**TECHNICAL SERVICE CENTER**
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# 2001 Status Report-Paradox Valley Seismic Network
# Paradox Valley Project
# Southwestern Colorado

*Prepared by*


Ken Mahrer
Jon Ake
Lisa Block



U.S. Department of the Interior
Bureau of Reclamation

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

**Technical Memorandum No. D8330-2002-003**

# 2001 Status Report-Paradox Valley Seismic Network
## Paradox Valley Unit
## Southwestern Colorado

**Prepared By**


Kenneth D. Mahrer — 4/25/02
Kenneth Mahrer
Geophysicist
Date

4/25/02
Jon Ake
Seismologist
Date

for 4/25/02
Lisa Block
Geophysicist
Date


**Peer Review**


4-25-02
Jerry Wright
Geophysicist
Date

## 1.0 Introduction

This report summarizes the calendar year 2001 seismic observations and related work for the Paradox Valley Seismic Network (PVSN). The network is operated by the Bureau of Reclamation as part of the Paradox Valley Unit (PVU) of the Colorado River Basin Salinity Control Project. PVU removes and disposes Paradox Valley brine (PVB) prior to it entering the Dolores River, a tributary of the Colorado River. PVB is extracted from the local aquifer via 9 shallow extraction wells along the eastern half of the Dolores River in its traverse across Paradox Valley. During 2001, as in previous years, PVB is filtered and treated with additives, cut to 70% PVB-30% Dolores River fresh water, before high-pressure injecting it ~4.5 km below the earth's surface through a deep injection well. The injectate intrusion into the subsurface induces small seismic events.

Monitoring, analyzing, and interpreting the seismic events is the mandate of the PVSN operations. Specifically, PVSN (1) gathers ground motion data originating in and around Paradox Valley and the surrounding region (2) electronically telemeters these data to the Denver Federal Center (DFC) in Lakewood, CO; (3) evaluates and catalogs local seismic events in the data; (4) locates the sources of the events; (5) determines source mechanics (e.g., focal mechanisms) of the events when feasible; and (6) identifies and evaluates relationships between seismicity, geology, tectonics, subsurface brine movement and location, and injection parameters.

In following order, this report discusses geological setting, PVSN instrumentation, well operations, seismic observations and analysis, rock properties modeling, conclusions and recommendations.

## 2.0 Local Setting

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. 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 msl and border Paradox Valley on the northwest. Paradox Valley has a relatively flat floor enclosed by steep walls of sandstone and shale. Elevations vary from about 1.5 km above msl in the valley to about 2.0 km above msl along the valley rim.

Paradox Valley is one of five northwest-striking, collapsed diapiric salt anticlines in southwestern Colorado and southeastern Utah. The formation of these anticlines began about 250 mya when the emergence of mountainous uplifts placed intensive lateral stresses on the intervening sedimentary formations, causing faulting and fracturing along weak axial zones. Subsequently the stresses relaxed and combined with the weight of overlaying strata forced a deeply buried, salt-rich layer to flow upward into the faulted area creating the anticline. Throughout the process, the Dolores River, a tributary of the Colorado River, stayed its course west to east normal to the strike of the anticline. As pressures eased, the crest of the anticline gradually dropped downward into fault blocks, creating Paradox Valley.

The Dolores River originates in the San Juan Mountains of southwest Colorado and flows generally northwest for about 300 km to Paradox Valley and another 110 km 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 has essentially no effect on the river flow. Over its path through Paradox Valley, the Dolores can pick up more than 180,000 metric tons (200,000 standard tons) of salts annually, primarily from brine ground water, PVB, percolating through seeps and springs in the salt and then through the Dolores' banks and beds. There are two general types of seeps and springs: relatively fresh water with total dissolved solids varying from about 1,500 milligrams per liter (mg/l) to 4,000 mg/l and brine with about 250,000 mg/l. Water pumped from the 9 extraction wells near the river has a salinity of about 260,000 mg/L. This brine, which is nearly eight times the salinity of sea water, consists almost entirely 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 limited amounts. Noticeable amounts of hydrogen sulfide gas are released as the brine surfaces, creating a noxious odor.

**2.1 PVU Salinity Control Well No. 1.** The PVU Salinity Control Well No. 1 was completed in 1987 at a total depth of 4.88 km (16,000 ft). The well penetrated rock from the Triassic into the Precambrian. Based on 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).

**2.2 Wray Mesa Fault and Fracture System.** PVU Salinity Control Well No. 1 was sited to intersect the NW-SE trending Wray Mesa fault system. Historical movement on the Wray Mesa faults has created a fracture field within the fault system. 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 and that the least resistance is to the northeast and updip along the fracture permeability of the Wray Mesa system. Our findings, based on seismic source locations, are consistent with this prediction.

## 3.0 Instrumentation

Paradox Valley Seismic Network 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 1**). PVSN was installed in late 1983 and has operated continuously since that time. For each station shown in **Figure 1**, **Table 1** gives station name, location, elevation, and operational parameters. 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 80 km.

Each PVSN station consists of a ground motion sensor or sensors (i.e., seismometer), amplifier, voltage control oscillator (VCO), low power telemetry radio, solar panel, and broadcast tower with antenna. All systems are powered by solar-recharged batteries. Most of the stations operate single, vertical-motion seismometers. The Davis Mesa and Nyswonger Mesa stations (PV11 and PV16, respectively), operate three-component seismometers, recording vertical, east-west, and north-south motion.

