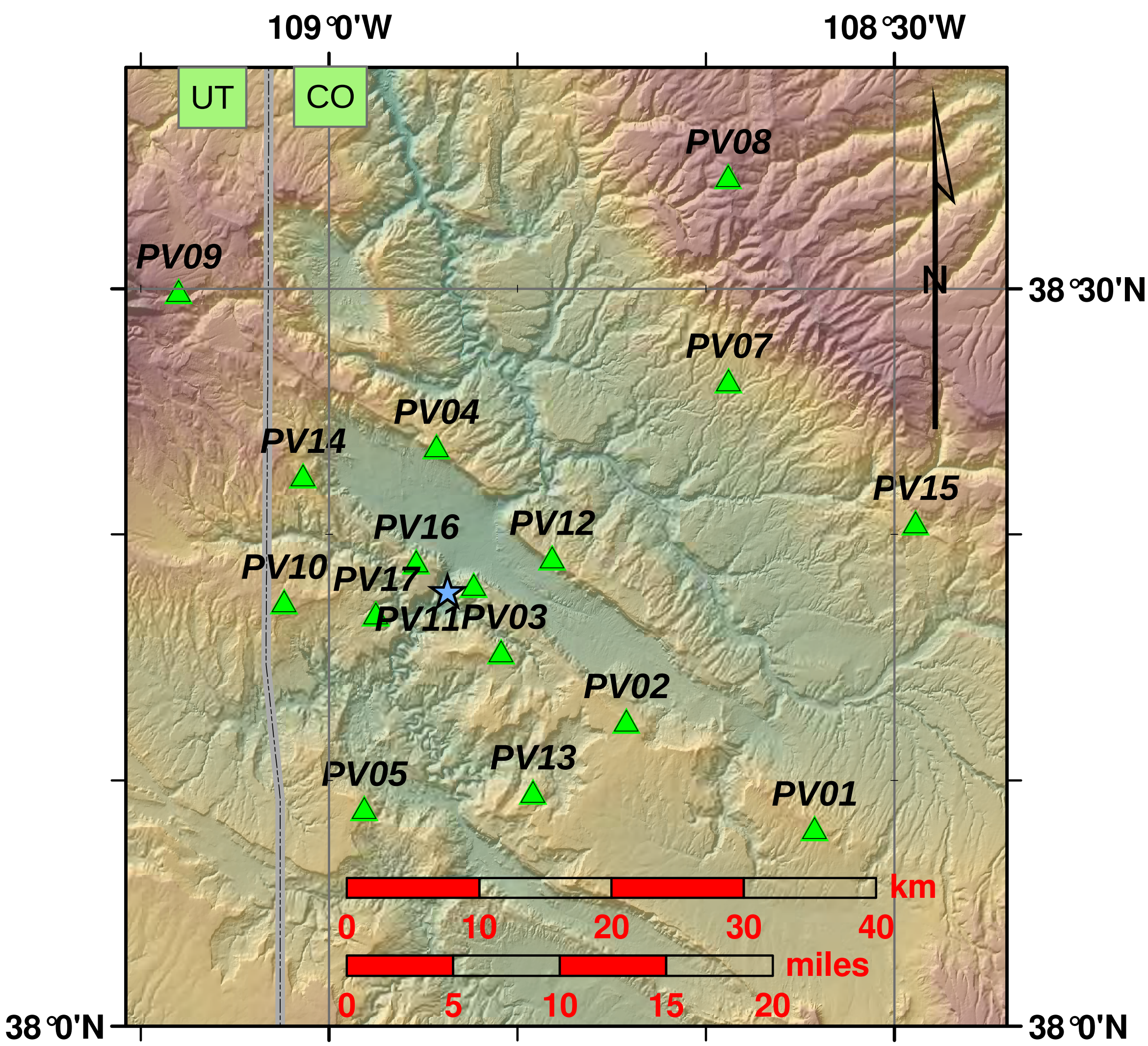


Figure 5-1 Locations and Names of the Paradox Valley Seismic Network Stations (triangles) and Injection Well (star) on Regional Topography.

network has operated continuously since that time. For each station shown in **Figure 5-1**, **Table** network has operated continuously since that time. Within the limits of terrain accessibility and radio telemetry linkage, the network is loosely arranged in two concentric rings centered on the brine injection well. The outer ring diameter is approximately 40 km. For each station shown in **Figure 5-1**, **Table 5-1** gives the station designation, latitude, longitude, elevation, installation date, station type (analog or digital) and number of components; **Table 5-2** gives the full station names and legal descriptions of the station locations. In 2000, for logistical reasons, PV08 was removed from PVSN.

Each PVSN analog station consists of one or three Teledyne Geotech S-13 ground motion sensors.

Table 5-1 PVSN Station Locations and Characteristics

Station Design.	Latitude deg., N	Longitude deg., W	Elev. m, msl	Date Inst;Updtd	Station Type	No. of Components
PV01	38.13	108.57	2190	5/83	analog	1
PV02	38.21	108.74	2158	5/83	analog	1
PV03	38.25	108.85	1975	5/83	analog	1
PV04	38.39	108.91	2152	5/83	analog	1
PV05	38.15	108.97	2150	5/83	analog	1
PV07	38.44	108.65	2001	6/83	analog	1
PV08	38.58	108.65	2941	6/83;removd	analog	1
PV09	38.50	109.13	2640	6/83	analog	1
PV10	38.29	109.04	2300	6/83	analog	1
PV11	38.30	108.87	1881	12/89	analog	3
PV12	38.32	108.80	2091	12/89;11/05	digital	3
PV13	38.16	108.82	2158	12/89	analog	1
PV14	38.37	109.02	2240	12/89	analog	1
PV15	38.34	108.48	2280	6/95	analog	1
PV16	38.32	108.92	2045	7/99	analog	3
PV17	38.28	108.96	1985	11/05	digital	3

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 number of components listed here are current as of the end of 2006.

Table 5-2 PVSN 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

(i.e., seismometer(s)), amplifier, voltage control oscillator (VCO), low-power analog telemetry radio, solar panel, and broadcast tower with antenna. The S-13 seismometer is a short-period, high-quality, reliable, ground velocity measuring instrument with flat response between 1 and 20 Hz (**Figure 5-2**). The external amplifiers and VCO's are also Teledyne Geotech (model 4250). The passband (i.e. filter) of each amplifier is set to minimize long-period noise (passband range: 0.2 - 25 Hz). The single-component stations have vertical-motion-only seismometers. The Davis Mesa and Nyswonger Mesa stations (PV11 and PV16, respectively) operate three-component S-13 seismometers, recording vertical, east-west, and north-south motion. All systems are powered by solar-recharged batteries. The signals from each analog PVSN site are broadcast to a receiver in Nucla, CO. At Nucla, these signals are digitized with a dynamic range of 16 bits at a sampling rate of 100 samples per second and then are transmitted as digital data to the Denver Federal Cen-

(PV11, PV16, PV12, and PV17, respectively), operate three-component seismometers, recording vertical, east-west, and north-south motion.

The Teledyne Geotech seismometers are Model S-13's, a high-quality, reliable, ground velocity measuring instrument with flat response between 1 and 20 Hz. At all sites, the amplifiers and VCO's are also Teledyne Geotech (model 4250). The pass band (i.e. filters) of each field amplifier is set to minimize long-period noise (**Table 5-1**). **Figure 5-2** shows the typical frequency

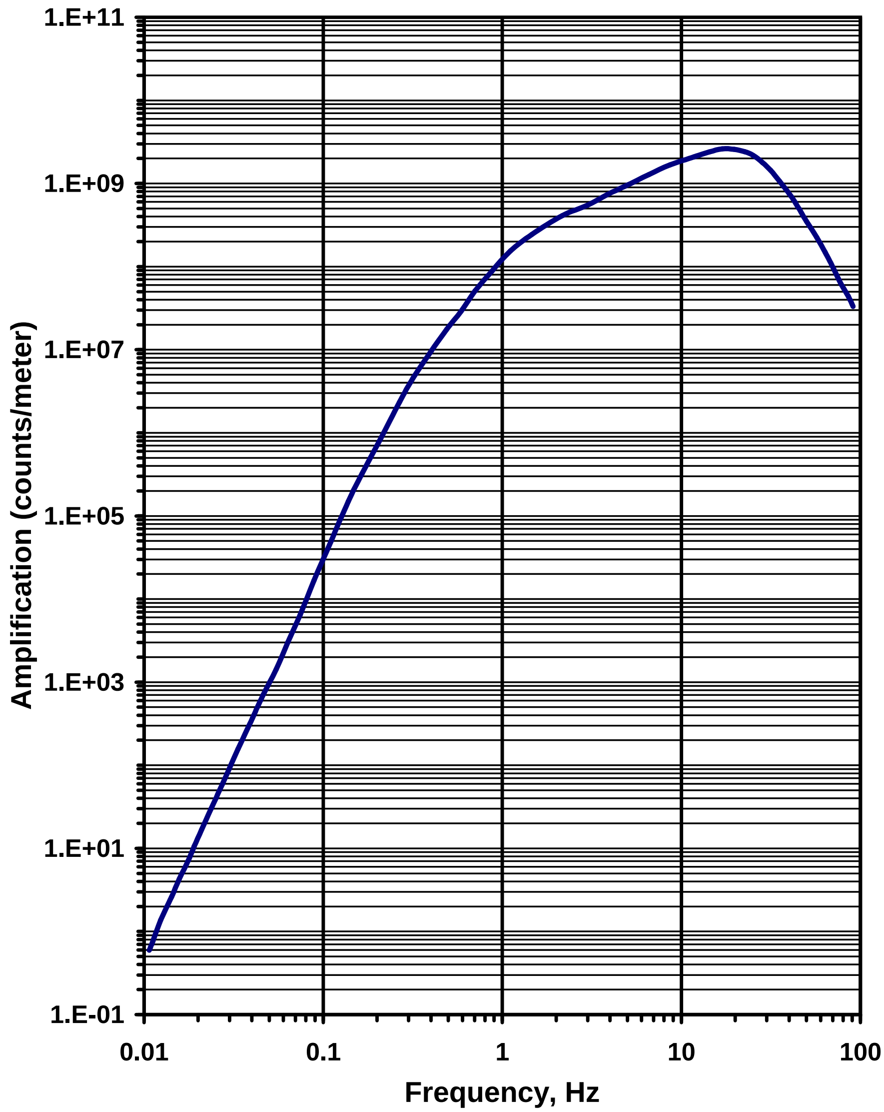


Figure 5-2 Typical System Response (i.e., amplification) of a Vertical-Component Teledyne Geotech S-13 Seismometer and the Electronics at Each PVSN site.

response/amplification curve of the full electronics and seismometer system at the PVSN sites with Teledyne seismometers. Nominal gain is 48 dB for the curve shown, Teledyne Geotech model 42.5 amplifier/voltage control oscillator (VCO) and model 4612 discriminator. Damping is 71% critical damping.

5.2 PV12 and PV17

In November of 2005, new equipment was added to PVSN. We reoutfitted site PV12 from a single component to a 3-component site and finished installing site PV17, also a 3-component site. Both sites are equipped with Guralp Model CMG - 40T. Of the 16 PVSN sites, 4 sites, PV11, PV12, PV16, and PV17, have 3-component motion sensors.

5.3 Paradox Data Digitization

PVSN data telemetry begins with continuous analog signals broadcast from each seismometer site to a receiver in Nucla, CO. At Nucla, these signals are each digitized at a frequency of 100 samples per second (Hz) and then are transmitted as digital data to the Denver Federal Center for analysis. All signals received by PVSN are comprised of a band of frequency components. Based on the Nyquist Theorem, any component of a digitized signal with frequencies higher than half the sampling frequency will be lost by the digitizing process. All components below half the sampling frequency are captured. The question arises as to whether 100 Hz is a high enough sampling frequency to capture the information within the signal or could vital information be lost by the digitalization these data at this rate. In the next section we show that information is not being lost.

5.4 Paradox Digital Sampling-Frequency Model

Below we construct a mathematical model of the expected frequency components of a typical signal from injection-induced seismicity at Paradox. To create this model, we used standard, accepted conventions from earthquake seismology. The mathematics of this model are beyond the scope of this report. However, we heuristically explain the model, its assumptions and results, and demonstrate that a 100-Hz sampling rate does not compromise (i.e., lose) any signal information from the Paradox seismicity.

Figure 5-3 shows a progression of the phenomenon that affect the final recorded data at each PVSN station. Each panel of the figure shows the frequency component of a typical signal after various stages of the signals development from nucleation at the source to digitization at the site or at Nucla.

Each stage (i.e., each panel) in **Figure 5-3** shows that the phenomenon at that stage changes the amplitude (i.e., the energy content) and frequency content of the signal. The output at each stage is the input of the next stage. That is, the curve shown in **Figure 5-3(a)** is the input to **Figure 5-3(b)**.

Figure 5-3(a) shows a typical frequency spectrum at the source for 3 different magnitude earthquakes (i.e., **M**0, **M**2, **M**4). To create these curves we used the accepted model: a single-corner ω^2 Brune source model (Brune, 1970, 1971). Note that the frequency content of each spectrum runs from 0.1 Hz to 500 Hz and shows significant seismic energy across this passband. The signal in **Figure 5-3(a)** contains all the source information that can be gleaned from seismic analysis. **Figure 5-3(b)** shows the spectrum after the seismic energy has propagated through the earth (i.e., a generalized Earth model with a propagation distance = 8 km). Propagating through the earth causes some loss of energy (i.e., called "path attenuation" with assumed quality factor, Q = 300; Lee and Wallace, 1995), as shown by the reduced amplitudes of the **Figure 5-3(a)** spectra compared to the **Figure 5-3(b)** spectra. **Figure 5-3(c)** shows the next stage of the model, energy loss by "near-surface attenuation" (i.e., called "kappa" with assumed kappa = 0.025 s; Anderson and Hough, 1984) caused as the signal reaches the Earth's surface, the location of the PVSN seismometry. Near-surface attenuation is a significant and unavoidable factor, as long as the seismometers are at the surface. Finally **Figure 5-3(d)** shows the effect of the PVSN system itself (see **Figure 5-2**) on the incoming signal (i.e., incoming signal = source + path-attenuated + near-surface attenuated) to the PVSN site seismometer and electronics. **Figure 5-3(d)** models the spectrum or frequency content of the signal from a typical PVSN station that would be recorded at Nucla for digitizing at 100-Hz sampling. Note that the portion of the signal in **Figure 5-3(d)** above 50 Hz (i.e. right of the dashed green line) is insignificant compared to the signal below 50 Hz. This

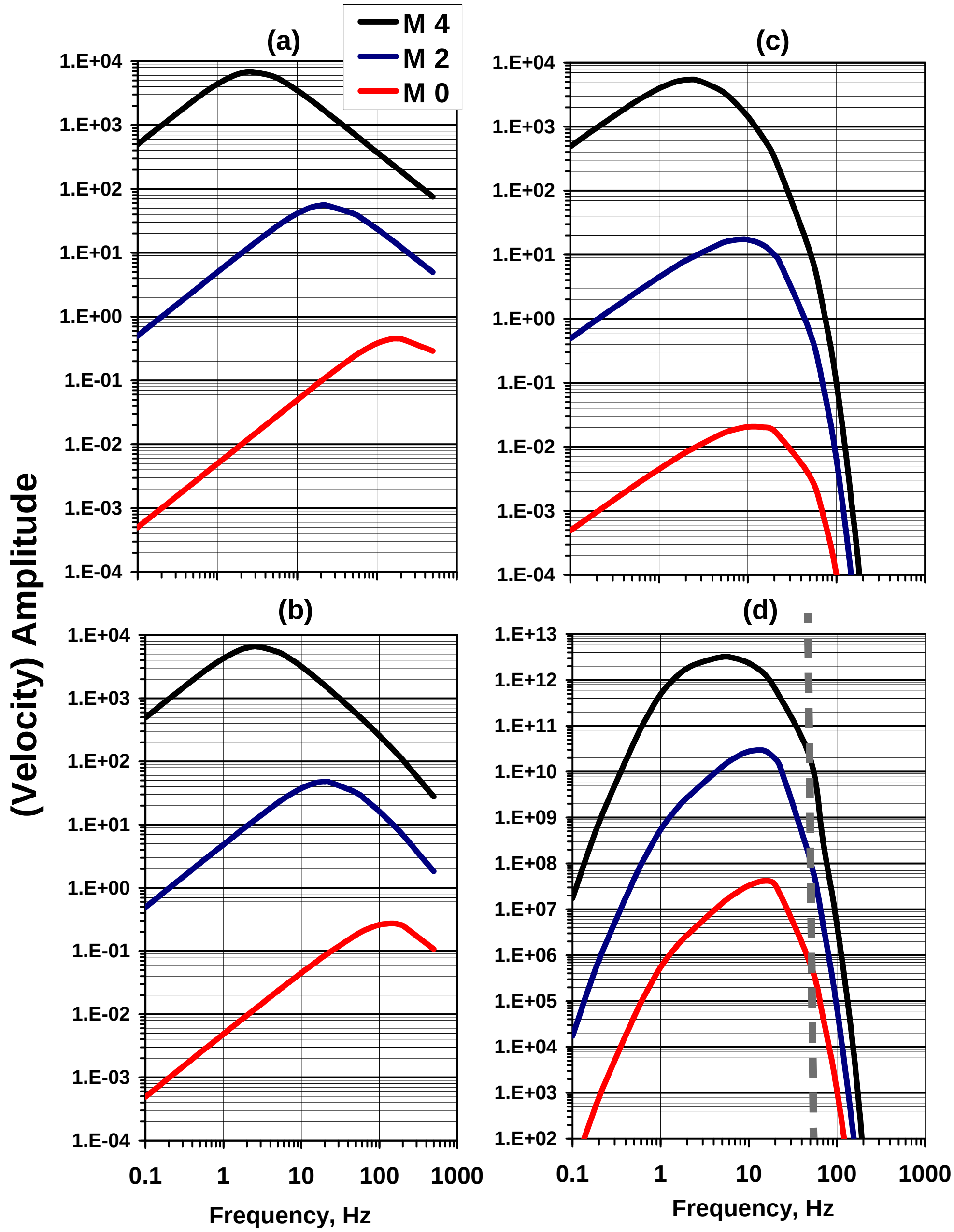


*Figure 5-3 Signal Spectra for Magnitude **M**0, **M**2, and **M**4 Events. Panel (a) shows source spectrum based on an ω^2 Brune Model; (b) shows the Brune Model combined with path attenuation; (c) shows the Brune Model and path attenuation combined with near-surface attenuation; and (d) shows the Brune Model, path attenuation and near-surface attenuation combined with the PVSN system response (Figure 5-2). Dashed (green) line in (d) is 50 Hz, half the 100-Hz digitizing frequency of the Paradox data.*

model shows, as stated earlier, that 100-Hz digital sampling captures nearly all of the energy (i.e., information) of signals generated at PVSN.

5.5 Telemetry and Software

In October of 2000, Reclamation upgraded the data telemetry system and the detection, location, and archiving software (Mahrer et al., 2001). Upgrading the software included adapting, refining, and implementing Earthworm, software developed by the US Geological Survey and used in its seismic arrays.

As noted above, at Nucla, the radio signals from each Teledyne-equipped PVSN site are digitized. The Guralp-equipped sites digitize at the site. At Nucla, the digitized data are transmitted via a digital telephone link to the Bureau of Reclamation processing center at the Denver Federal Center (DFC) in Lakewood, Colorado. At the DFC, Earthworm detects events in the data stream, then classifies, locates, and archives the detected events. Subsequently, each event is re-evaluated by a Bureau of Reclamation seismologist.

5.6 PVSN Strong Motion Instruments

In addition to the high-gain PVSN instruments/array noted in **Table 5-1** and **Table 5-2**, PVSN includes three strong-motion, digital-recording instruments. These instruments are Kinemetrics's Altus K2. One is sited near the injection wellhead (38.30^{o} N, 108.90^{o} W); a second instrument is at PVU's extraction well field (38.33^{o}N, 108.85^{o}W), and the third instrument (installed in 2005) is in downtown Paradox, next to the Paradox Community Center (21665 Road, Paradox, CO). **Figure 5-4** graphically shows the locations of these strong motion instrument stations. The wellhead and downtown instruments record data on an internal EpicSensor: the extraction field instrument uses an external Kinemetrics FBA-2 recorder. All three instruments are triggered instruments (i.e., they only record ground motion greater than a fixed amplitude) and all have direct telephone links to the DFC. The data from these instruments are not part of our normal analysis stream, but, if any of the instruments trigger, its data can be and has been integrated into the analysis. In the May 2000, **M**4.3 event, the data from two of these instruments were used for analysis, since the induced ground motion had overdriven the other high-gain PVSN instruments.