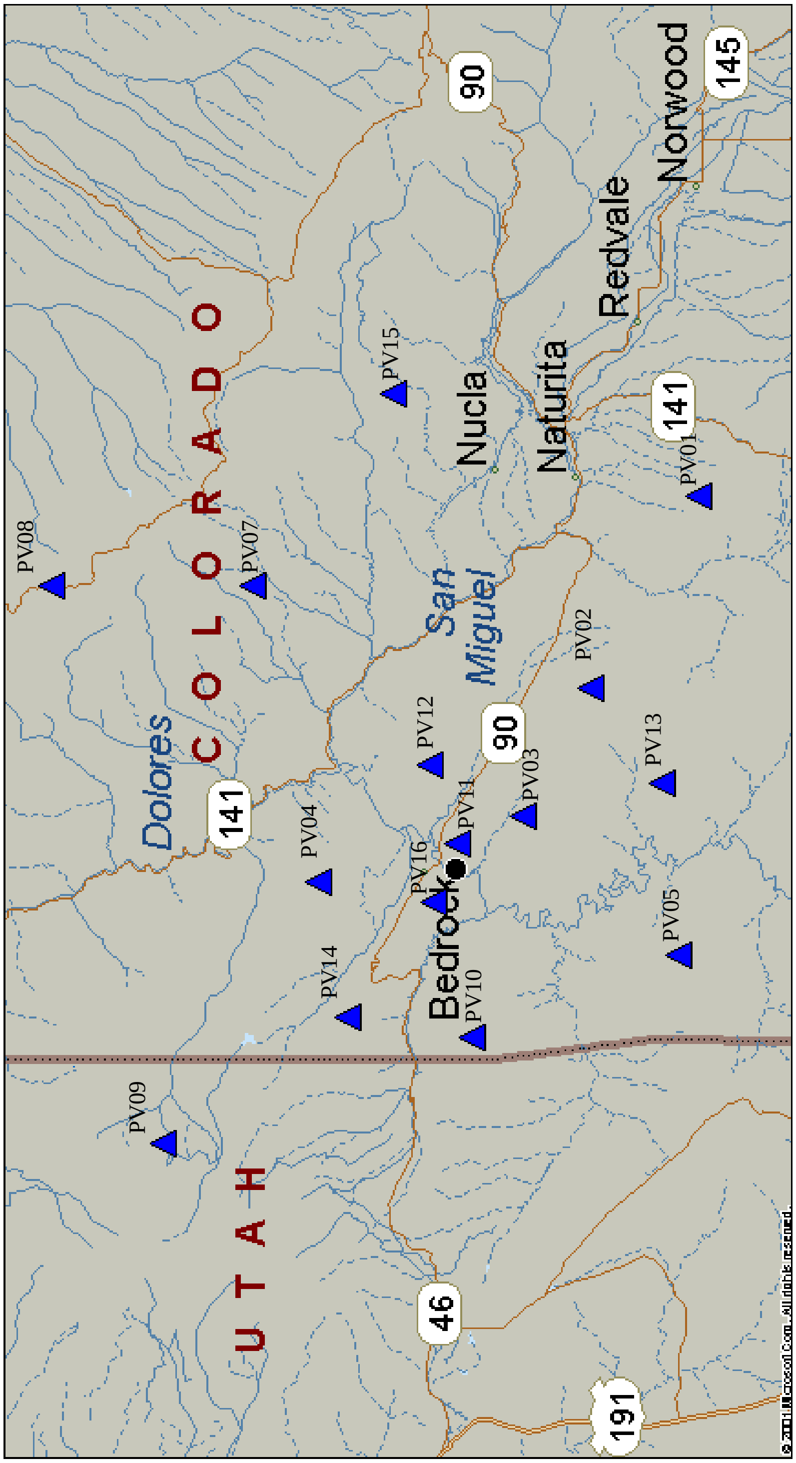


***Figure 1. Locations of Paradox Valley Seismic Network stations (blue triangles), and Paradox Valley Unit Injection Well (black circle).***

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

**Table 1: PVSN Instrument Locations and Characteristics**

| Station Designation | Station Name | Latitude deg., N | Longitude deg., W | Elevation m, msl | Date Installed | Gain, dB/ Filters, Hz |
|---|---|---|---|---|---|---|
| PV01 | The Burn | 38.13 | 108.57 | 2190 | 5/83 | 78 / 0.2-25 |
| PV02 | Monogram Mesa | 38.21 | 108.74 | 2158 | 5/83 | 78 / 0.2-25 |
| PV03 | Wild Steer | 38.25 | 108.85 | 1975 | 5/83 | 78 / 0.2-25 |
| PV04 | Carpenter Flats | 38.39 | 108.91 | 2152 | 5/83 | 78 / 0.2-25 |
| PV05 | E. Island Mesa | 38.15 | 108.97 | 2150 | 5/83 | 78 / 0.2-25 |
| PV07 | Long Mesa | 38.44 | 108.65 | 2001 | 6/83 | 78 / 0.2-25 |
| PV08 | Uncompahgre Butte | 38.58 | 108.65 | 2941 | 6/83 | 78 / 0.2-25 |
| PV09 | North LaSalle | 38.50 | 109.13 | 2640 | 6/83 | 78 / 0.2-25 |
| PV10 | Wray Mesa | 38.29 | 109.04 | 2300 | 6/83 | 78 / 0.2-25 |
| PV11Z | Davis Mesa | 38.30 | 108.87 | 1881 | 12/89 | 78 / 0.2-25 |
| PV11N | Davis Mesa | 38.30 | 108.87 | 1881 | 12/89 | 60 / 0.2-25 |
| PV11E | Davis Mesa | 38.30 | 108.87 | 1881 | 12/89 | 60 / 0.2-25 |
| PV12 | Saucer Basin | 38.32 | 108.80 | 2091 | 12/89 | 78 / 0.2-25 |
| PV13 | Radium Mtn | 38.16 | 108.82 | 2158 | 12/89 | 78 / 0.2-25 |
| PV14 | Lion Creek | 38.37 | 109.02 | 2240 | 12/89 | 78 / 0.2-25 |
| PV15 | Pinto Mesa | 38.34 | 108.48 | 2280 | 6/95 | 78 / 0.2-25 |
| PV16Z | Nyswonger Mesa | 38.32 | 108.92 | 2045 | 7/99 | 78 / 0.2-25 |
| PV16N | Nyswonger Mesa | 38.32 | 108.92 | 2045 | 7/99 | 60 / 0.2-25 |
| PV16E | Nyswonger Mesa | 38.32 | 108.92 | 2045 | 7/99 | 60 / 0.2-25 |
| ***Notes: Elevations are relative to mean sea level (msl), the surface elevation of the injection well is 1540 m above msl. Designations "Z", "N", & "E" stand for instruments that sense motion in the vertical, north- south, and east-west directions, respectively.*** | | | | | | |

**3.1 Telemetry and Software.** In October of 2000, Reclamation upgraded its 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.

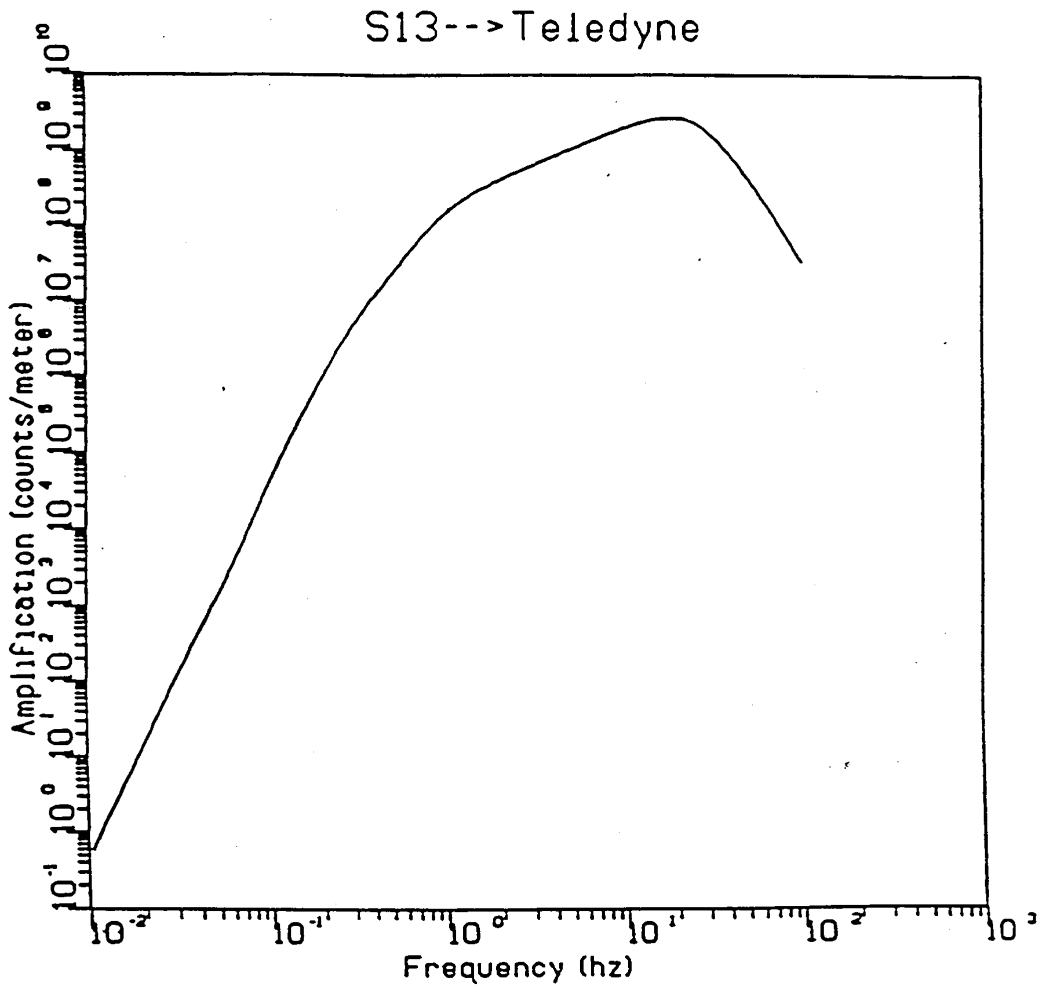


***Figure 2. Typical response of a vertical-component Teledyne Geotech S13 seismometer, electronics, and digital recording system used by PVSN. Nominal gain is 48 dB for curve shown, Teledyne Geotech model 42.5 amplifier/VCO and model 4612 discriminator. Damping is 0.71 of critical.***

PVSN data telemetry begins with continuous analog signals broadcast from each seismometer site to a receiver in Nucla, CO. At Nucla, the signals are digitized and transmitted via a digital telephone link to the Bureau of Reclamation processing center at the Denver Federal Center (DFC) 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.

**3.2 PVSN Efficiency**. During 2001, the seismic network and telemetry system operated at 100% efficiency. [Efficiency is the percentage operational data channel days which is calculated by multiplying the number of channels in operation times the number of days in operation and dividing by 6570; 6570 equals 365 days times 18 data channels]. In 2001, instrument and data telemetry operations were essentially flawless. Previous years averaged about 90% efficiency.

**3.3 PVSN New Instrumentation.** In late 2001, we installed the infrastructure for two additional, 3-component stations. One station will be a new site on Wray Mesa, ~8 km east of PV10. The other is an upgrade to PV12 at Saucer Basin. Both sites will be instrumented with Guralp CMG-40T seismometers. The new instrumentation will digitize on site and record broader frequency and amplitude ranges than the existing instruments. We expect to bring these stations online by mid 2002.

## 4.0 Well Operations

The PVU Salinity Control Well No. 1 is located at $38^{o}$ 17.73'N and $108^{o}$ 53.72'W along the western boundary of Paradox Valley, approximately 1.5 km up a canyon formed by Dolores River (see **Figure 1**). **Figure 3** shows a plan view and a north-viewing cross-section depth profile of the well. The plan view, whose origin is the wellhead, shows the well is essentially vertical, drifting only ~0.3 km to the east and slightly to the north over its 4.8+ km depth. The cross section in **Figure 3** shows the well deviation to the east plus the stratigraphic column through which the well is drilled. Note also the location of the two perforation intervals of the wellbore casing. The primary target injection internal is the Mississippian-aged limestone, Leadville formation.

During 2001, PVU pumped approximately 380 million liters (100 million gallons) of injectate, 70% Paradox Valley Brine - 30% Dolores River fresh water. This compares to 424 million liters (112 million gallons) in 2000, 568 million liters (150 million gallons) in 1999 and 632 million liters (167 million gallons) in 1998. The reduced injectate volumes in 2000 and 2001 are a result of reducing the injection rate following a magnitude **M** 4.3 earthquake on May 27, 2000.