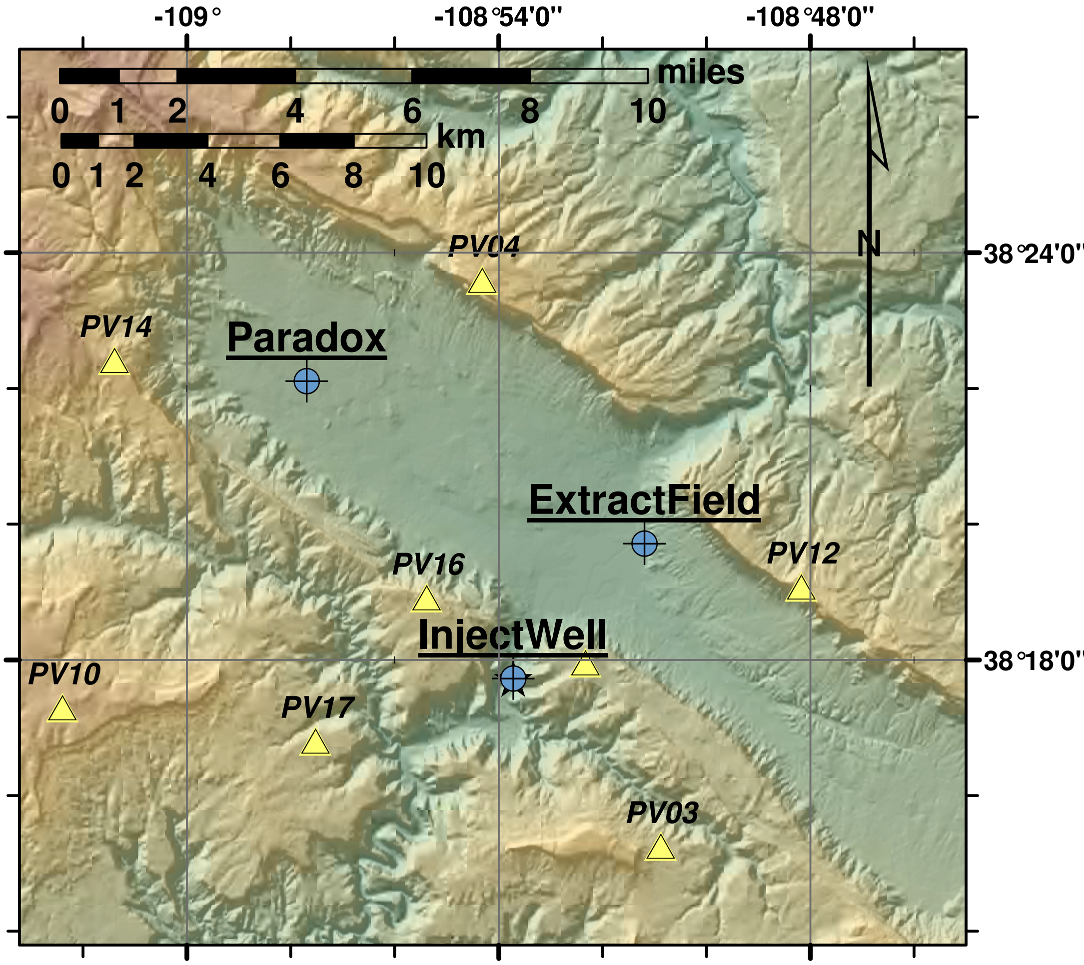


Figure 5-4 Names (underlines) and Locations (blue circles with centered "+" signs) of the PVSN Strong Motion Instrument Sites.

5.7 PVSN Detection Efficiency

[*Detection Efficiency (DE) is the percentage of day during the year that PVSN is capable of detecting seismic signals. Simply, even if some PVSN channels are not operating (see next section) the overall system can still detect events. DE is then related to phenomenon like power failures and system failures in which the DFC is not recording any data. The DE is calculated by dividing the number of days when at least some of the PVSN stations are operating by the number of days in a year and then multiply by 100%*]

DE quantifies the percentage of days per year in which seismic events could be recorded by PVSN. For example, if the DE is 80%, the system as a whole has been recording 80% of the time and we can assume that, as an average value, PVSN has detected and recorded 80% or 4/5ths of the events from PVU. We must be aware that this average value can be misleading: we do not know whether or not the 20% down-time consisted of aseismic, normally-active (i.e., seismic) or highly-active days. For example, in May '05 approximately 30% of the total number of events in 2005 occurred over 6 days. Hence, in subsequent analysis we present the annualized event statistics using only recorded data. As noted below in **Table 5-3,** PVSN's detection efficiency is typically above 95%. During 2005 it dropped to 91% with most of the reasons (e.g., aging, faulty equipment at Nucla airport; field sensors and ancillary equipment offline, being updated/replaced; power failures at the DFC) having been rectified.

Table 5-3 PVSN Detection Efficiency

Year	Total - Down Days*	Detection %
2000	24	93%
2001	**	---
2002	5	99%
2003	14.5	96%
2004	16	96%
2005	34	91%

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

5.8 PVSN (Daily-Average) Channel Efficiency

[*Channel Efficiency (CE) is the percentage of data channels online and working, based on 100% being all channels working, everyday for the whole year. The daily-averaged CE is calculated by summing the number of online, working PVSN data channels for each day of the year and dividing that total by 8760 (i.e., 24 channels x 365 days or 366 for leap year), the maximum number of possible data channel days for a year. If DFC witnesses a power failure resulting in the loss of data recording, this is included in the calculation as if all PVSN stations were down for the dura-*

tion of the power failure. Note also that a data channel may be entered as operating for a fractional part of a day. This can occur because the power at each site is a combination of solar cells (daytime) and batteries (night) and the batteries age and won't accept a full recharge from the solar cells. Thus a site will only be operational during daylight and none or limited hours at night. CE is important in evaluating the accuracy/error in the data analyses.]

During 2005, the seismic network and telemetry system operated at about 75% efficiency. Previous years averaged between 85% and 90% efficiency. **Figure 5-5** shows individual data channel online percentages and the operational efficiency of the whole network ("cumulative") for 2005. In the figure, the suffixes on PV11, PV12, PV16 and PV17, "Z", "N", and "E", correspond to the instruments that record vertical, north-south, and east-west motion, respectively, at these sites. **Figure 5-6** shows the total number of seismic data channels in operation at any time during 2005. Note the new channels mentioned earlier and on-line beginning in November. The data drop-outs in the figure were caused by short-term power failures and power (maintenance) shut downs at the DFC. Note also that throughout 2005, PV08 and PV14 were offline and PV07, PV03, and

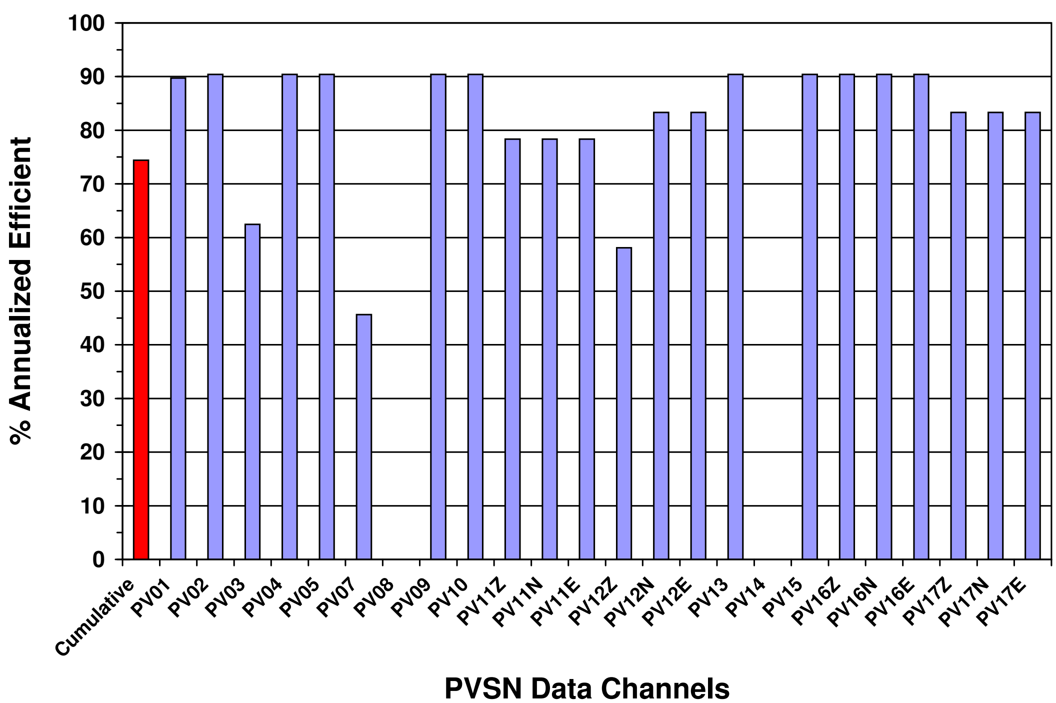


Figure 5-5 PVSN Operational Efficiency: Cumulative (red) and By Individual Data Channel (blue) for 2005.

PV12Z were marginal.

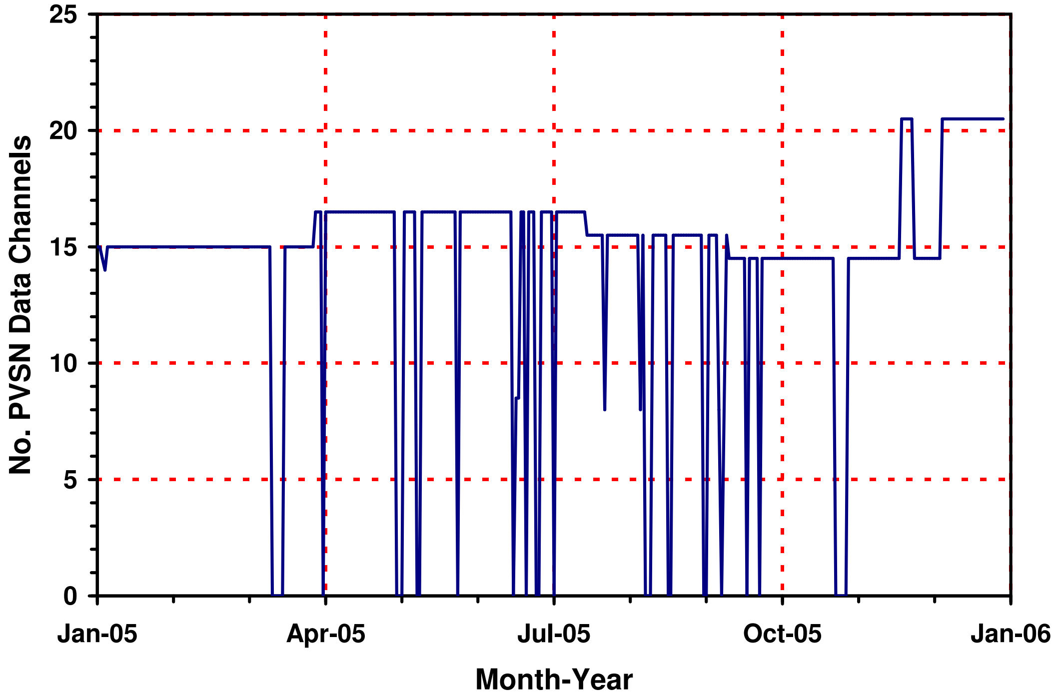


Figure 5-6 PVSN Channel Operations: Cumulative Number of Instrument Data Channels Online versus Time for 2005.

6.0 PVU INJECTION OPERATIONS

PVU operates the Salinity Control Well No. 1, which is located at 38.2995° N and 108.8953° W along the western boundary of Paradox Valley, approximately 1.5 km up the canyon formed by the Dolores River (**Figure 4-1**, **Figure 4-2** & **Figure 4-3**). As shown in **Figure 4-4**, the well is essentially vertical, deviating only ~0.3 km to the east and slightly to the north over its 4.8+ km depth. **Figure 4-4** also shows the two major perforation intervals of the wellbore casing. The upper perforation interval is within the primary injection target, the Mississippian-aged Leadville Limestone formation.

6.1 PVU Operations by Injection Phase

As noted throughout this report, 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 6-1** summarizes the injection phases. In the table the averaging of values includes both active pumping and shut-down days.

6.1.1 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. The injectate during *Phase I* was 70% Paradox Valley Brine (PVB), 30% fresh water. Throughout *Phase I*, injection was continuous with the exceptions of unscheduled mainte-

Table 6-1 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	1100	29.6	76.7	1029.6	70:30	No	2502
II	332	29.3	76.3	934.6	70:30	Yes	441
III	566	27.5	74.6	732	70:30	Yes	219
IV	1454+**	27.9	77.1	720	100:0	Yes	405

*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 12/31/05
***Includes all recorded events not only magnitude M>=0, as used in later analysis.
"**MPa**" = megapascals & 1 MPa = 145 psi; "**lpm**" = liter/minute & 1 lpm = 0.26 gal/minute

nance and pressure-diffusion shut downs. [*Note*: A pressure-diffusion shut down is a stoppage of injection because the wellhead pressure is approaching the wellhead safety limit. By shutting down injection and waiting, the pressure reduces to an acceptable margin from the safety limit of the surface facility; the pressure reduction is due to fluid diffusion into the reservoir rock matrix (i.e., diffusing from the pressured fractures and faults and invading the small fractures and pores of the rock matrix, thereby, increasing the volume containing the fluid and decreasing the fluid pressure).] During *Phase I*, pressure-diffusion shut downs were often and ran for minutes, hours, a few days. Maintenance shut downs run 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.

6.1.2 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). When injecting during this phase, injection continued at the same pressure and rate as *Phase I*.

6.1.3 Phase III - (23-June 2000 through 7-January 2002)

Following a magnitude **M**4.3 earthquake in May 2000, the largest to date, PVU reduced the injection rate ~33% to ~870 l/min (~230 gpm) while maintaining the 70:30 ratio of brine to fresh water and the bi-annual, 20-day shutdowns. The lower injection rate reduced surface pressure about 10%. This new injection rate constitutes *Phase III* injection.

6.1.4 Phase IV - (8-January 2002 through the Present)

In January 2002, PVU began *Phase IV*, injecting 100% brine (i.e., PVB) using the *Phase III* injection schedule: ~870 l/min (~230 gpm) and a scheduled 20-day shutdown every six months. Since the specific gravity of PVB is ~5% greater than the 70:30 mixture, surface pressures initially decreased while maintaining the same downhole pressure. [Note: At the beginning of *Phase IV*, the surface pressure was ~30 MPa (~4,400 psi), and downhole pressure was ~79 MPa (~11,500 psi). Figures giving injection pressure and injection rates along with induced seismicity per day can be found in chapter **8.0 OBSERVATIONS**.

6.2 PVU Injection History By Year

Table 6-2 summarizes PVU Well No. 1's annual injection history. For expected reader convenience, the values in **Table 6-2** are in standard units, millions of gallons (Mgal) and thousands of tons (ktons).

6.3 Injection Adjustments Explanation

As noted above, PVU has instituted 3 major injection changes, resulting in 4 injection phases. Each of these changes invoked a strategy either to help reduce unacceptable seismicity or to optimize brine emplacement. The motivations behind these strategies are discussed in the following sections.

Table 6-2 Annualized Summary of PVU Injection

Year	Phase	Injectate (approx.)	Paradox Valley Brine (approx.)	Salt Disposed (approx.)
		Mgal	**Mgal**	**ktons**
1991	Tests	11.7	3.9	4.3
1992	Tests	9.8	7.8	8.4
1993	Tests	26.2	10.0	10.8
1994	Tests	81.7	58.7	63.7
1995	Tests	34.4	24.1	26.2
1996	*Phase I*	44.6	31.1	33.7
1997	*Phase I*	127.8	89.4	97.0
1998	*Phase I*	166.2	116.1	126.0
1999	*Phases I & II*	150.4	104.5	113.3
2000	*Phases II & III*	112.4	85.4	92.7
2001	*Phase III*	99.6	69.7	75.6
2002	*Phase IV*	103.0	103.0	111.8
2003	*Phase IV*	104.2	104.2	113.0
2004	*Phase IV*	94.8	94.8	102.8
2005	*Phase IV*	93.6	93.6	101.5
TOTAL	**--**	**1,261**	**996**	**1080**

6.3.1 Bi-Annual Shutdowns

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). Scheduled shut-downs were implemented to mitigate seismicity following the **M**3.5 event and a month later the **M**3.6 event in mid 1999. Prior to these events, we had noted that the rate of seismicity in the near-wellbore region (i.e., within about a 2-km radius from the wellbore) reduced during and following unscheduled, maintenance shutdowns and during the shutdowns following the injection tests of

1991 through 1995. Based on these observations and following the two mid-1999 (large) events, PVU began a program of two scheduled, 20-day shutdowns each year, one in December-January and one in May-June. As detailed below (e.g., **Figure 8-4**), the shut downs reduced the seismicity, but did not sufficiently reduce the proclivity to produce large seismic events.

During 2005, PVU witnessed all or parts of three, scheduled shutdowns: 12/19/04 to 1/5/05, 5/27/05 to 6/15/05, and 11/13/05 to 1/24/06.

6.3.2 Reduced Injection Rate

Prior to May 27, 2000, PVU pumped injectate at a maximum rate of ~ 1,100 lpm (1,100 lpm =345 gal/min). To maintain this rate, 3 constant-rate pumps were used with each operating at ~115 gpm. This rate resulted in an average wellhead pressure of ~4,800+ psi.

During 3-pump operations, 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 sometime two pumps, reducing injection rate, and letting pressure drop a few hundred psi before returning to 3-pump operations; this resulted in an overall average injection rate of ~300 gpm. These shut-downs normally lasted hours.

Immediately following the May 27, 2000 **M**4.3 event, PVU shutdown 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, resulting in an injection rate of ~230 gpm. At this reduced rate, surface pressure normalized between ~4,400 and 4,500 psi. When first initiated, it was believed that reducing the injection rate combined with previously-instituted, bi-annual 20-day shutdowns would reduce the potential for large events. Together, the bi-annual, 20-day shutdowns and lower injection rate reduced earthquake production. From 1998 through the **M**4.3 event, PVSN recorded an average ~81 earthquakes/month; following the reduced injection in late June 2000 through the end of 2001, that average dropped to ~13 earthquakes/month.

As demonstrated by the May 27th 2000 event, 20-day shutdowns alone were not sufficient for stemming large event production. The combination of shutdowns and reduced injection rate is not a perfect solution; however, these are the only means to date that we have found to mitigate unacceptable seismicity. No matter what method of event control or mitigation is invoked, mitigation is not equivalent to elimination. As we understand seismic source generation, larger (i.e., **M**3 or greater) events are still probable, as demonstrated by the November 7, 2004 **M**3.9 event. However, we believe that careful monitoring and the methods discussed above will continue to minimize the rate of event production.

6.3.3 Injectate: 70%:30% PVB:Fresh Versus 100% PVB

Beginning with continuous operations in 1996, PVU diluted the injectate to 70% PVB and 30% Dolores River fresh water. A geochemical study had predicted 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, injection 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. Injecting 100% PVB began on January 8, 2001, after the December-January-2001 20-day shutdown, and has been maintained throughout 2005. To date, the only affect has been increasing bottom hole pressure because of the increased density of 100% PVB over the 70%:30% mix. No discernible affect on the induced seismicity has been seen.

7.0 SEISMIC ANALYSIS METHODS

7.1 Local Seismic Magnitude Scale

Typically, seismologists calculate the size of an earthquake using one or more methods. In most cases, seismologists calculate magnitude for local events following a procedure calibrated for local conditions. For PVSN, we compute magnitudes from the duration of the recorded signal. This scale, called the duration or coda magnitude, is denoted **M** in this report. [For a more complete discussion of the magnitude scale for PVSN see 2000 PVSN Annual Report (Mahrer et al., 2001) and given on the accompanying CD.]