**4.1 Operations to Mitigate Seismicity**. Prior to May 27, 2000, PVU pumped the 70/30 injectate

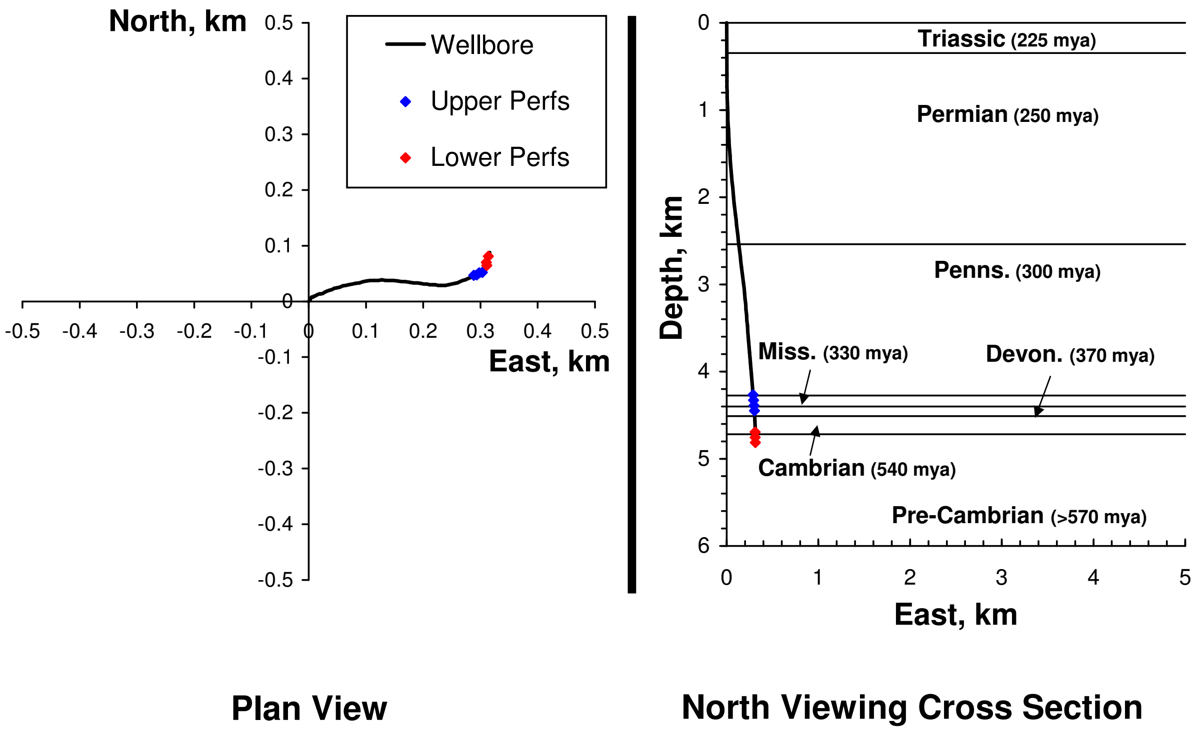


***Figure 3. Plan view and north-viewing cross section of PVU Salinity Control Well No. 1, including the stratigraphic column.***

at a maximum rate of 345 gal/min (gpm). Operationally this meant 3 constant-rate pumps, each operating at 115 gpm, resulting in an average wellhead pressure of ~4,800 psi. (*Note*: add ~7,000 psi, the static pressure of the fluid column of 70/30 injectate in the wellbore, to approximate the injection pressure at the casing perforations, ~12,000 psi).

During 3-pump operations, the surface pressure on occasion approached the wellhead pressure safety limit of 5,000 psi; at these times PVU shutdown one injection pump, 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.

Immediately following the May 27, 2000 event, PVU shutdown for 28 days. During this shutdown period, BOR evaluated operations and its effect on seismicity and decided on a new strategy to reduce the seismicity. The new strategy reduced injection from 3 injection pumps to 2. On June 23, 2000 pumping resumed using 2 pumps giving an injection rate of ~230 gpm. At this reduced rate, surface pressure normalized at ~4,400-4,500 psi. It was believed that reducing the injection rate combined with previously-instituted bi-annual 20-day shutdowns would mitigate the potential for large events.

Prior to May 27, 2000 pumping shutdowns, specifically 20-day shutdowns, one in December and one in June, were used to mitigate dangerous seismicity. During 2001, PVU witnessed all or parts of four shutdowns: 12/19/00 to 1/7/01, 6/2/01 to 6/24/01, 9/6/01 to 9/12/01, and 12/18/01 to 1/07/02. PVU implemented scheduled bi-annual shutdowns to combine routine maintenance and mitigate seismicity following the second-largest PVU event, a **M** 3.3 in June 1999.

Prior to the June 1999 event, we had noted that the rate of seismicity in the near-wellbore region (i.e., about 2 km from the wellbore) reduced during and following maintenance shutdowns. Based on this observation, PVU scheduled bi-annual, 20-day shutdowns. However, as demonstrated by the May 27 event, 20-day shutdowns alone were not sufficient for stemming large event production. The combined shutdowns and reduced injection rates have, to date, mitigated seismic production. Based on the 18 months of monitoring seismicity (i.e., 6 months in 2000 and 12 in 2001), this strategy has mitigated seismic event production, inferring a reduced proclivity for larger or felt events. However, mitigation is not equivalent to elimination. Larger (i.e., **M** 3 or greater) are still probable, but their rate of production has most likely been significantly reduced by the combined shutdowns and reduced injection rate.

**4.2 Injectate: 70/30 versus 100% PVB.** Since continuous pumping began in 1996, PVU has cut the injectate to 70% PVB and 30% Dolores River fresh water. This cutting was based on a geochemical prediction that 100% PVB would interact with connate fluids and the dolomitized Leadville Limestone causing calcium sulfate precipitation that would clog injection, halting operations. During 2001, the injectate concentration question was reconsidered and it was decided that following the December 20, 2001 20-day shutdown, the injectate would be 100% PVB.

The discussions during 2001also indicated that, if precipitation occurs, its maximum expected rate is ~8 tons of calcium sulfate per day. To put this into perspective, injection at ~230 gpm, assuming a density of 8.33 lbs/gal, gives a daily injection tonnage of ~1380 tons/day. Comparing, the maximum expected precipitate is ~0.6% of the daily injection.

We are particularly interested in this change of injectate as it may affect seismicity. Possible effects include: (1) reduced seismicity, since flow paths become clogged and more injectate is forced into the native porosity away from activatable faults; (2) increased seismicity since clogging established flow paths will cause injectate diversion into untouched reservoir regions causing additional seismicity and expansion of the seismicity cloud, or (3) no noticeable change.

## 5.0 Seismic Analysis

**5.1 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 $\mathbf{M_D}$. (For a more complete discussion of the magnitude scale for PVSN see Mahrer et al., 2001)

**5.2 Preliminary Event Location Method.** Accurately locating earthquakes requires (1) identifying and measuring 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 in 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. A minimum of four arrival times from at least three stations is required 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 (Davis Mesa) and PV16 (Nyswonger Mesa) and from the closest single-component station to the injection well, PV03 (Wild Steer). Although S-wave arrival times are very important to the analysis, we use only 3 stations because the closeness of the sources to the stations and the complexity of local geology facilitate mis-identifying the S-phase in the signals causing mis-located events. This is especially true when picking S-arrivals from stations with only vertical-component instruments.

We determine preliminary earthquake locations using a flat, one-dimensional, layered earth velocity model and the computer program SPONG (Malone and Weaver, 1986). The velocity-depth profile of the one-dimensional model is summarized in **Table 2**. The P-wave velocity depth profile began using Wong and Simon's (1981) results, to which were added results from seismic refraction surveying and sonic logging. The refraction data were obtained using local mining explosions and the sonic logs were obtained during drilling the injection well. We computed the S-wave velocities from P-wave velocities using the traditional assumption, Poisson's ratio = 0.25 (i.e., ratio of P-wave to S-wave velocity is 1.732). To augment our preliminary analysis, we upgraded the velocity model and increased event location accuracy using seismic tomography; these are described later.

In addition to the earthquakes, PVSN records non-seismic signals. These signals are caused by thunder, lighting strikes, landslides, low-flying aircraft, oil and gas exploration blasts, and mine and quarry blasts. The discrimination of PVU injection-induced signals from other signals requires processing experience and consistency. Knowing the locations of established mining facilitates differentiating local earthquakes from noise. Blasts signals arrive from a distributed area around Uravan, as far away as Paonia (e.g., West Elk Coal Mine) and Rifle (e.g., Rifle Quarry), and from mining west of Nucla (e.g., West End Gravel pit). Since local explosions generate distinct waveforms (e.g., impulsive or very abrupt P-waves, unusually weak S-waves, and enhanced surface waves for small magnitude events) our analysts can discriminate between the blasts, regional earthquakes, and the PVU induced microseismicity. We know of no explosive sources near the PVU injection well that produce signals that could be misidentified as induced microseismicity.

**Table 2: PVSN Velocity Model**

| Depth below Surface (km) | P-Wave Velocity (km/sec) | S-Wave Velocity (km/sec) |
|---|---|---|
| 0.00 | 3.595 | 2.076 |
| -0.20 | 3.950 | 2.281 |
| -0.60 | 4.330 | 2.500 |
| -1.00 | 4.650 | 2.685 |
| -1.40 | 5.050 | 2.916 |
| -2.20 | 5.100 | 2.945 |
| -2.80 | 5.340 | 3.083 |
| -4.00 | 5.420 | 3.129 |
| -4.20 | 5.700 | 3.291 |
| -4.60 | 5.850 | 3.378 |
| -5.80 | 5.872 | 3.390 |
| -11.0 | 5.897 | 3.404 |
| -18.0 | 6.000 | 3.464 |
| -40.0 | 7.200 | 4.157 |
| ***Notes: Depth indicated is relative to a datum of +1850 m above msl. The wellhead is 1540 m above msl*** | | |

## 6.0 Observations

Prior to injection at PVU, the Paradox Valley region witnessed one or two recordable events per year (EnviroCorp, 1995; Ake and others, 1996). Beginning with the injection tests in 1991 through 2000, PVSN recorded and located more than 3740 events within 10 km of the injection well. As a result, we can safely infer that PVU injection induced the events recorded in 2001 and located within this bound.

**6.1 Event Production Rates.** During 2001, PVSN recorded and located 84 earthquakes within 10 km of the PVU brine injection well. Before discussing these data we must clarify a point. We have found that the Earthworm system, discussed above, is less sensitive for detecting 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, all subsequent discussions and figures will only use **M** 0.0 or greater data.

During 2001 PVSN recorded and located 83 events with **M** 0.0 or greater. Compared to 2000 (282 events), 1999 (1070 events) and 1998 (1098 events), this is a substantial reduction in the number of induced events. **Figure 4** shows the cumulative event production and the total injection volume for years 1998 through 2001. Note decreases in average slope of the event production and their correspondence in time with periods of zero injection (i.e., flat portions of the volume curve). This correspondence supports our assessment that shutdowns reduce event production. In support of **Figure 4**, **Figure 5** shows histograms of monthly injection volume and monthly event production since continuous pumping began in 1996. In the figure there is some question as to the completeness of the data in the later months of 1997. **Figures 4** and **5** emphasize how dramatically event production has reduced since mid-2000 with the injection rate reduced from 345 gpm to 230 gpm.

For the years that we have complete data sets, 1998, 1999, 2000, and 2001, the average number of events per day were 3.15, 3.14, 0.85, and 0.23, respectively. **Figures 6** and **7** show events per day for these years and the years 1996 and 1997 plus average daily injection rate and average daily wellhead pressure, respectively. As noted, the reduction in event rate after mid-2000 is dramatic.

To fully understand the 2001 data, we considered it with the data from the later half of 2000. We did this because the data divides into categories: those recorded with injection at 345 gpm (i.e., before May 27, 2000) and those recorded with injection at 230 gpm (i.e., after June 23, 2000). In 2000, 130 events occurred on or before May 27, 37 occurred during the shutdown from May 28 through June 22, and 139 occurred from June 23 through the end of the year. By average, this breaks down to 0.9 events per day prior to the May 27 event, and 0.7 after the event.