7.2 Typical Seismograms from PVU

The following figure, **Figure 7-1**, shows typical seismic signals (i.e., seismograms) recorded by PVSN and induced by PVU injection. **Figure 7-1(a)** is an **M**0.9 event recorded on January 29, 1994; **Figure 7-1(b)** is also an **M**0.9 event but was located about 3 m from **(a)** and was recorded in February 7, 1994; **Figure 7-1(c)** is also an **M**0.9 event located about 9 m from **(a)** but was recorded on February 11, 1997; and **Figure 7-1(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 uses a 4-pole, zero-phase Bessel filter.

7.3 Preliminary Event Location Method

Accurately locating earthquakes requires (1) identifying arrival times of specific phases in the recorded signals, (2) appropriate array geometry, and (3) an accurate velocity model of the region through which the signals travel. As noted above, seismologists manually pick the phase 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 pick the primary or P-wave arrival times from all stations with acceptable signal-to-noise ratios. We then pick secondary or S-wave arrival times from only the three-component stations PV11, PV12, PV 16 and PV17 and from the closest single-component station to the injection

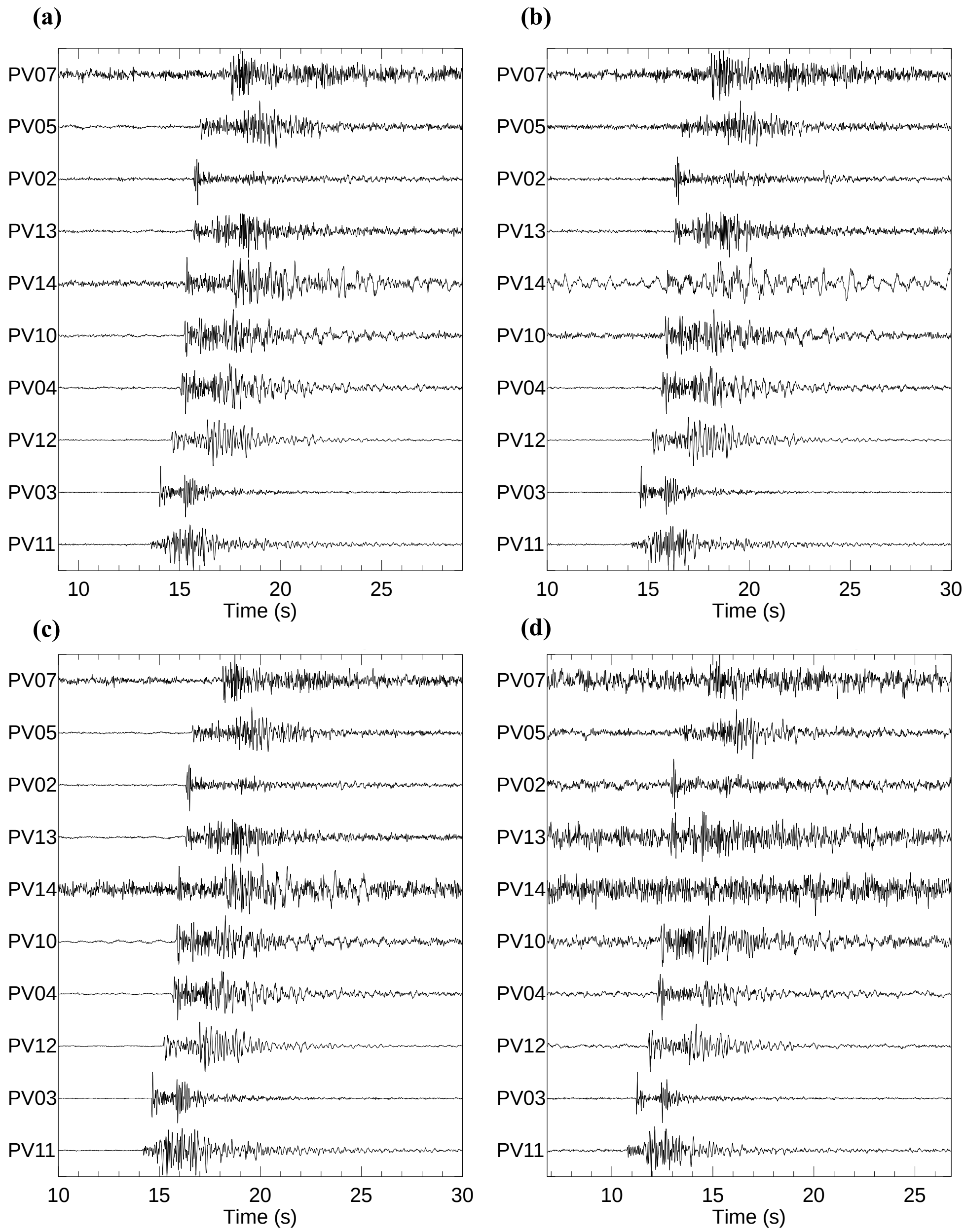


Figure 7-1 Examples of Vertical-Component Seismograms from Four Closely-Spaced Events Recorded by the Indicated PVSN stations.

well, PV03 (Wild Steer). Although S-wave arrival times are very important to the analysis, we use only these stations because of the closeness of the sources to these stations and the difficulty with correctly picking S-wave phases from vertical-only signals. For the other stations of PVSN, the complexity in the local geology leads to mis-identifying S-phases which causes mis-locating events.

We currently determine preliminary earthquake locations using a flat, one-dimensional, layered earth velocity model and the computer program SPONG (Malone and Weaver, 1986). [For a complete description of our Premininary Event Location Scale, see the 2003 PVSN Annual Report (Mahrer, et al, 2004) on the accompanying CD.]

7.4 Advanced Analysis: Event Re-Location

To evaluate the potential relationship of seismicity to reservoir and fluid transport characteristics, we made a significant effort to improve the accuracy of the preliminary earthquake locations (see previous section). First, we developed a three-dimensional velocity model for the Paradox Valley area using a progressive, three-dimensional velocity-hypocenter inversion (Block, 1991). In this inversion, we used a data set consisting of 682 earthquakes with **M** greater than **M**0.7 and good signal-to-noise ratios. Second, we performed a relative relocation of as many earthquakes as possible (i.e., clean waveforms with strong signal-to-noise ratios) using the three-dimensional velocity model developed in the first step (Waldhauser and others, 1999). Approximately 95% of the events recorded between 1991 and 2005 had sufficient signal-to-noise ratios to be included in the relative relocation. For the remaining events we used the original one-dimensional model locations. As an example of the effect on epicentral location by the relative relocation procedure, **Figure 7-2** shows the 1-D (i.e., preliminary) located and the relative relocation epicenters for 2005. Note the tighter groupings of epicenters from the relative relocation method.

The immediate goal of this modeling is reducing the arrival-time root-mean-square (rms) residuals (i.e., the difference between the observed and the model or theoretical travel times). Compared to the one-dimensional model residuals, the three-dimensional velocity model reduced the rms residuals by ~14%. The relative relocation procedure resulted in more than a 90% reduction in rms residuals relative to the three-dimensional results. The final, most-accurate earthquake epicenters for the 1991 through 2005 seismic data are shown in **Figure 7-3** The linear groupings of seismic event epicenters is quite evident in this figure.

As discussed in previous annual reports (e.g., Ake et al., 2000; Mahrer et al., 2001), the loci of

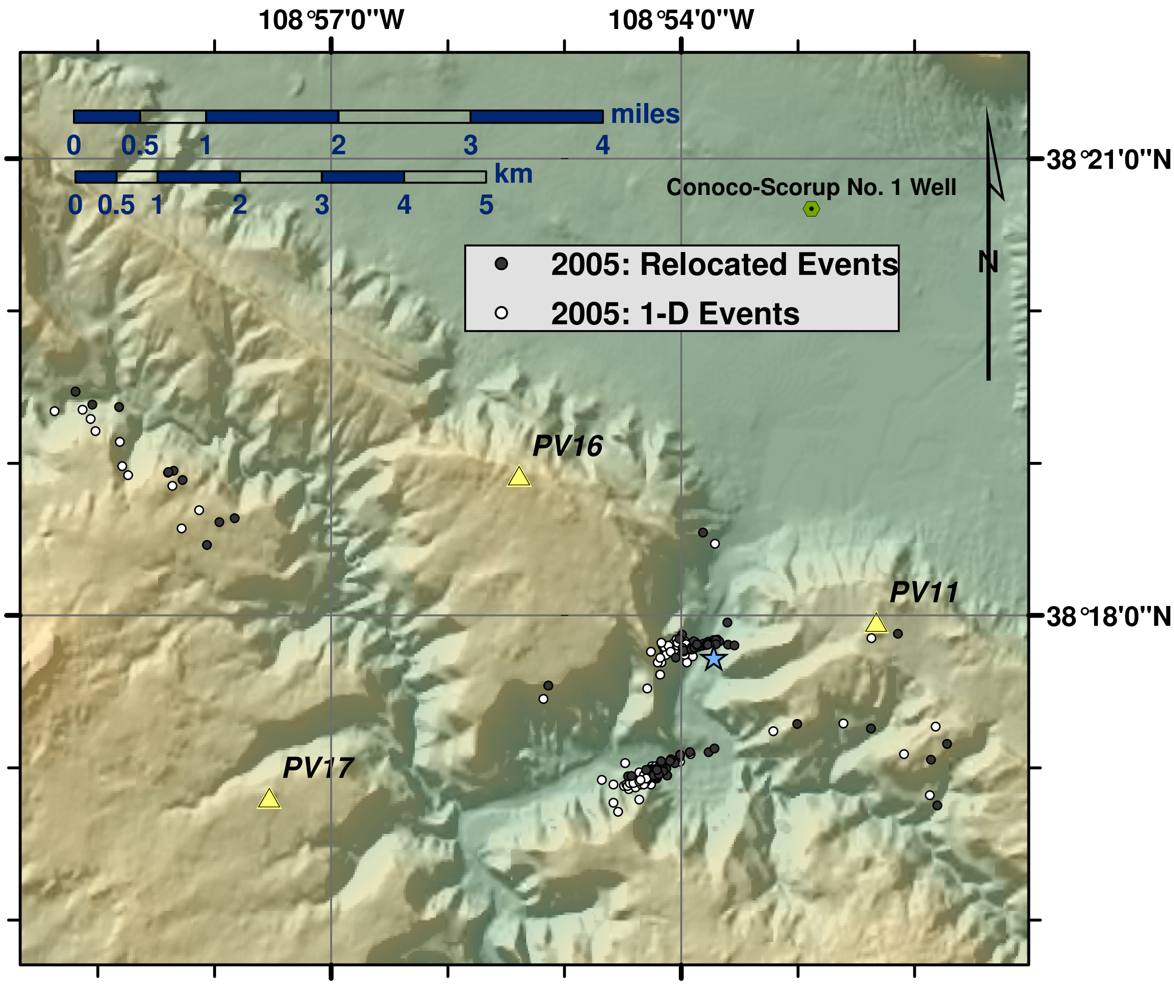


Figure 7-2 Comparison of 2005 Epicenters Determined by the 1-D Model and by the Relative Relocation Method. Star is Injection Well; Triangles are named PVSN sites.

relocated earthquakes are consistent with our interpretation that most of the tectonic stress release takes place along (existing) linear features with orientations consistent with either the two sets of focal mechanisms (set 1: N81°W and N9°E; set 2: N21°W and N69°E) or the two sets of fractures observed in the oriented core samples (primary: N69°W and N74°W; secondary: N38°W and N42W; Ake and Mahrer, 1999). Very little seismicity appears to be occurring along planes with strike consistent with the Wray Mesa fault system, as defined by Bremkamp and Harr (1988). Bremkamp and Harr (1988) estimated the strike of the Wray Mesa fault system to be ~N55°W. It is likely that these features are the most through-going structures in the area. The locations of the linear features in **Figure 7-3** suggests communication through "conduits" in a ~N55°W direction.

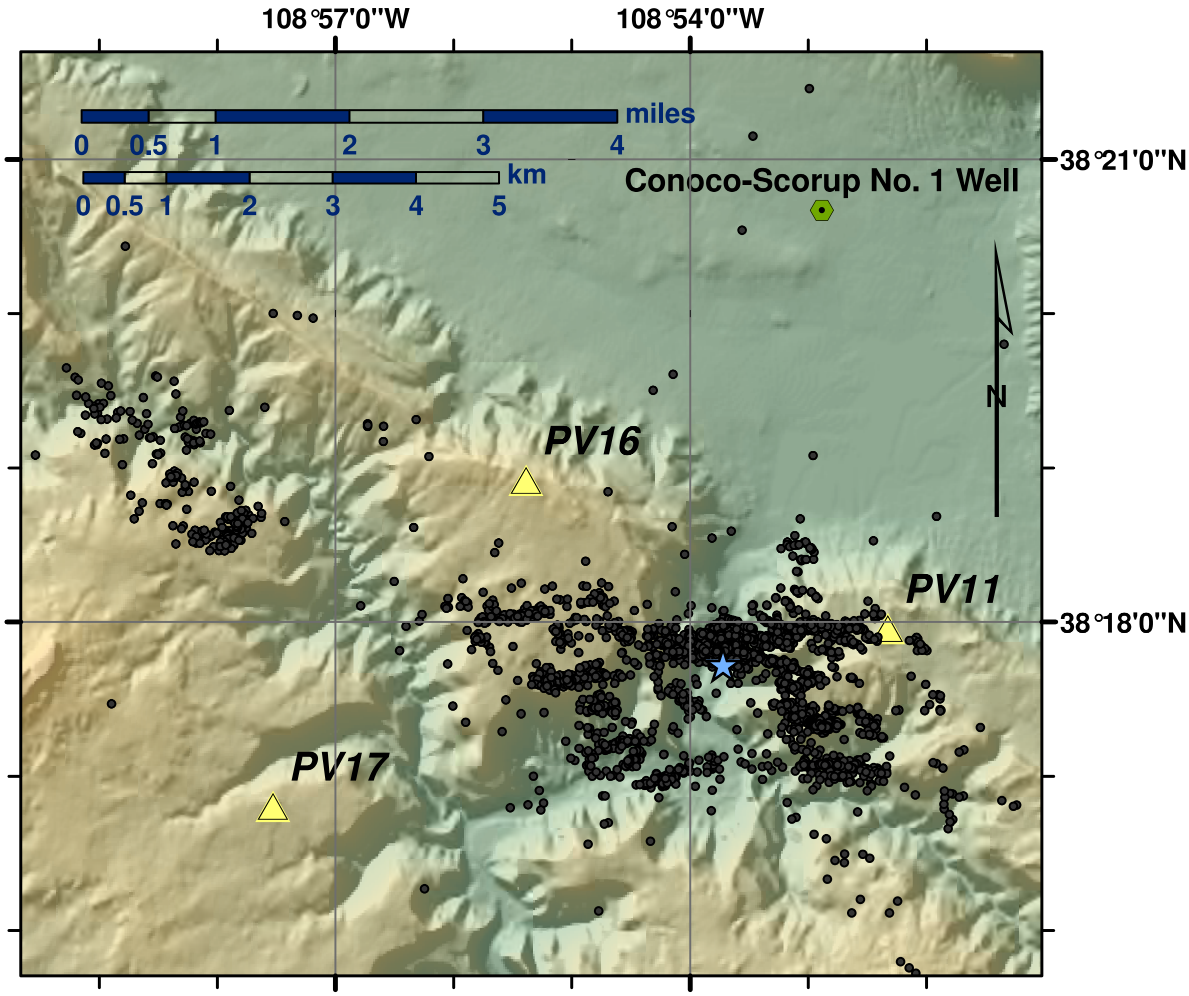


Figure 7-3 Relative-Relocated, PVU Injection-Induced Seismic Epicenters from 1991 Through 2005. Star in center of main event cluster is the injection well; triangles are sites of named PVSN stations.

We believe this behavior suggests fluid is being preferentially carried along these steep planes with a northwest strike (i.e., the through-going elements of the Wray Mesa system). Opening of these planes will require the least energy and are less likely to induce surface-measurable events, since these planes are oriented normal to the least principal stress direction.

8.0 OBSERVATIONS

8.1 Local, Pre-Injection Seismicity

In the 1960's, the US Army high-pressure injected waste fluids ~3,000 m deep at the Denver Arsenal, north east of Denver, CO. As a result, hundreds of seismic events were induced (Healy, 1968) in a nominally aseismic region. Recognizing the implication, that the proposed injection at Paradox Valley would, most likely, induce seismicity, Reclamation prepared to record pre-injection, background seismicity in the region surrounding the proposed Paradox injection site. In 1983 the US Geological Survey began installing the first 10 stations of PVSN, PV01 through PV10 (PV06 eventually became PV15); recording seismic data began in 1986, 5 years prior to the PVU injection tests. **Figure 8-1** shows the epicenters of the pre-injection data. None of the earthquakes were within 15 km of the future injection well.

From the injection tests in 1991 through 2005, PVSN recorded and located more than 4,200 events within 10 km of the injection well. Based on the lack of pre-injection seismicity, we can safely infer that PVU injection induced these events.

8.2 Seismic Events and Well Testing (1991-1995)

As shown in **Figure 8-1**, prior to injection at PVU, the Paradox Valley region witnessed few seismic events (EnviroCorp, 1995; Ake and others, 1996) and none close to the injection well site. 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. The tests were implemented to qualify the well for an EPA Class V disposal well permit. (PVU Injection Well No. 1 is permitted as an EPA Class I well -- Isolate hazardous, industrial, and municipal wastes through deep injection -- run under EPA Class V guidelines -- Manage the shallow injection of all fluids to prevent contamination of drinking water resources.) **Table 8-1** summarizes the injection tests including injected volume, pumping duration, and number of local (i.e., induced) seismic events recorded. In conjunction with **Table 8-1**, **Figure 8-2** shows the injection rate and induced seismic events per day. The boxed numbers at the top of the figure identify the

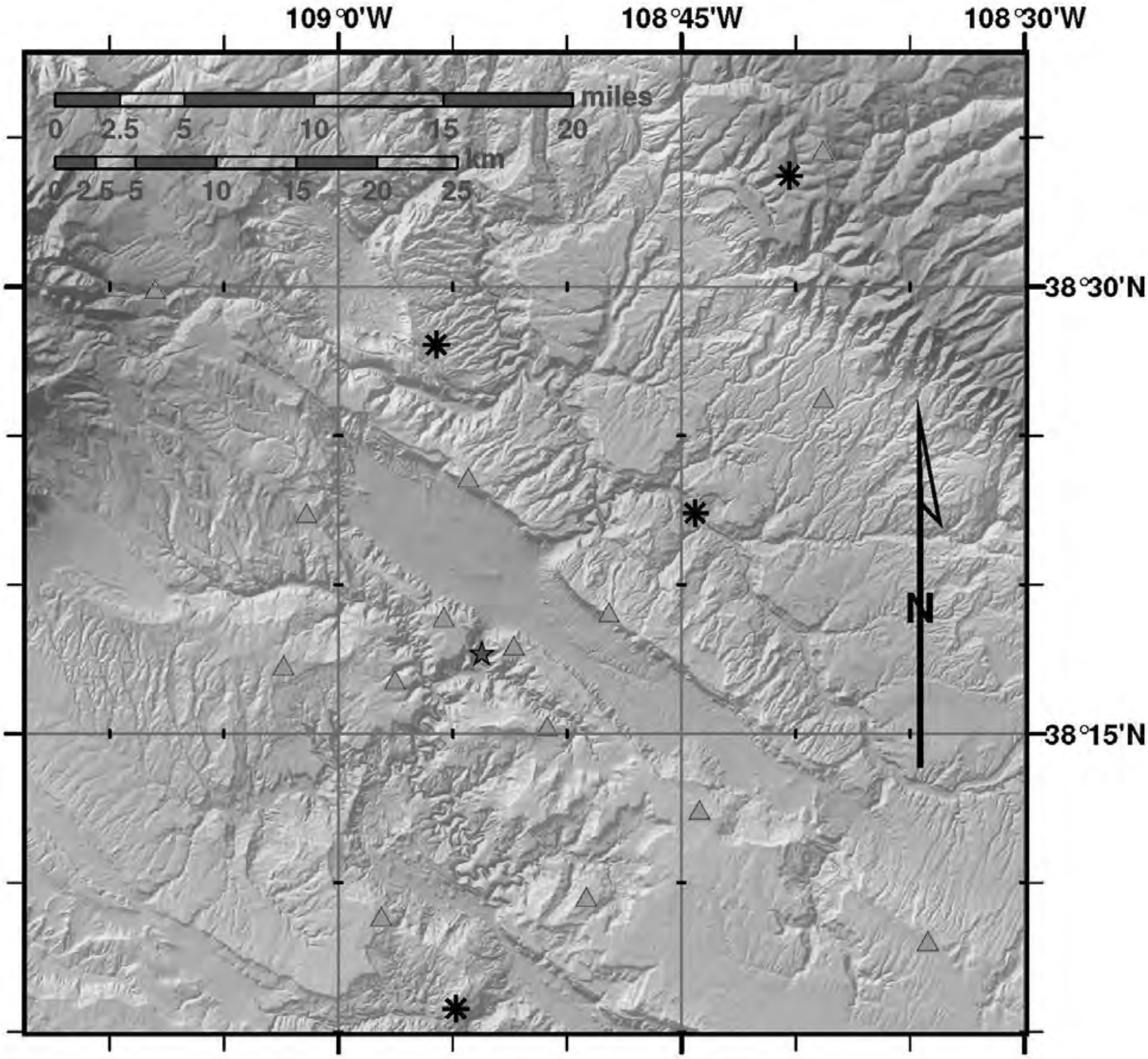


Figure 8-1 Paradox Region Natural Seismicity Recorded in 1985-1991. Asterisks are the epicenters of the natural seismicity, triangles show PVSN sites, and the star is the injection well.

tests; the boxed numbers at the bottom of the figure are the number of seismic events recorded during and immediately following the specific tests. Also noted in the figure is the 1993 acid stimulation. The stimulation was performed to increase the imbibition of the well (Envirocorp, 1995). **Figure 8-3** shows the cumulative epicenters induced by the injection tests.

8.3 Seismic Events and Continuous Injection (1996-Present)

{Note: We have found that the Earthworm system, discussed above, is less sensitive for detecting

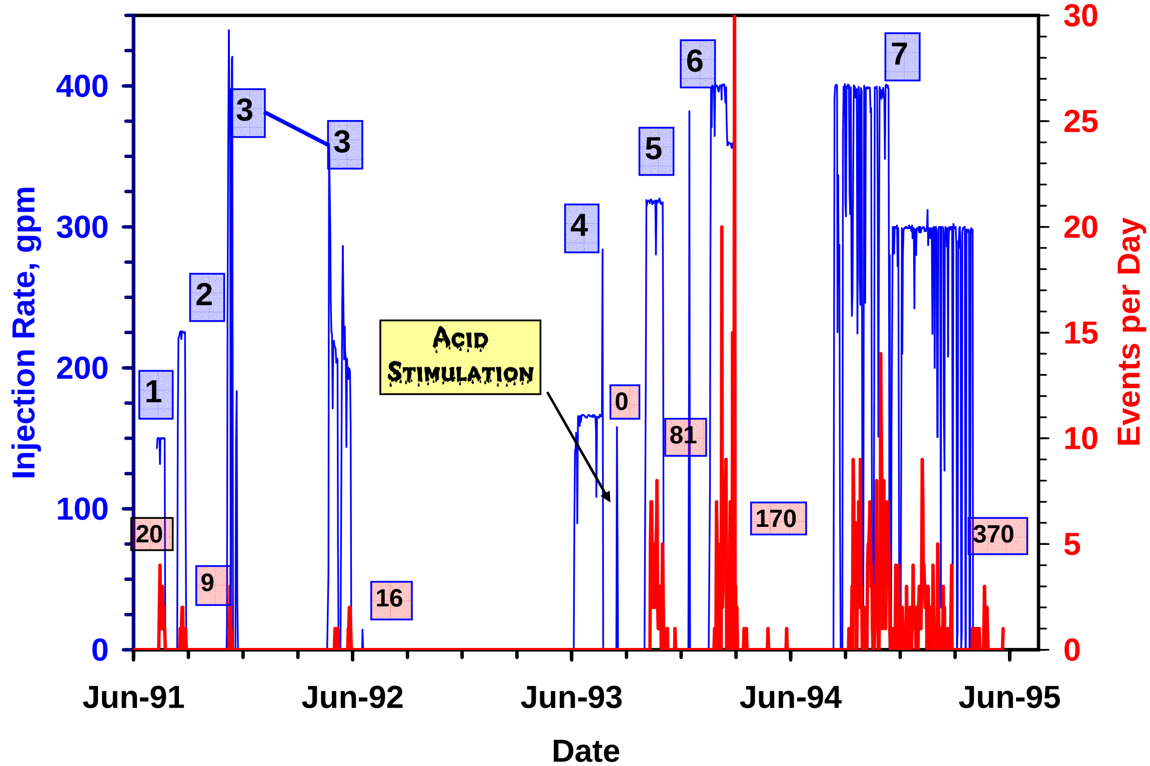


Figure 8-2 Injection Rate and Injection-Induced Seismic Events (red boxes) for Tests. Tests (number blue boxes) were needed to qualify injection well for an EPA Class V well disposal permit.

very small events (i.e., events < **M**0.0) than the system it replaced. Overall these events are not significant, having very small signal to noise ratios (i.e., poorly constrained locations) and representing only a few percent of the old data. Therefore, for consistency with the pre-Earthworm data, all subsequent discussions and figures will only use **M**0.0 or greater data.}

During 2005 PVSN recorded and located 101 events with **M**0.0 or greater. **Table 8-2** gives a year-by-year listing of event production. Note that the table does not include 1996 (it was only a partial year of pumping) and 1997 (we have some concerns about the completeness of the data set due to computer problems). We have included **Table 8-2** for comparison of 2005 data with previous years' annual activity. However, we feel that much more insight is gained when examining the Paradox seismic data by the injection phases described above. **Table 8-3** presents these data by PVU injection phase of which the 2005 data is included in *Phase IV.* Note the event count and number of days in *Phase I* in **Table 8-3** includes 1996 (111 days from pumping inception to first recorded event) and 1997 data and therefore the average events per day appear much lower than

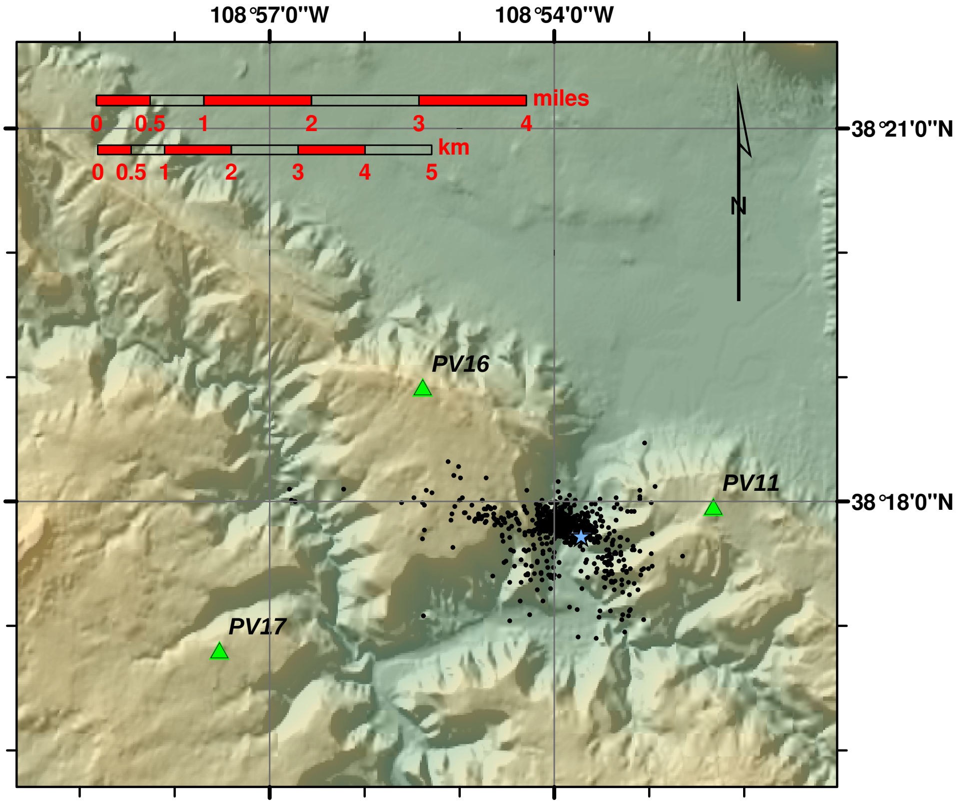


Figure 8-3 Epicenters of Seismic Events Induced By and During Injection Tests, 1991-1995. Triangles shows local stations of PVSN and star is the injection well.

the values for 1998 and 1999. We feel that the real average events per day for *Phase I* should match the 1998 and 1999 values at about 3.15. Therefore in **Table 8-3** we have added an * to the *Phase I* average events per day. **Table 8-3** supports our assessment that shutdowns and reduced injection rate reduce event production. In support of **Table 8-2** and **Table 8-3**, **Figure 8-4** shows histograms of monthly injection volume and monthly event production the beginning of continuous pumping in 1996 through the end of 2005. 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 8-5** and **Figure 8-6** show events per day for PVU operation since 1996 (i.e., continuous pumping) plus average daily injection rate and average daily downhole pressure, respectively.

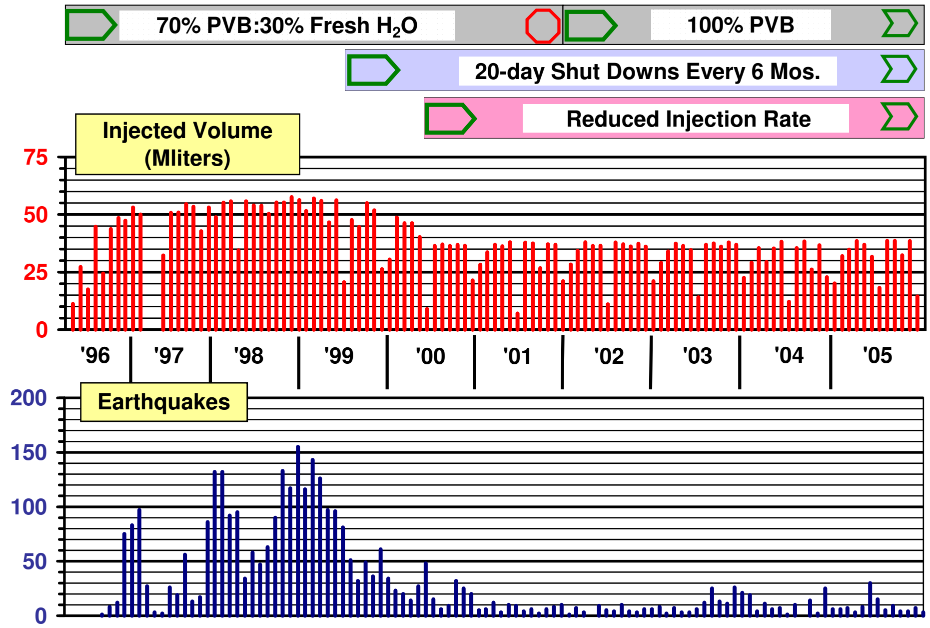


Figure 8-4 Injection Volume (top) and Earthquake Production at PVU by Month for Each Year Since Continuous Injection Began in 1996. Note the four injection phases: the bi-annual, 20-day shutdowns beginning in 1999, the reduced injection rate beginning in 2000, and the change in injectate ratio in 2002 noted at top.

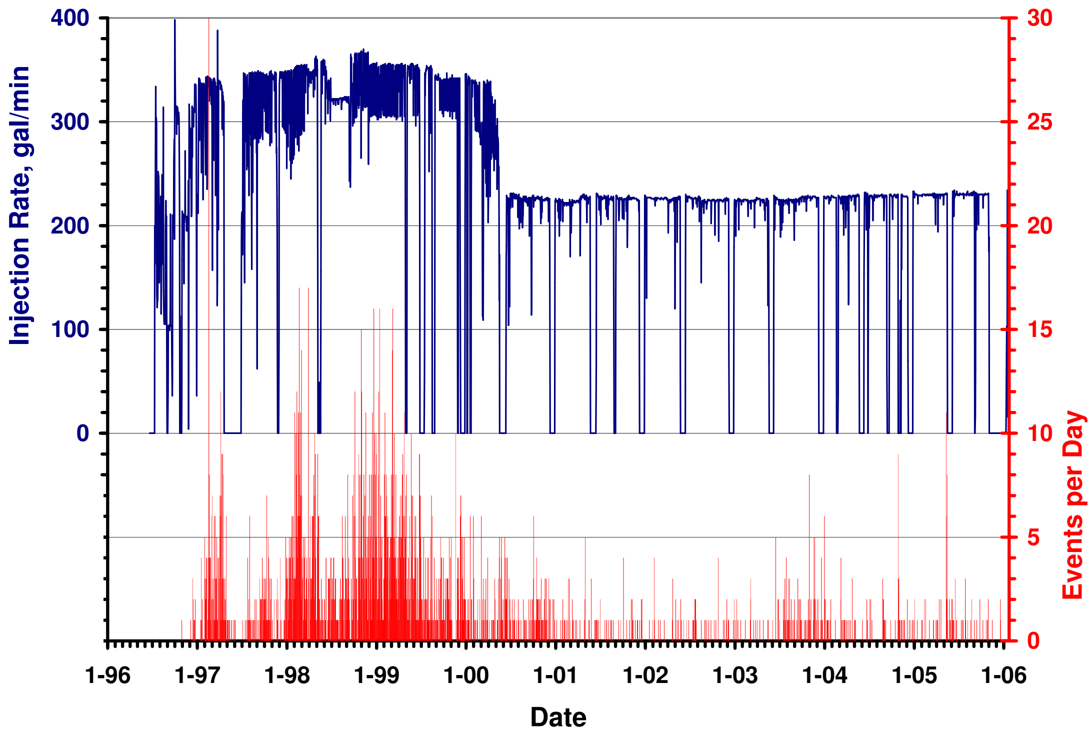


*Figure 8-5 Number of Events per Day (red) and Average Daily Injection Rate (blue) Versus Time. In this figure and in **Figure 8-4**, event count only includes events with magnitudes **M**0.0 and larger.*

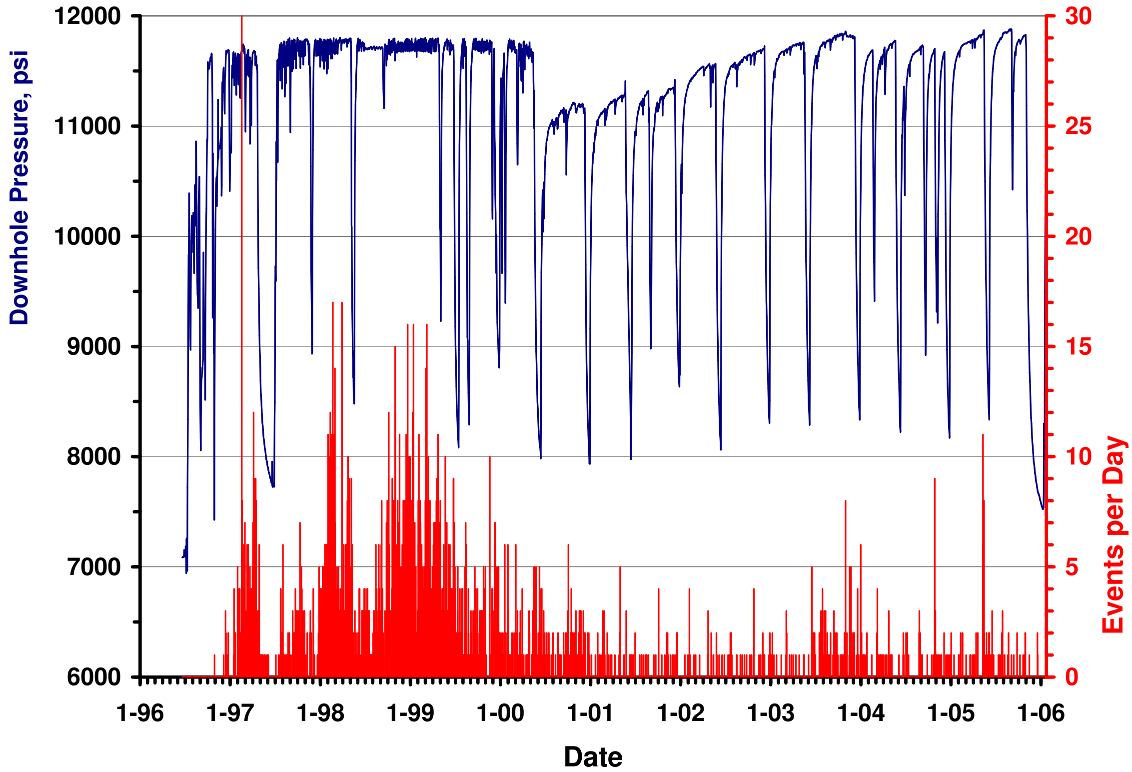


*Figure 8-6 Number of Events per Day (red) with Magnitudes **M**0.0 and Larger and Downhole Injection Pressure (blue) Versus Time. Downhole pressure is calculated at 4.3 km (14,080 ft).*

8.4 Event Magnitudes

As shown in **Table 8-2**, in 2005, the daily seismic event rate was 0.28; this about the same as the 2004 rate, but more than 2003 and 2002, which are the other years of *Phase IV* injection.

Table 8-4 shows the event magnitude distribution by year for 0.5-magnitude wide bins. **Table 8-4** shows that, there was an insignificant decrease in total number of events during 2005 compared to 2004. A more complete discussion of magnitudes and recurrence statistics is given below. However, the largest magnitude event recorded in 2005 was a magnitude **M**2.6.

8.5 Events by Depth

Figure 8-7 shows the Paradox epicenters color-coded by depth in km relative to the wellhead.

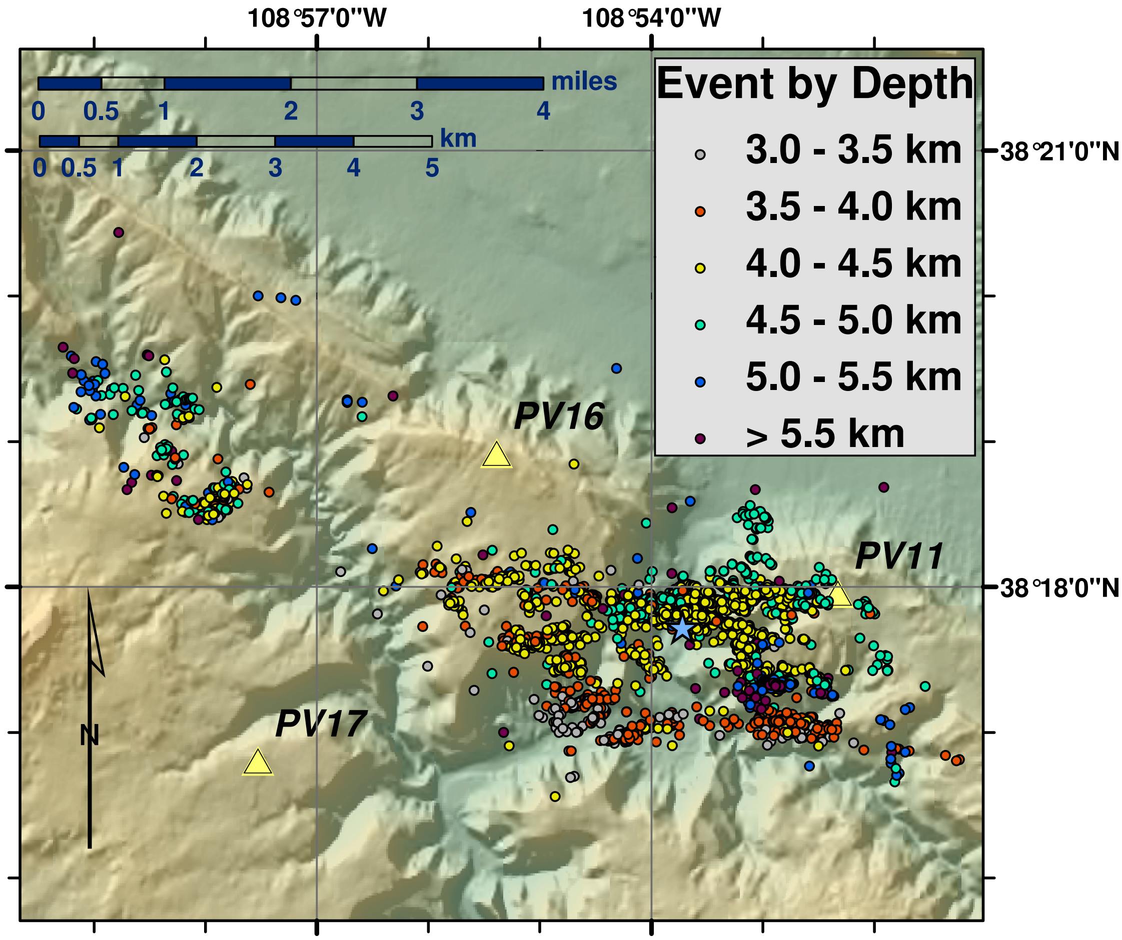


Figure 8-7 1991-2005 Epicenters Color-Coded by Depth, in Kilometers, Relative to Injection Wellhead (star).