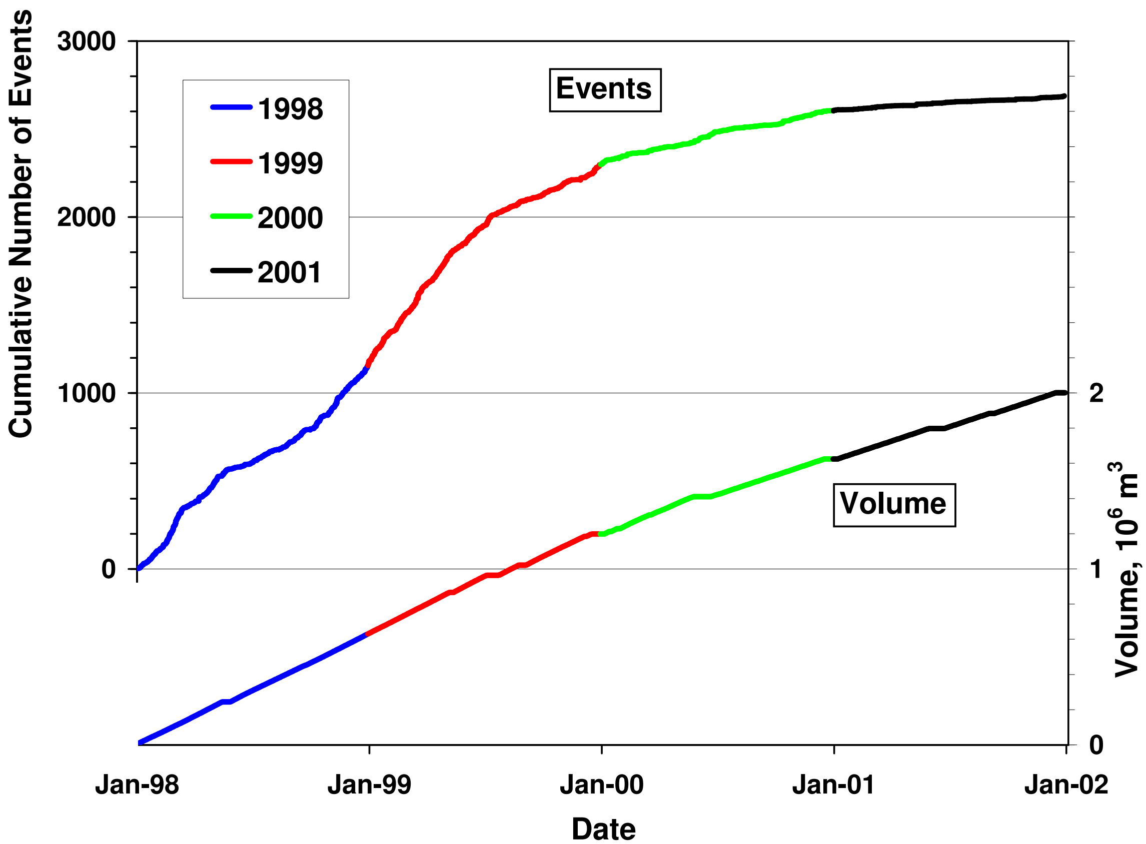


***Figure 4. Cumulative number of seismic events and cumulative injection volume versus time. Flat portions in volume curve are shutdown periods (i.e., no injection). Note correspondence between many of the shutdowns and the change in slope (i.e., rate) of event production.***

We compared the post-June 23rd 2000 mean event rate to the 2001 mean rate using a *t*-Test. We wanted to determine if these means, despite their numerical difference, were statistically different. We found the means of post-June 23rd 2000 rate and the 2001 rate were statistically different to a 95% confidence level. We believe this shows the reduced event production following the reduced injection rate is not only immediate but continued to decrease into 2001 and will take many months to come to an equilibrium.

To test whether the reduced event production following June 23rd was statistically significant, we *t*-Tested the mean daily event rate from 1998 through June 22, 2000, 2.7 events/day, to the mean rate from June 23rd 2000 through the end of 2001, 0.40 events/day. The *t*-Test showed that these

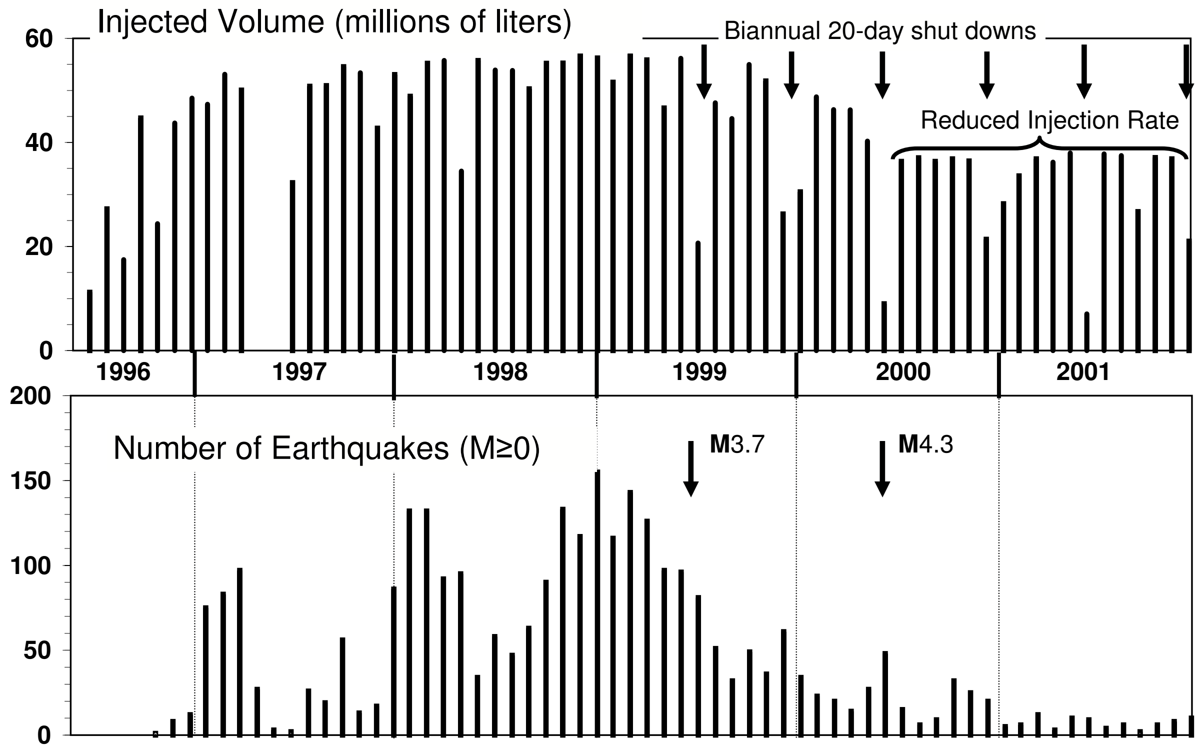


***Figure 5. Monthly injection volume (top) and monthly earthquake production at PVU versus time. Noted are onsets of bi-annual, 20-day shut downs, reduced injection rates and the M3.7 and M4.3 earthquakes.***

means are also statistically different to a 95% confidence level.

**6.2 Event Magnitudes.** As noted, the daily seismic event rate in 2001 was substantially less than earlier years. We believe this results from the combined shutdown periods and reduced injection rate. Similarly, in 2001, fewer larger magnitude events were observed. **Figure 8** shows the event magnitude distribution for 1998, 1999, 2000, and 2001. The insert shows a close up of the distribution for events $M_D$ 2.0 and larger.