Note that these data show a shallowing of the event depth to the west south west, which is consistent with the description of the local geology given above. This indicates that the seismicity follows both the stratigraphic shallowing and the fault-fracture structure of the Wray Mesa system.

8.6 Felt Events

By the end of 2005, PVSN recorded more than 4,200 seismic events attributed to PVU injection. Of these, more than 99.9% were imperceptible (i.e., magnitude < **M**2.4) to people at the surface. From 1991 to 1996 no events were felt. Between August, 1997 (i.e., the first reported felt event) and the end of 2005 about 15 events were felt. During 2005, no felt-events were reported to PVU.

Table 8-1 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	(3Oct94) 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;

During 1996-2005, 22 events **M**2.5 or greater were recorded, indicating not all larger events are felt. Of the larger events, 3 occurred in 1998, 7 in 1999, and 5 in 2000. In 2000 only 1 **M**2.5-or-greater event occurred after the reduction in injection rate following the May 27th event. In 2001 no events **M**2.5 or greater occurred. In 2002, 1 event **M**2.5 or greater occurred. In 2003, no events **M**2.5 or greater occurred; in 2003, 3 events **M**2.5 or greater occurred; and in 2004, 3 events **M**2.5 or greater occurred. In 2005, 1 event **M**2.5 or greater occurred.

Table 8-2 Yearly Event Production for M>=0

Year	Induced Events	Average Events Per Day
1998	1071	2.93
1999	1051	2.88
2000	272	0.75
2001	83	0.23
2002	58	0.16
2003	137	0.37
2004	106	0.29
2005	101	0.28

Table 8-3 Event Production by Injection Phase Through 2004

Phase	Induced Events	Duration	Avg. Events per Day	Injected Volume
--	--	Days	--	(Gltr) Ggal
I	2369	1100	2.15*	(1.62) 0.427
II	402	335	1.20	(0.447) 0.118
III	208	565	0.37	(0.591) 0.156
IV	402	1455	0.28	(1.49) 0.394
**Validity of this value is questionable, see text for explanation*				

8.7 2005 Event Locations

Figure 8-8 shows a plan view (i.e., epicenters) of the 101 injection-induced earthquakes recorded by PVSN during 2005 and located using the preliminary one-dimensional model and the relative relocation method. The relocated events are plotted by the indicated magnitude bins. The magnitudes of these events range from **M**0.0 to **M**2.6, the largest event in 2005 (see **Table 8-4)**. With regard to magnitude, the error in locating events generally decreases with increasing magnitude. For smaller events, noise is proportionately larger, obscuring identification of the initial P and S-arrivals. As a result, most of our conclusions for these data are based on events with magnitude >

Table 8-4 Distribution of Seismic Magnitudes by Year

Phase	1999	2000	2001	2002	2003	2004	2005
Magnitude Range	**No.**	**No.**	**No.**	**No.**	**No.**	**No.**	**No.**
0.0-0.4	419	114	17	6	10	13	3
0.5-0.9	388	98	35	23	44	40	44
1.0-1.4	160	41	18	17	55	34	41
1.5-1.9	64	18	11	8	17	11	8
2.0-2.4	31	7	2	3	11	5	4
2.5-2.9	5	3	0	1	0	2	1
>2.9	2	1	0	0	0	1	0
Total	**1070**	**282**	**83**	**58**	**137**	**106**	**101**

M0.6.

As in previous years and discussed below**, Figure 8-8** shows that the epicenters recorded in 2005 lie, within the two distinct regions, one surrounding the injection well and one displaced to the northwest of the wellbore. These are the two seismogenic zones induced by the PVU injection. The first and most populated zone surrounds the injection well in an elongated envelope whose long axis runs approximately NW-SE and extends to a maximum of ~4 km west of the injection well and ~2 km east of the well. The second zone is centered about 8 km northwest of the injection well. The figure also shows the swarm events (discussed above) located to the north west and very near the injection well.

Figure 8-9 compares the epicenters for all events from 1991 through 2004 to the 2005 events. The figure uses only relocated data using the new relocation method (discussed above).

As noted earlier, **Figure 8-9** shows the relocated 2005 events within the two groups defined by previous year events. As discussed in previous annual reports (e.g., Mahrer et al., 2002; Mahrer et al., 2003, Mahrer et al., 2004), the epicenter locations suggest the strike (N55^{o}W) of the Wray Mesa fault and fracture system.

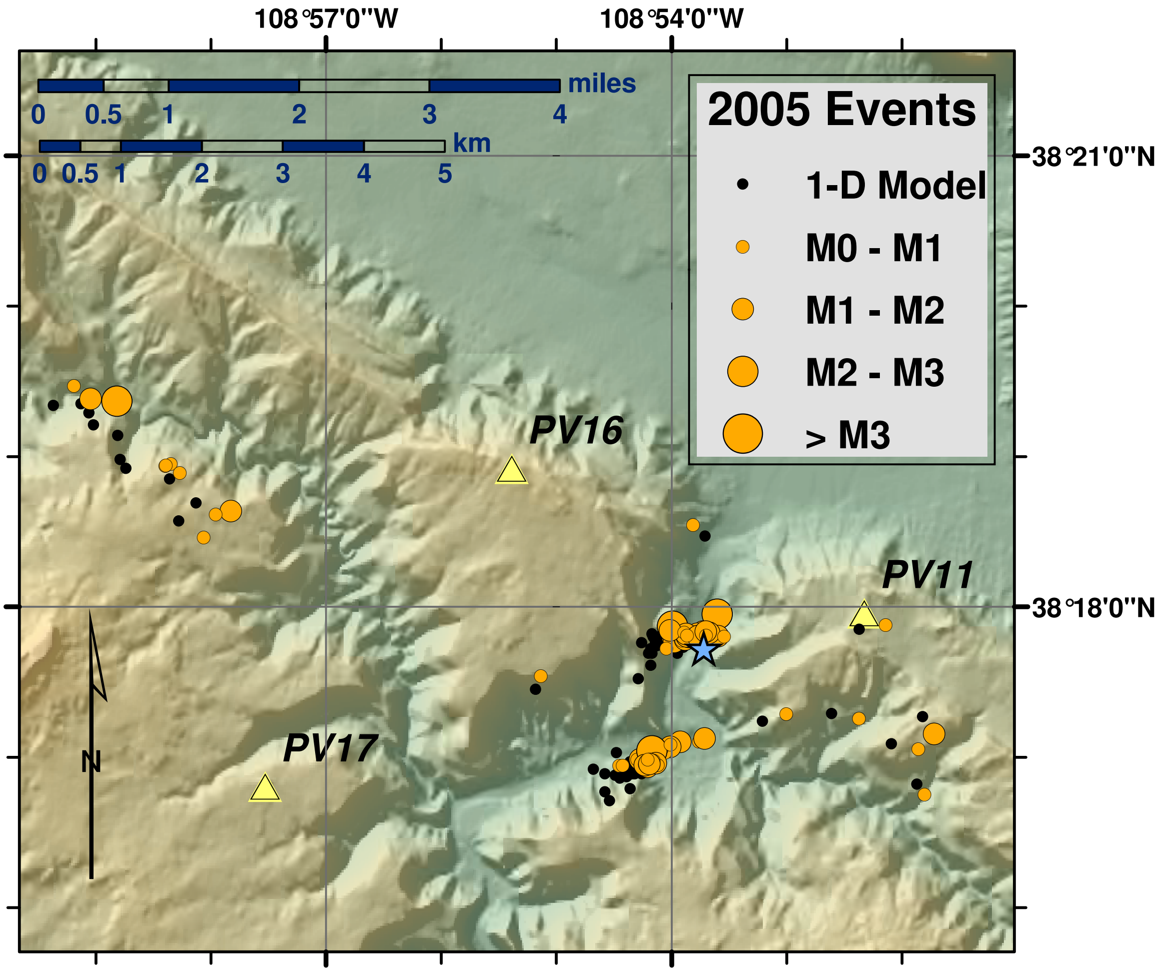


Figure 8-8 2005 Epicenters Located Using One-Dimensional Velocity Model and Relative Relocation Method. 101 events are plotted; relative relocations are plotted by magnitude. Injection wellhead is star.

The group 8 km northwest of the well first appeared in 1997. We believe that the paucity of events between the two groups, which has been maintained for almost 9 years, indicates the zones communicate hydrologically by a conduit(s) of fluid, probably through one or more principal faults of the Wray Mesa system. And, that conduit aligns with a principal stress direction. Otherwise the first appearance of a fluid-base perturbation in the conduit in 1997 would have been marked by microseismicity, the cause of which would be the liberation of the shear stress across the previously stress-locked conduit.

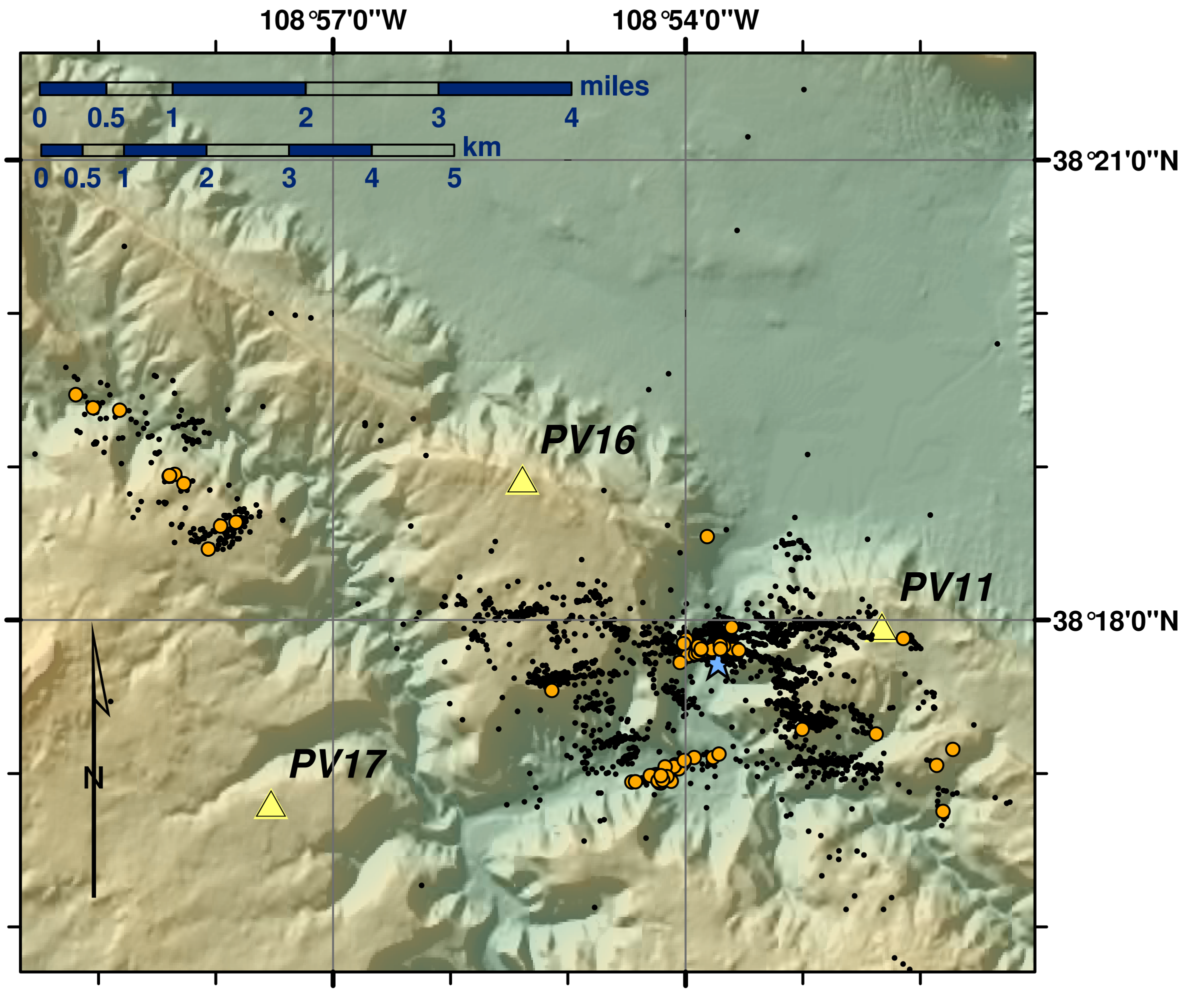


Figure 8-9 Relocated PVU-Induced Earthquake Epicenters for 2005 (circles) and years 1991-2005 (black dots). Star is PVU injection wellhead. Named triangles are PVSN sites.

Complementing **Figure 8-8** and **Figure 8-9**, **Figure 8-10** 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. Note that in this figure, the locations of these events are based on the pre-2005 relocation method discussed above. Even though we have upgraded this method, the conclusion we draw from the **Figure 8-10** are still valid.

Figure 8-10 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

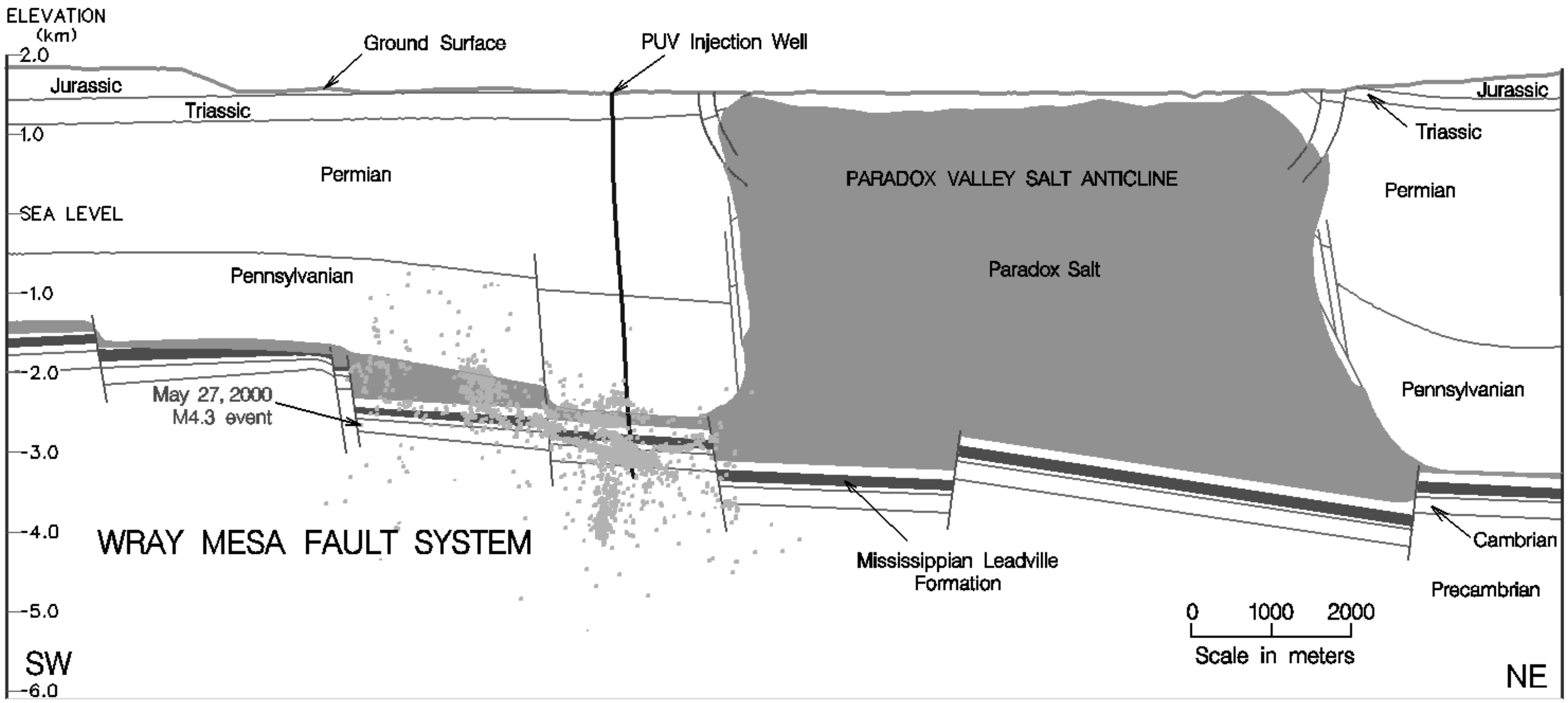


Figure 8-10 Bremkamp and Harr (1988) Cross Section Interpretation of Paradox Valley and Bordering Stratigraphy. Section passes through PVU injection well and run normal to strike of the valley. Projected on to cross section are seismic events (1991-2002) within 1.5 km of the viewed plane.

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 8-10** 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 8-10 shows a significant number of earthquakes appear 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 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. Note that since the Precambrian shallows to the west, these numbers represent a minimum number of events in the Precambrian.

8.8 1991-2005 Event Locations By Year

For comparison with the event locations in 2005 (previous section), **Figure 8-11** through **Figure 6-20** show event locations by years from initial injection testing in 1991-1995 (**Figure 8-11**) through annual figures for 1996-2004 (**Figure 8-12** - **Figure 8-19**). This time sequence shows the growth of the near-wellbore seismic zone indicating that by the end of 1998, the expansion of the seismic zone surrounding the well had reached maturity and further expansion is very slow, if at all. Note that all of these epicenter locations in these and subsequent figures used the 2005 relative relocation method discussed earlier.

8.9 Earthquake Recurrence

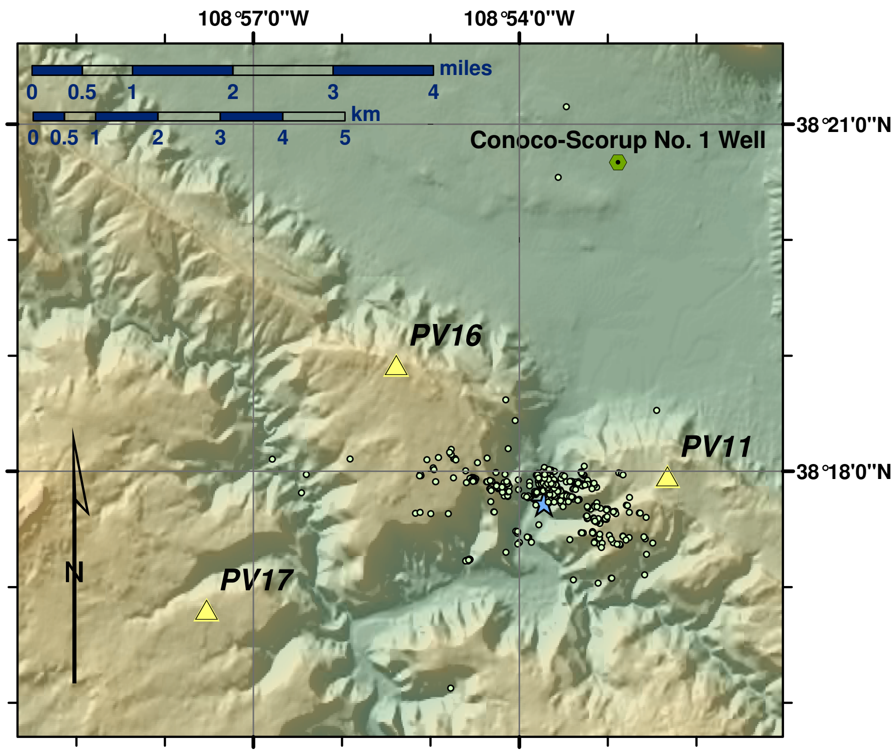


Figure 8-11 1991-1995 Epicenters. Star is injection wellhead.