Compilation of the data in **Figure 8** shows that during 1998 88 or 8.0% of the events were larger than $\mathbf{M_D}$ 1.5. During 1999, 94 or 8.7% were larger than $\mathbf{M_D}$ 1.5. During 2000, prior to and including the May 27th event, 11 or 8.5% were larger than $\mathbf{M_D}$ 1.5. After pumping resumed on June 23,

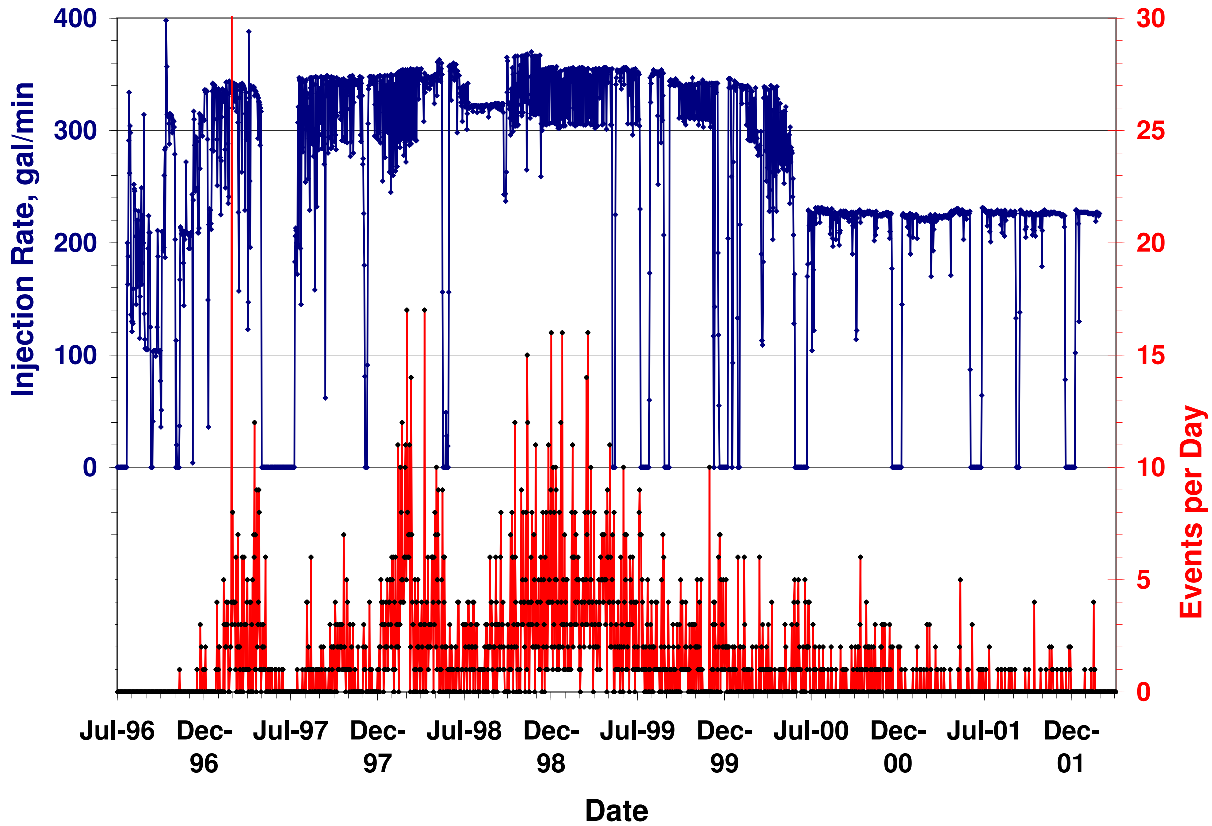


***Figure 6. Number of events per day (red) and average daily injection rate (blue) versus time. Event count only includes M 0.0 and larger.***

2000 only 8 or 5.5% were larger than $\mathbf{M_D}$ 1.5; during 2001 11 or 13% of the events were larger than $\mathbf{M_D}$ 1.5. This should not be construed that 2001 showed a percentile increase in larger event production. First, in 2001 only one event $\mathbf{M_D}$ 2.0 or greater was recorded. Second, the shape of the magnitude distribution curve for 2001 in **Figure 8** is different than the shapes of the curves for the previous years. In 2001 the distribution is nearly flat from $\mathbf{M_D}$ 0.4 to almost 2.0. In the other years, over the same range, 0.4 to 2.0, the number of events decreased approximately by a factor of 10. Hence, these data do not show that pumping at a lower rate increases the proclivity for producing larger events. Instead, we believe it shows that inducing earthquake at PVU is strongly dependent on injection rate.