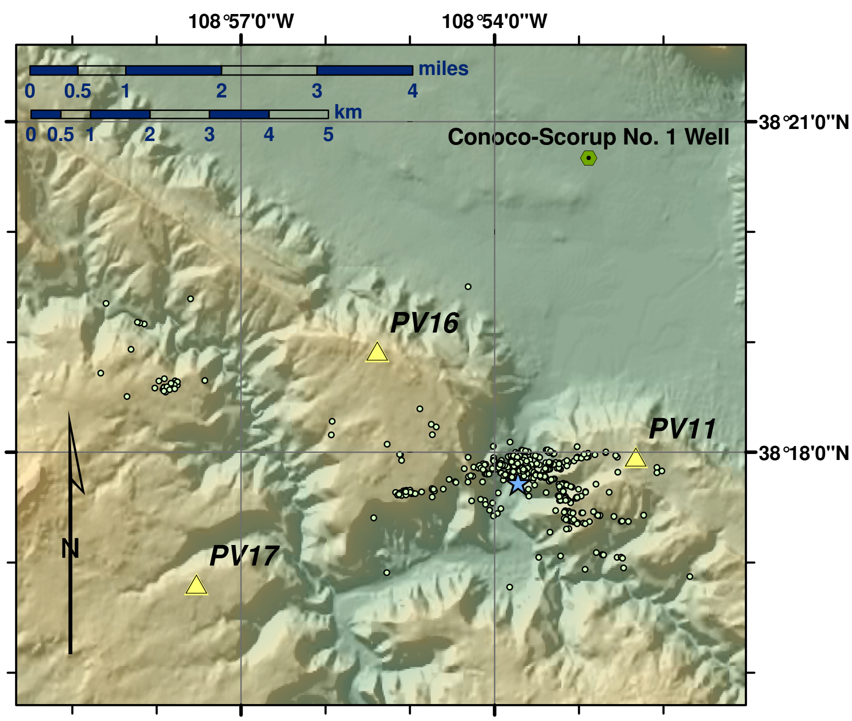


Figure 8-12 1996-1997 Epicenters. Star is injection wellhead.

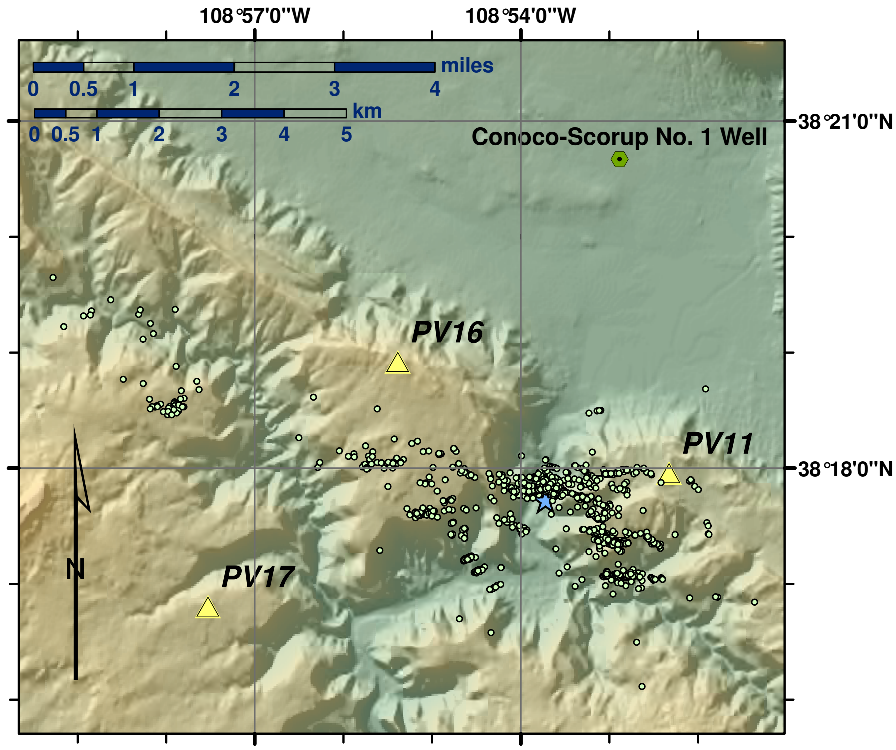


Figure 8-13 1998 Epicenters. Star is injection wellhead.

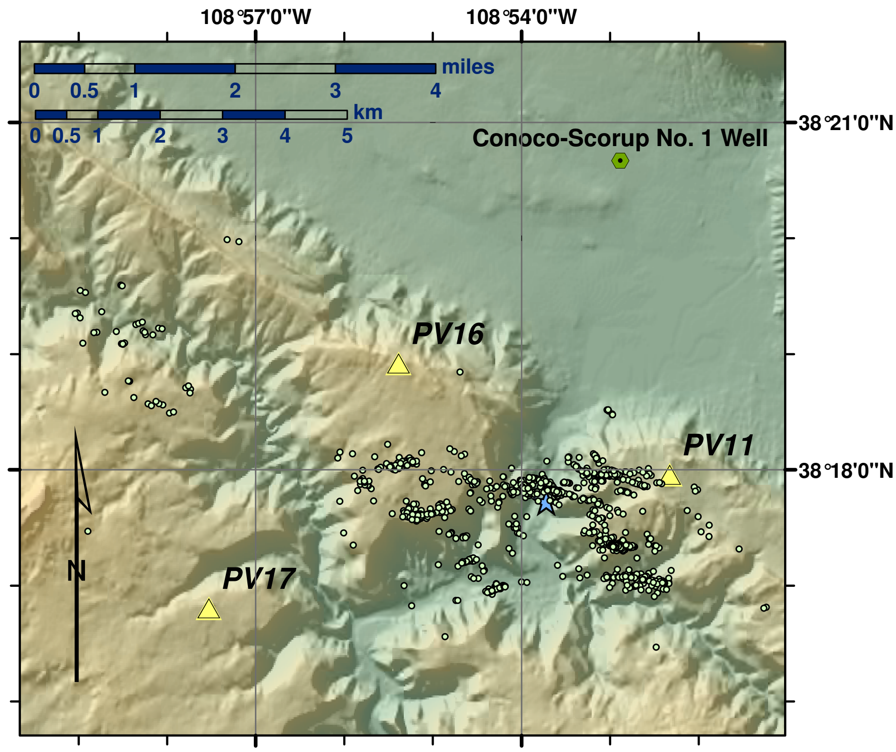


Figure 8-14 1999 Epicenters. Star is injection wellhead.

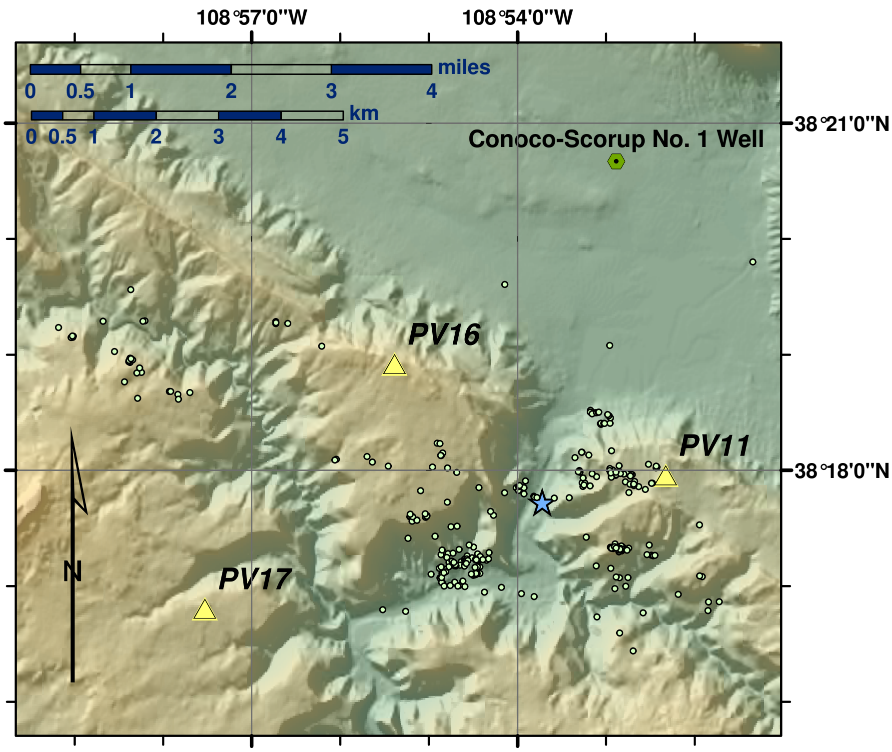


Figure 8-15 2000 Epicenters. Star is injection wellhead.

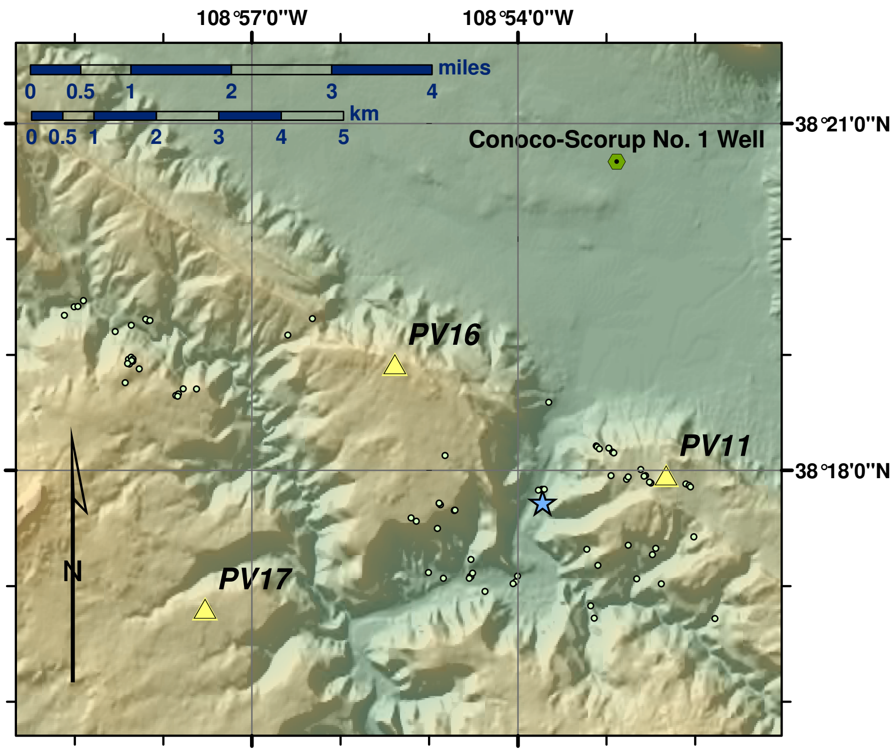


Figure 8-16 2001 Epicenters. Star is injection wellhead.

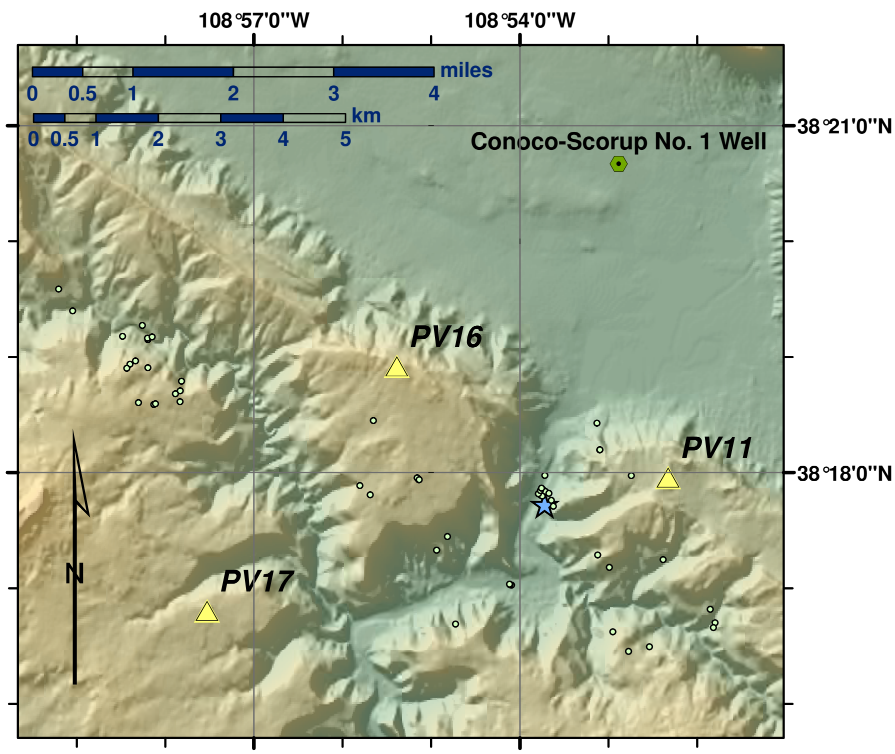


Figure 8-17 2002 Epicenters. Star is injection wellhead.

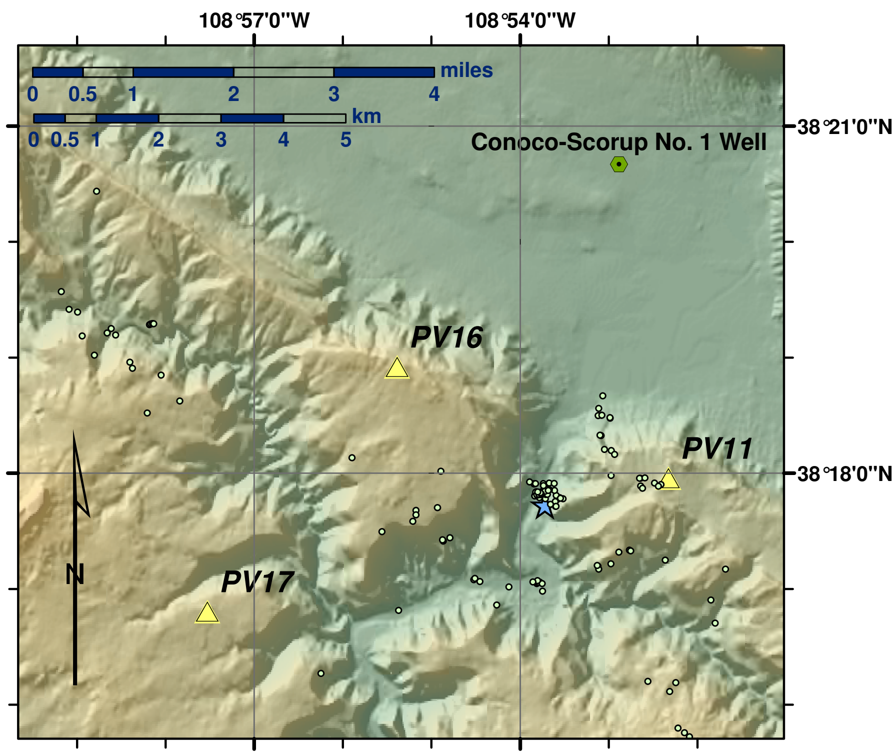


Figure 8-18 2003 Epicenters. Star is injection wellhead.

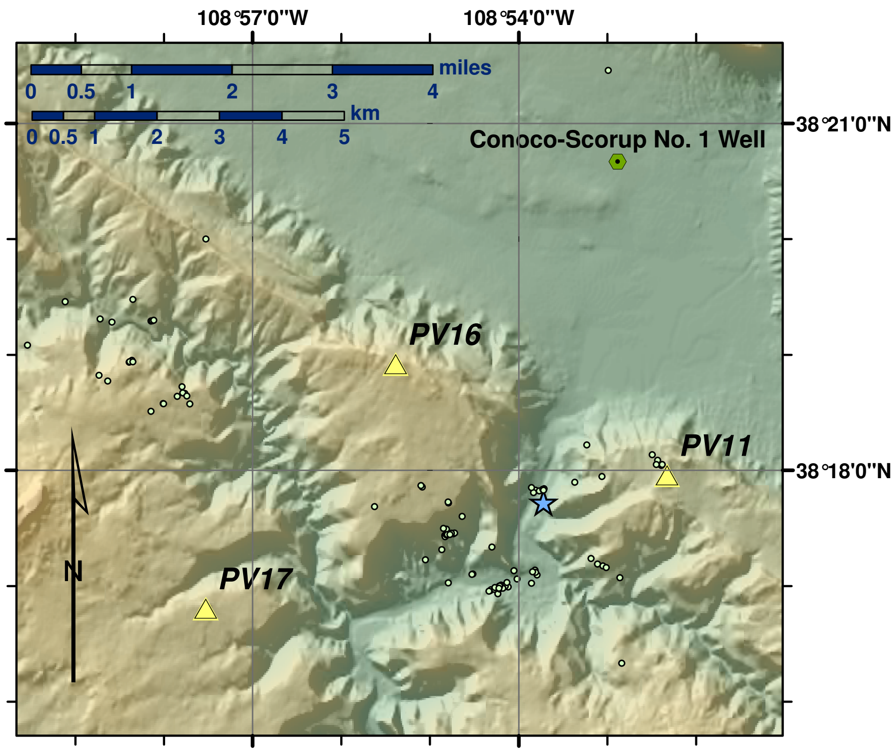


Figure 8-19 2004 Epicenters. Star is injection wellhead.

Table 8-5 shows the data and calculated *b*-values and **Figure 8-20** shows the calculated cumula-

Table 8-5 Number of Events by Magnitude Range and Pumping Phase Used in Calculating Earthquake Recurrence Curves (Figure 8-20)

Magnitude Ranges	**All** (7/96-12/05)	***Phase I*** (7/96-7/99)	***Phase II*** (7/99-7/00)	***Phase III*** (7/00-1/02)	***Phase IV*** (1/02/-12/05)
	no. events	**no. events**	**no. events**	**no. events**	**no. events**
0.5-0.9	1254	878	151	74	151
1.0-1.4	587	355	48	39	145
1.5-1.9	229	141	23	20	45
2.0-2.4	87	51	10	3	23
2.5-2.9	18	8	5	1	4
3.0-3.4	0	0	0	0	0
3.5-3.9	3	2	0	0	1
4.0-4.4	1	0	1	0	0
***b*-value**	0.889	0.963	0.901	0.858	0.685

tive recurrence data, linear fits to the data (solid lines), and back projection of the linear fits (dashed lines) for small magnitude events, respectively for the **Table 8-5** data. The *b*-value relates

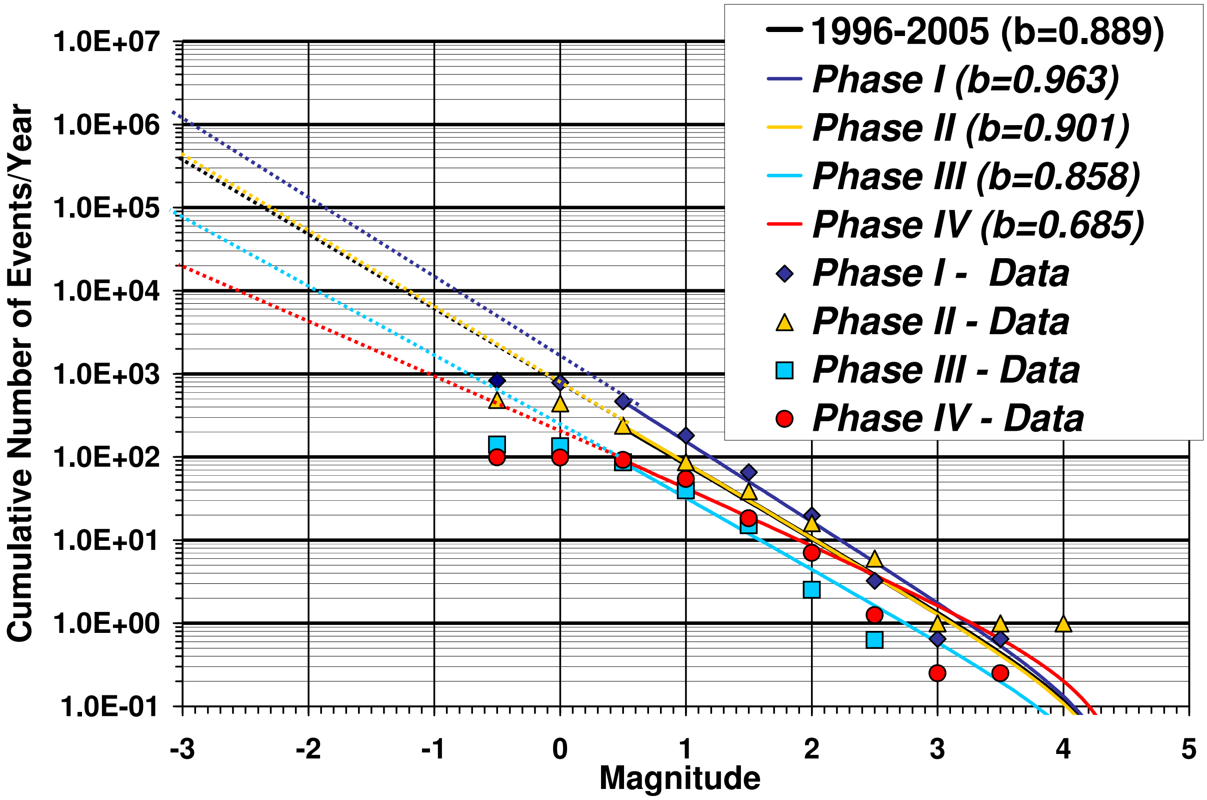


Figure 8-20 Cumulative Recurrence Curve for PVU-Induced Earthquakes, 1996 through 2005, and Curves for Each Injection Phase. Colored symbols are data by phase; solid lines are statistical fits to those data; and dashed lines are projections of the solid lines to magnitudes below PVSN's detection threshold.

the change in the number of earthquakes with a unit change in magnitude. In **Figure 8-20** we plot the data such that the *b*-values are annualized (i.e., relate the change in the number of earthquakes *per year* with a unit change in magnitude). In most tectonic settings, the *b*-value is typically about 1 which means each unit change in magnitude corresponds to a factor of 10 change in number of events. For a *b*-value of 0.8, the factor changes from 10 to 10 x 0.8 or 8.

Figure 8-20 uses all the events recorded since continuous injection began through the end of 2005 and for each of the injection phases described above. These calculations assumed a maximum magnitude of **M**5. The flattening in the data at **M**0.5 suggest that **M**0.5 is the lower detection threshold of PVSN (i.e., below ~**M**0.5 ground motion is small and, although, some Paradox events are detected, some are not.)

The *b*-values for *Phases I*, *II*, and, possibly, *III* in **Figure 8-20** are consistent with observations of earthquake recurrence within the seismically inactive Colorado Plateau (Wong and others, 1996; LaForge, 1996). This similarity of the Paradox *b*-values to other studies in the Colorado Plateau supports the concept that during *Phase I*, *II*, and *III*, many of the induced earthquakes at the Paradox site were due to the release of tectonic shear-stress. This observation agrees with our source (i.e., focal mechanism) studies of the PVSN data discussed below. However, the *b*-value for *Phase IV* is significantly lower than the earlier phases. This may mean a change in the nature of the induced seismicity. We are still investigating this possibility.

8.10 Focal Mechanisms - Preliminary Analysis

The waveforms of the 2005 data are consistent with previous years. Hence we did not feel a need to calculate new fault plane solutions. For a complete discussion see Mahrer et al., 2004 (on attached CD).

8.11 Focal Mechanisms - Advanced

Focal mechanisms for the entire data set were calculated using *P*-wave first motion polarities and S_V/P amplitude ratios on vertical component seismograms (Kisslinger, 1980; Kisslinger and others, 1981). This has been discussed in detail in previous report (Mahrer et al., 2004: on attached CD) and is not included here.

8.12 Induced Event Slip Mode

The source mechanics of the PVU earthquakes recorded by PVSN is shear slip on existing faults and fractures. These faults are not sufficient to hold the volume of injectate emplaced at PVU. Hence, within the formations, the injection process creates additional “volume” (i.e., new fracture and pore space and opens existing fractures and existing pore space) to accommodate the injectate. This means injection creates and opens tensile fractures (i.e., hydraulic fractures) into which the injectate squirts. The question then arises: Is any portion of the seismicity recorded by PVSN due to these tensile events? Based on oil and gas field hydraulic fracture studies run at pressures comparable to PVU injection pressure, the hydraulic fracture opening or aperture is on the order of a few millimeters, at most. With this size opening and subsequent fluid squirt, the (new) surface area of a fracture is on the order of 10’s of square centimeters, or less. Based on calculation of seismic moment (Wells and Coppersmith,1994), **Figure 8-21** shows the slippage on surfaces this size will generate tiny events (**M**<-3)and these events will radiate minimal seismic energy. At the ground surface, this radiation is well below the detection threshold of PVSN. In addition, based on the area of the opened fracture, this radiation is in the frequency band of a few 100 hertz to a couple of kilohertz. As discussed previously, the recording systems at PVSN operate at frequencies below a few 10’s of Hz. Hence, based on the focal mechanics studies and the aforementioned arguments, the ground motions recorded by PVSN are due to shear events, not tensile openings.

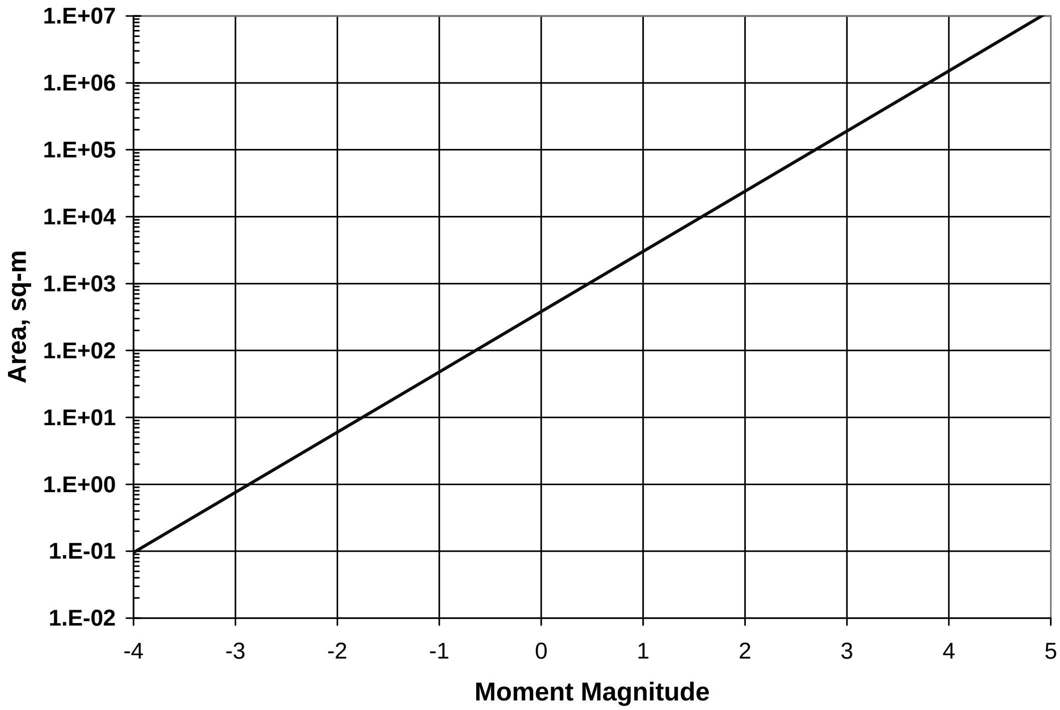


Figure 8-21 Earthquake Fault (i.e., Slip) Area Versus Earthquake Size (i.e., Moment Magnitude). The line is extrapolated from Wells and Coppersmith (1994)

8.13 Seismic Magnitude versus Location

With the highly accurate event location data, how do the locations correlate with event magnitude? **Figure 8-22** and **Figure 8-23** show all events a magnitude **M**1.7 and greater plotted against a background of all the events. **Figure 8-22** is a plan view and **Figure 8-23** and **Figure 8-24** are depth cross sections looking north and west, respectively. The depth sections in **Figure 8-23** and **Figure 8-24** are horizontally drawn, but not indicating horizontal bedding. They are indicating the unit depths 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) host larger events. Only a subclass of the fractures and faults have larger events. Also, some of the

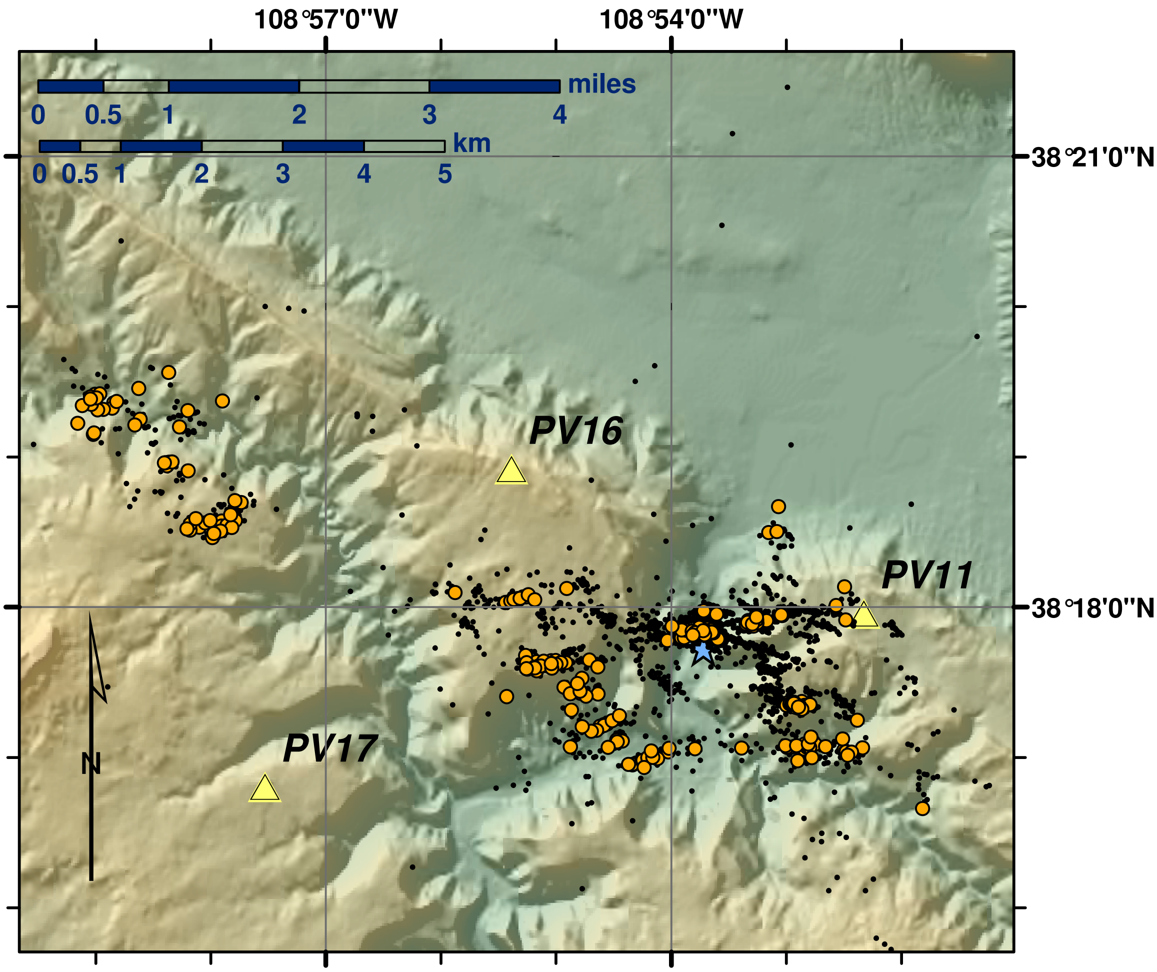


*Figure 8-22 PVU Epicenter Map of Events with Magnitude **M**1.7 and Greater (gold circles) Superimposed on All of the Seismicity (small black dots).*

fractures and faults have many larger events and some have only one or two. Initially we expected

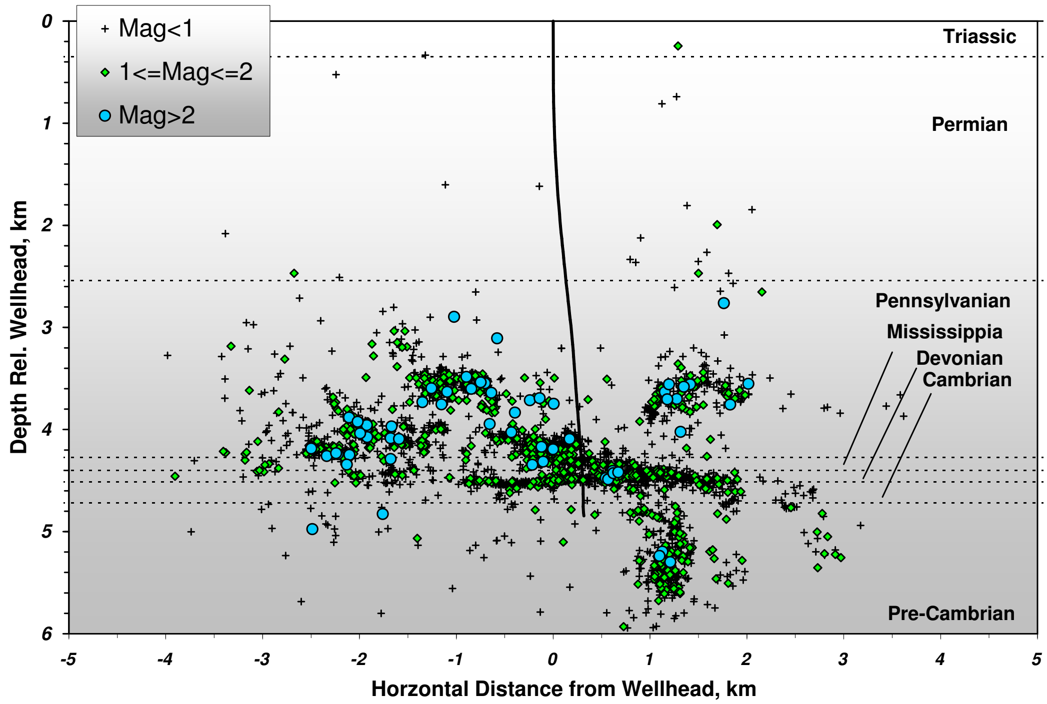


Figure 8-23 Depth Cross Section of Event Locations Superimposed on an East-West Plane, i.e., Viewer is Looking North. Events are shown by magnitude range.Line bending to the right in the middle of the figure is wellbore profile

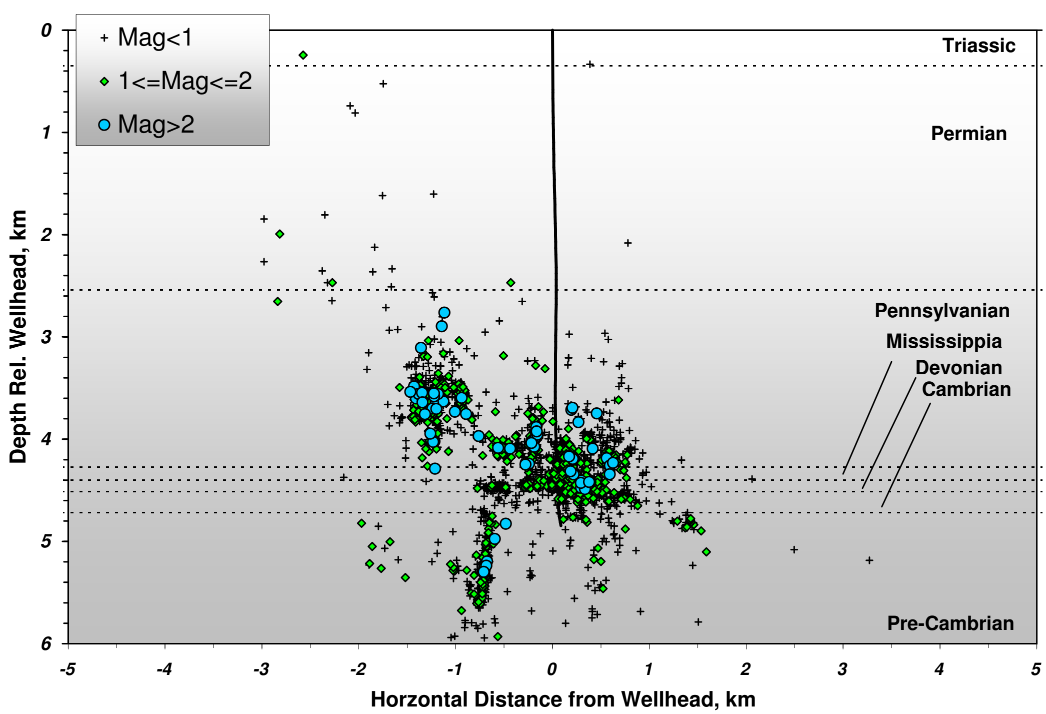


Figure 8-24 Depth Cross Section of Event Locations Superimposed on a North-South Plane, i.e., Viewer is Looking West. Events are shown by magnitude range.Vertical line in middle is wellbore profile.

the larger events to be more uniformly distributed. Also note that a disproportionately larger number of larger events occur in the secondary seismogenic region, ~8 km to the northwest of the injection well.

8.14 Injective-Sensitive, Swarm ("Hot") Zone

For some years we have noted that some regions within the seismogenic zone surrounding the injection well seem to vacillate between active and inactive. During 2003 we isolated a region ("hot" zone) that seems to respond directly to large-scale changes in injection. We defined the region as a square region running from -0.2 km south of the well to 0.5 km north of the well and west from the well to -0.7 km (i.e., area = ~0.5 km^2). During 2004 this region witnessed 7 events. In 2005, using the 2005 relocated data, we redefined this "hot" zone with boundaries of the wellhead on the south, an east-west line 1.0 km north or the wellhead, north-south lines 0.5 km east and 0.5 km west of the wellhead (i.e. area = 1.0 km^2). The 2005 data of the "hot" region is shown in **Figure 8-25**. Since 1996, this redefined region has generated ~840 or ~20% of the near-wellbore events. By comparison, it covers less than 5% of the near-well seismogenic zone.

We have found that within the redefined region designated above and shown in **Figure 8-25**, the seismicity is very responsive to wellbore injection. **Figure 8-26** shows the downhole pressure (since 1996) and the occurrence times of events (yellow diamonds) within the swarm region (see **Figure 8-25**). To prevent confusion, the y-axis location of the occurrence data is arbitrary. The only important parameter of the occurrence data is time. Note how closely the gaps in the occurrence data follow the gaps (i.e., shut downs) in the pressure data. When the injection is shut down, the swarm region very quickly stops being seismically active. Normally, the delay between seismic response and injection cessation is much longer, weeks to months. In this swarm zone, this time delay is hours to a few days. Note also in **Figure 8-26**, when the downhole (injection) pressure is below a threshold of about ~80 MPa (~11,600 psi), the region becomes inactive even though PVU is still injecting.

Figure 8-27 shows a repeat of **Figure 8-26** with the additions of vertical lines marking the onsets times of subswarms in the "Hot Zone". In **Figure 8-27** we used psi or pounds/square inch in the

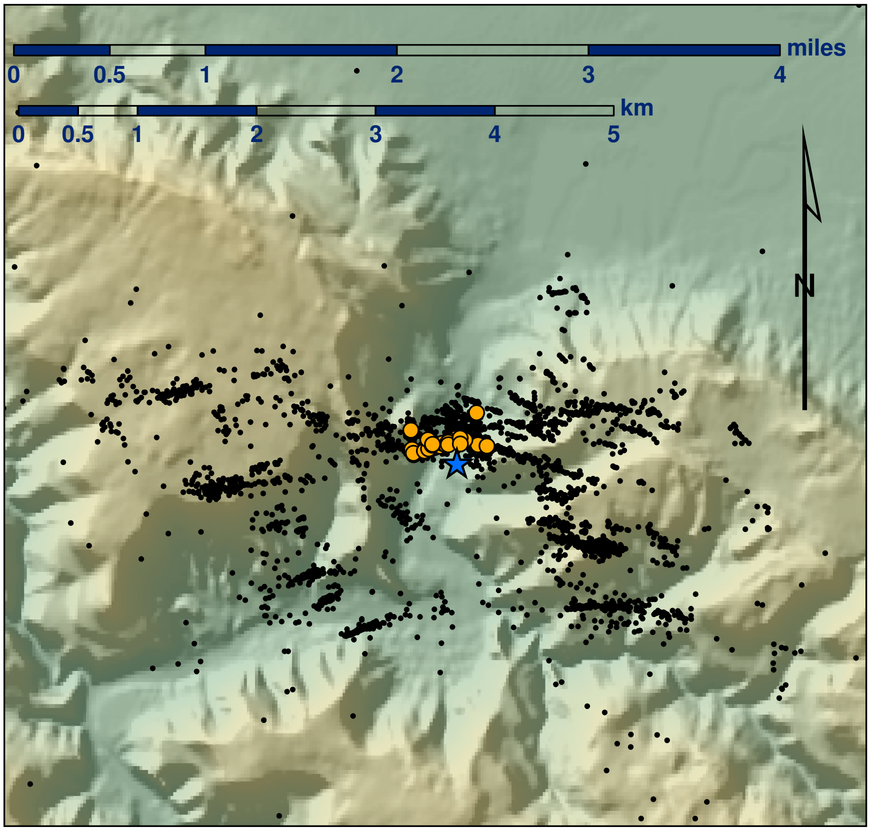


Figure 8-25 "Hot" Zone [Relative to Injection Well (star) @ North: (+1.0>y>0.0) km; East (0.5>x>-0.5) km] Identified as an Injection-Sensitive Active Swarm Zone. Black dots shows epicenters of all the local seismicity.

vertical axis for increased sensitivity and the benefit of those more familiar with psi. In **Figure 8-27**, a subswarm is the group of events that occurs after a 20-day shut down and continues through the 6-month pumping interval, ceasing with the next 20-day shutdown or other, non-scheduled shutdown. Note an interesting trend in the average bottomhole pressure that occurs at the sub-swarm onset times, i.e., the dotted lines. From early 2002 through the end of 2004, the pressure at which the subswarm initiates tends to increase about 10 psi (i.e., the left dotted line). Then, beginning of 2004, that initiation pressure seems to drop between 20 and 30 psi and the initiation pressure beginning a second period of increased pressure (right dotted line) per 6-month pumping cycle. This period of increase is at approximately the same slope, again at about 10 psi per 6-month pumping, as the first period. We are evaluating the cause and importance of this seismicity-pressure relationship and have not reached a substantive conclusion.

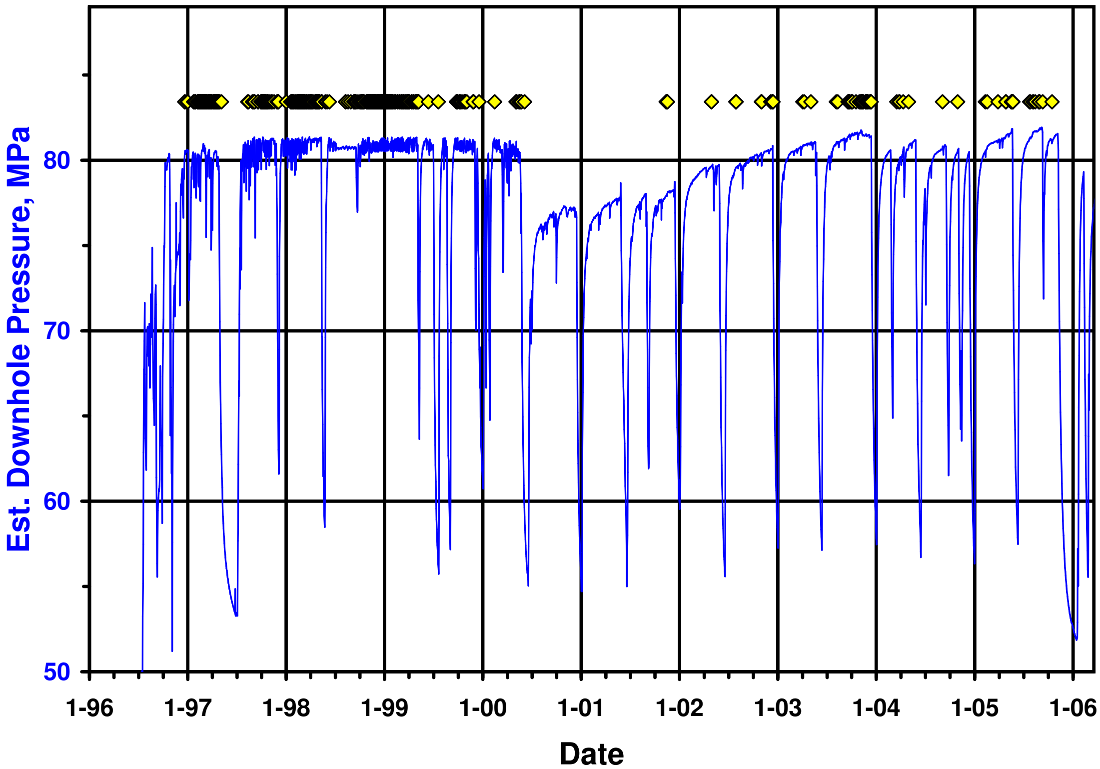


Figure 8-26 (Estimated) Downhole Pressure at 4.3 km (14,080 ft) Versus Date and Occurrence Time of Events (yellow diamonds) in the Swarm ("Hot") Zone Shown in Figure 8-25.

8.15 Remote (Northern) Seismic Swarms

PVSN is a local seismic network, but is not limited to only events near the injection well and injection-induced events. **Figure 8-28** shows events located between 10 and 20 km north of the injection well. During 2005 this region, as shown in **Figure 8-28**, saw 3 minor events in the general region and 1 near the known clusters. With no events occurring during 2004, this region has been reasonably quiet for the last two years. However, during 2003 this region saw active swarms. One was in January and consisted of 7 events spread over about 21 days. All the events were **M**1.8 or smaller, well below human detection. This swarm is centered ~11 km north and 3 to 4 km west of the injection well. The second swarm occurred in August '03 and consisted of 16 events spanning 6 days and all of magnitude **M**1.5 or smaller. In the figure it is a very tight swarm located ~10.5 km north and ~1 km east of the injection well (northeast of PVSN station PV04). As noted in earlier reports (e.g., Mahrer et al., 2004), we continue to believe these events are not induced by the PVU injection. Harr and Bremkamp (1988) and the established seismicity induced

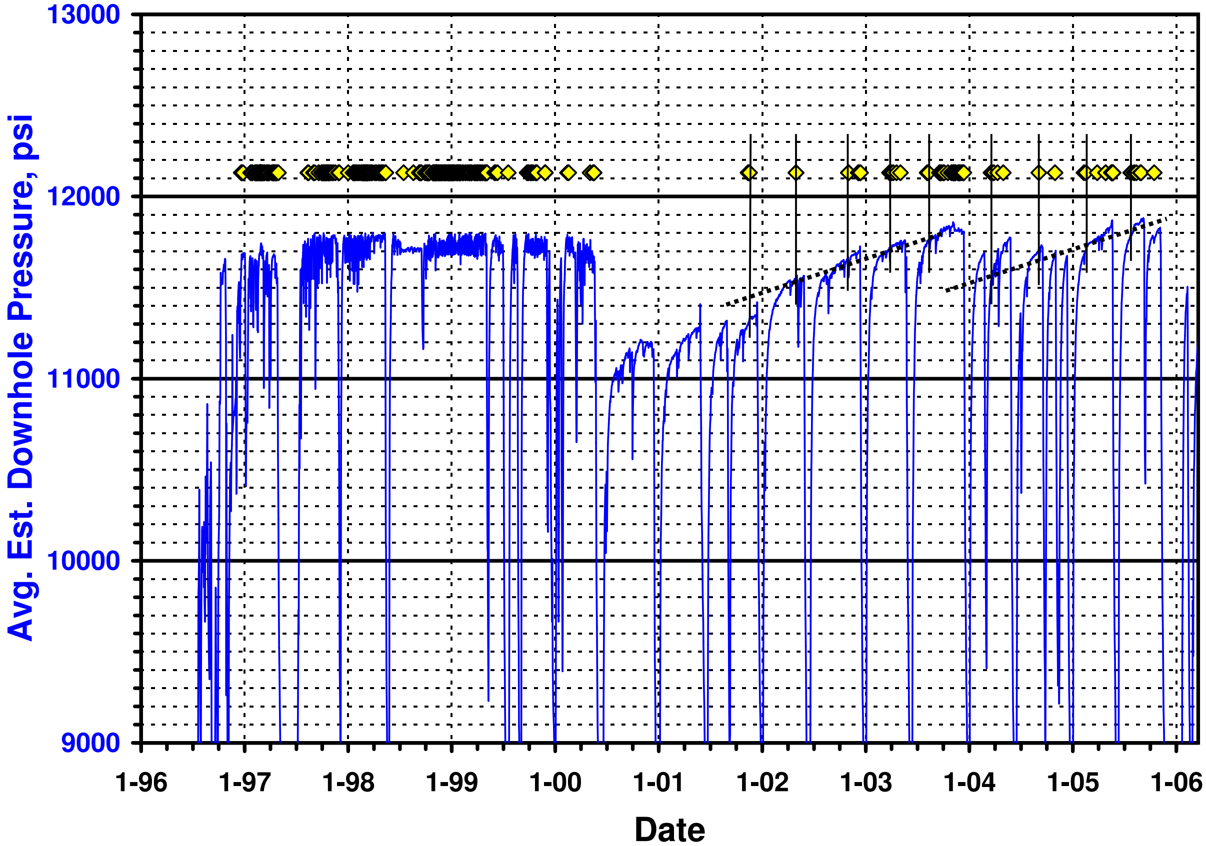


*Figure 8-27 (Estimated) Average Downhole Pressure at 4.3 km (14,080 ft) Versus Date and Occurrence Time of Events (yellow diamonds) in the Swarm ("Hot") Zone Shown in **Figure 8-25**.Shown also are the trends of time onsets of subswarms.*

by injection do not strongly support fluid or pressure migration this far north of the well. The shape and time histories of the induced seismic regions support pressure migration to the north-west. However, we add a minor note of caution. Although they don't predict it, neither Harr and Bremkamp's model nor the present extent of the induced seismicity preclude migration of the seismicity to the north. Also recall that in this area, PVSU recorded two events (**Figure 8-1**) between 1986 and 1991, the 5 years prior to injection. Although not noted in the figure, the typical depths of the events in these swarms are between 10 and 15 km.

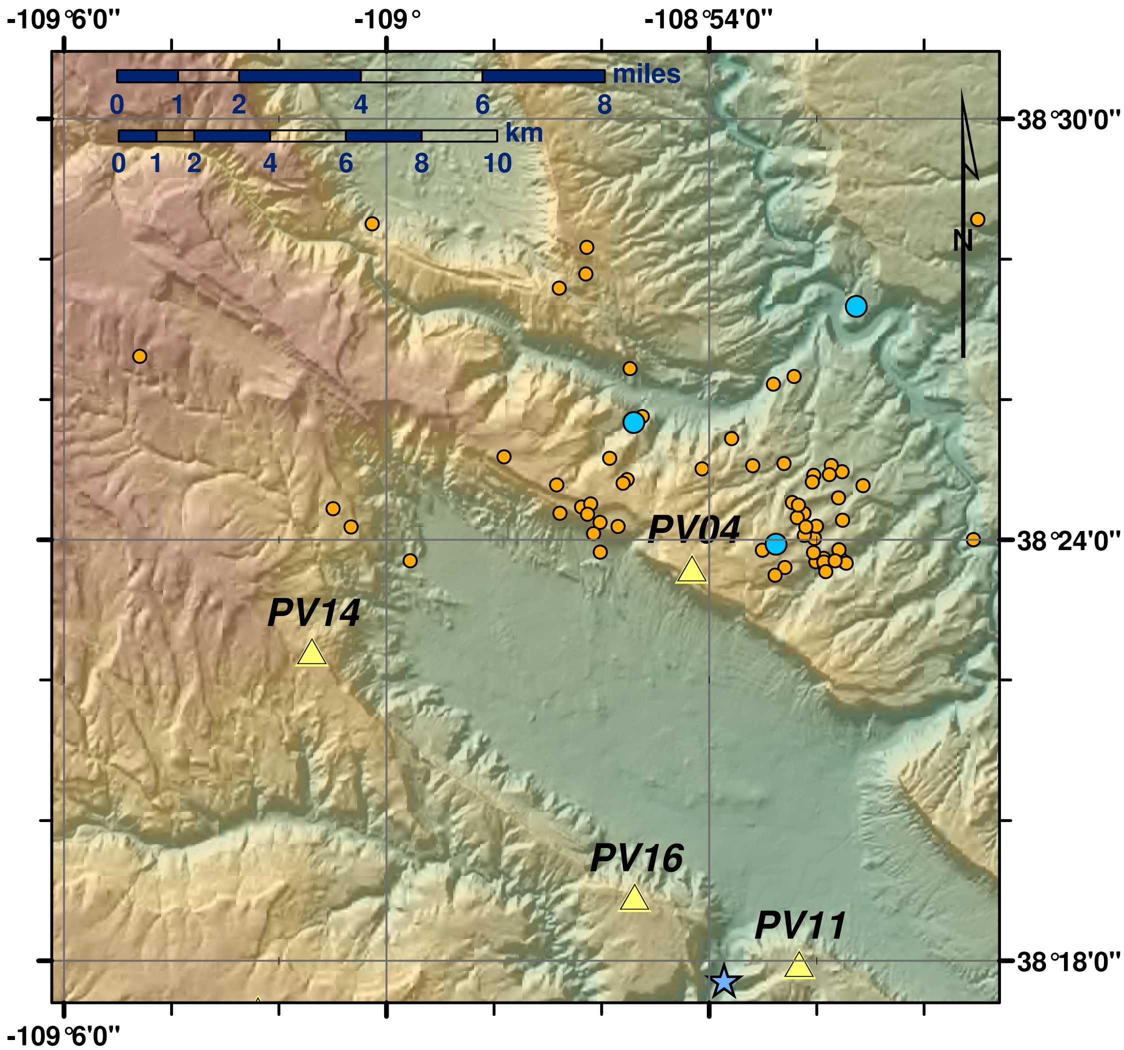


Figure 8-28 Seismically Active Swarms North of PVU Injection Well. Gold circles are pre-2005 events; blue are 2005 events.

9.0 CONCLUSIONS

9.1 Specific to 2005

The general objectives of recording, analyzing, and interpreting seismicity in the Paradox Valley region were successfully carried out during 2005. The seismic data showed that the adjustment to the PVU injection schedule in 2000 continued to maintain a low level of seismicity. Relevant observations from this reporting period include:

(1) The 101 microearthquakes of 2005 locate within the two seismogenic zones defined by previous years' microearthquake locations;

(2) Induced earthquakes continued to occur ~8 km northwest of the injection well with a gap between those events and the event zone surrounding the injection well;

(3) As in previous years, the spatial patterns of observed seismic sources and observed seismic source mechanics seem to follow the Wray Mesa fault and fracture system and are consistent with relevant tectonic stress characteristics.

(4) No large (magnitude **M**3.0 or great) events occurred during 2005.

(5) Injection controls (i.e., reduced injection rate and biannual 20-day shut downs) were continued during 2005 and the rate of seismic event production remains very low compared to the early years of continuous pumping.

9.2 Since Inception of Continuous Pumping

Throughout the continuous pumping, beginning in 1996, the nominal injection pressure at PVU exceeds fracture pressure.

The initial induced seismicity was probably due to injectate or connate fluids reducing the friction across faults, liberating pre-existing, *in situ* tectonic stress across the faults. Later events may also include those resulting from changing the *in situ* stress due to pore and fault inflation from the injectate and displaced connate fluids.

The induced seismicity at Paradox illuminates an extensive, non-symmetric connected network of fractures, faults, joints, etc. and does not demonstrate the traditional hydraulic fracture picture of two, vertical, symmetric fractures emanating from opposite sides of the injection well.

The surface-recorded seismic events radiate shear energy on pre-existing faults, joints, planes of weakness, not tensile or the openings of new fractures.

Injection has induced two, distinct seismic event zones: a primary zone, asymmetrically surrounding the well to a radial distance of ~3+ km and a secondary zone, displaced ~8 km to the northwest of the injection well along the trend of the known Wray Mesa fault system. The primary zone is within a reservoir covering between 20 and 30 cubic kilometers

More than 99.9% of the over 4,000 surface-recorded events induced at the Paradox Valley injection since 1991 have magnitudes less than **M**2.0. The human detection threshold at Paradox is ~**M**2.5; There have been ~20 induced events felt at the region.

Our best estimate indicates PVU has induced ~2 million events with magnitude **M**-3.0 and greater. Being a surface array, PVSN's recording sensitivity is ~0.1% of these events which includes those events with magnitude ~0.0 and greater.

The largest seismic event, an **M**4.3 in May 2000, occurred after ~4 years of continuous injecting.

The first seismic event induced by continuous pumping occurred 111days after pumping began.

The general rate of seismicity is not uniform nor following any discernible pattern; during periods of continuous injection, there are one-day, multi-day, and multi-week quiet periods and multi-hour to multi-day active periods.

Spatially, seismic events occur as isolated events and in swarms; swarms can occur over hours to days in a single location.

The seismic swarms at Paradox are like typical earthquake swarms that culminate in one large event and some smaller foreshocks and a few smaller aftershocks or have one large event followed by 5 to 15 aftershocks.

The seismicity continuously occurs within the interior and on the border of the existing seismic zones; since mid-1999, the expansion of the zones seems negligible, if at all.

By the end of 2005, PVU injected >0.004 cubic kilometers of injectate. Because connate fluid has been displaced and this fluid can trigger seismic events, the volumetric extent of the injectate is probably less than the volumetric extent of the seismic zone

Seismic event depths are vertically contained between ~3.5 km and ~6.0 km below the injection wellhead.

Epicenters pattern of the secondary fracture and fault network seems to align with (e.g., terminate along) the major, through-going faults of the Wray Mesa system and follows the predicted hydraulic gradient of target formation.

The major fault system aligns with the principal stress direction and acts as a fluid conduit showing only minor, if any, surface-recordable seismicity.

The fault-planes defined by focal mechanism solutions (i.e., moment tensors) align with the strikes of the faults and fractures or with the predict shear planes.

Economically reasonable, 20-day shut downs has somewhat reduced the proclivity for large events by relaxing the local state of stress.

Percentage of brine (i.e.,% PVB) in injectate has not affected seismicity directly; however, it has increased the bottom-hole pressure due to the increase in specific gravity of injectate.

The storage of injectate is facilitated by the injection pressure exceeding the fracture pressure and creating new volume plus creating pathways to additional pore space; the seismically-illuminated faults and fractures can only accommodate a few percent of the injectate volume.

The *b*-value, a parameter related to the number of seismic events per size and indirectly related to repeatability of seismic events, seems to have been altered by the changes in injection phases.

10.0 MISCELLANEOUS

10.1 Acceptable Ground Motion Regulations

As best we have been able to determine, the Federal Government has no published regulation or regulations regarding acceptable ground motion amplitudes resulting from seismic events induced by injection. The same is true for the State of Colorado. However the State of Colorado does have regulations for acceptable ground motion from blasting associated with coal mining (Colorado Division of Mineral and Geology, 1980), specifically the Rules and Regulations of The Colorado Mined Land Reclamation Board Pursuant to the Colorado Surface Coal Mining Reclamation Act, Rule 4: Performance Standard. Under Section 4.08.4(10) states "Except as provided by 4.08.4(10)b, the maximum peak particle velocity in blasting operations shall not exceed the following limits at the locations of any dwelling, public building, school, church, or community or institutional building, outside the permit area:..." At a distance from the blasting site of 5001 or more feet, maximum allowable peak particle velocity (in inches/s) is 0.75. Section 4.08.4(10)b noted in the previous quotation states, "The Division may allow a variance from the maximum peak particle velocity limits if it determines that the structure is owned by the person conducting the surface coal mining operations, and the structure is not leased to another party, or if leased to another party, that a written waiver by the lessee is submitted to the Division prior to blasting."

We offer this section as a reference, since, as noted, we know of no regulations governing acceptable-sized induced ground motion. The applicability of blasting regulations and the noted variance to Paradox injection is not a subject with which we are mandated to pursue nor have any legal standing, therewith.

10.2 Supplemental PVSN Staff Activities During 2005

(1) Published Papers

"*Deep Injection and Closely-Monitored Seismicity at Paradox Valley, Colorado*," by J. Ake, K. Mahrer, D. O'Connell, and L. Block, **Bulletin of Seismological Society of America** (April, 2005).

“*Injection Brine and Inducing Seismicity a the World’s Deepest Injection Well, Paradox Valley, Southwest Colorado, USA*,” by K. Mahrer, J. Bundy, J. Ake, L. Block, and D. O’Connell, in **Underground Injection Science and Technology**, ed by C-F Tsang and J.A. Apps, Vol 52 of Elsevier’s series: Developments in Water Sciences (2005).

10.3 Accompanying CD File List

The accompanying CD contains 7 files:

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

(2-7) PDF files of this year’s, the 2004, 2003, 2002, 2001, and 2000 PVSN annual reports

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