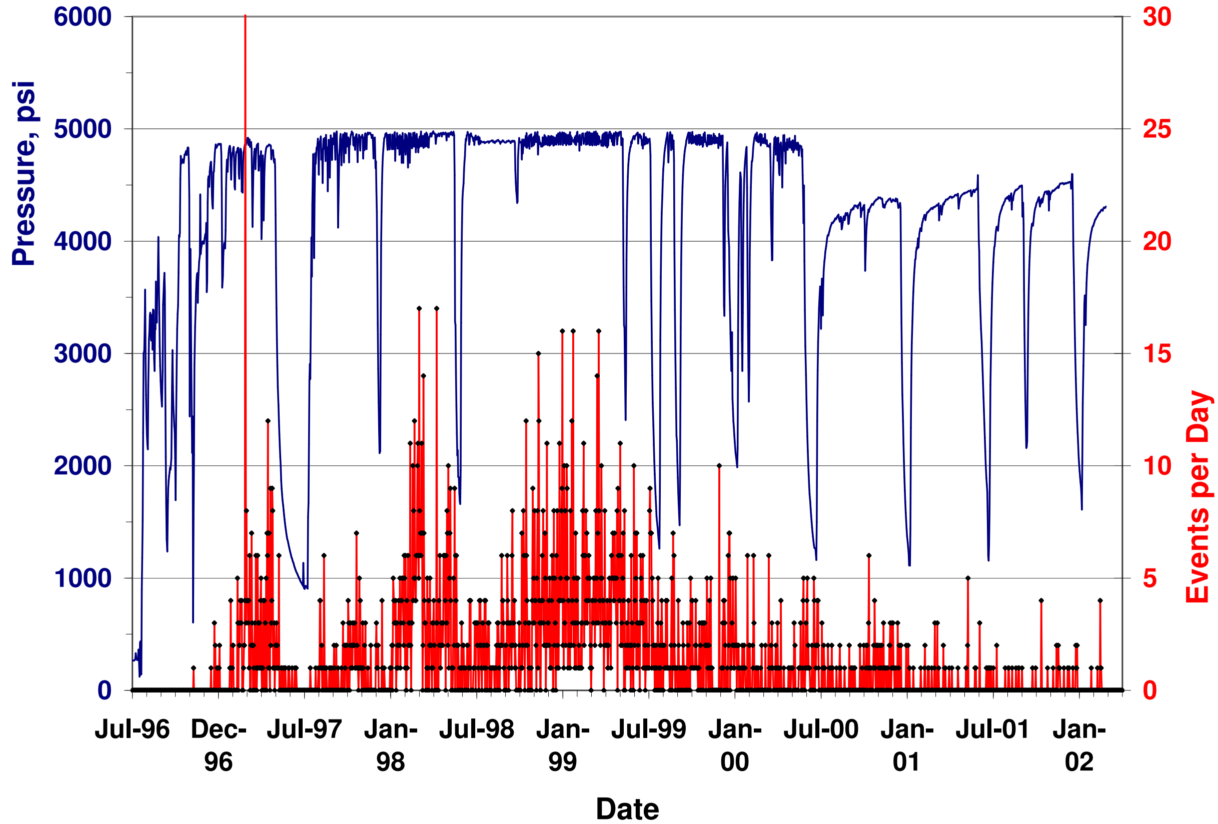


*Figure 7. Number of events per day (red) and surface injection pressure (blue) versus time.*

**6.3 Felt Events.** By the end of 2001, PVSU recorded more than 3,800 events attributed to PVU injection. Of these, more than 99% were imperceptible (i.e., < $\mathbf{M_D}$ 2.4) to people at the surface. From 1991 to 1996 no events were felt. Between 1996 and the end of 2000 about 12 events were felt; During 2001, no felt-events were reported. During 1996-2001, 17 events $\mathbf{M_D}$ 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 4 in 2000. In 2000 only 1 $\mathbf{M_D}$-2.5-or-greater event occurred after the injection reduction following May 27. In 2001 no events $\mathbf{M_D}$ 2.5 or greater occurred.

**6. 4 Event Locations. Figure 9** shows a plan view (i.e., epicenters) of the 83 earthquakes associated with the injection during 2001. The magnitudes of these events range from $\mathbf{M_D}$ 0.0 to $\mathbf{M_D}$ 2.3. With regard to magnitude, the error in locating events generally decreases with increasing

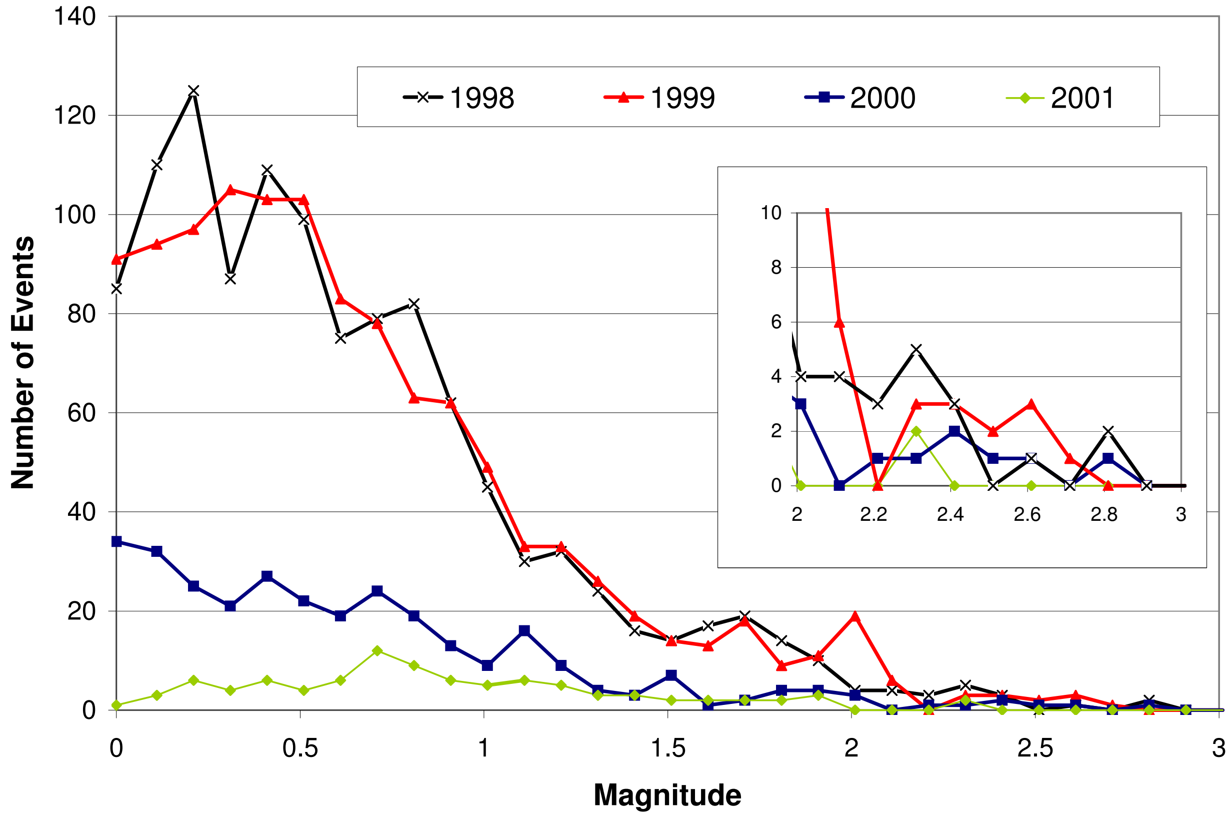


***Figure 8. Comparison of number of events as a function of event magnitude from 1998 through 2001. Insert shows blowup of distribution for magnitudes 2.0 through 3.0.***

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 this data set are based on events with $\mathbf{M_D} > 0.6$.

**Figure 9** shows that the epicenters recorded in 2001 are contained within two groups. The first and most populated group sits near the injection well in an elongated envelope whose long axis runs approximately E-W and extends to a maximum of about 4 km from the well. The second group is centered about 8 km northwest of the injection well. **Figure 10** compares the epicenters for all events from 1991 through 2000, and the 2001 events. This figure is an upgrade to **Figure 9**, all epicenters have been relocated from the original one-dimensional model. The relocation method was discussed in the 2000 annual report (Mahrer et al., 2001).

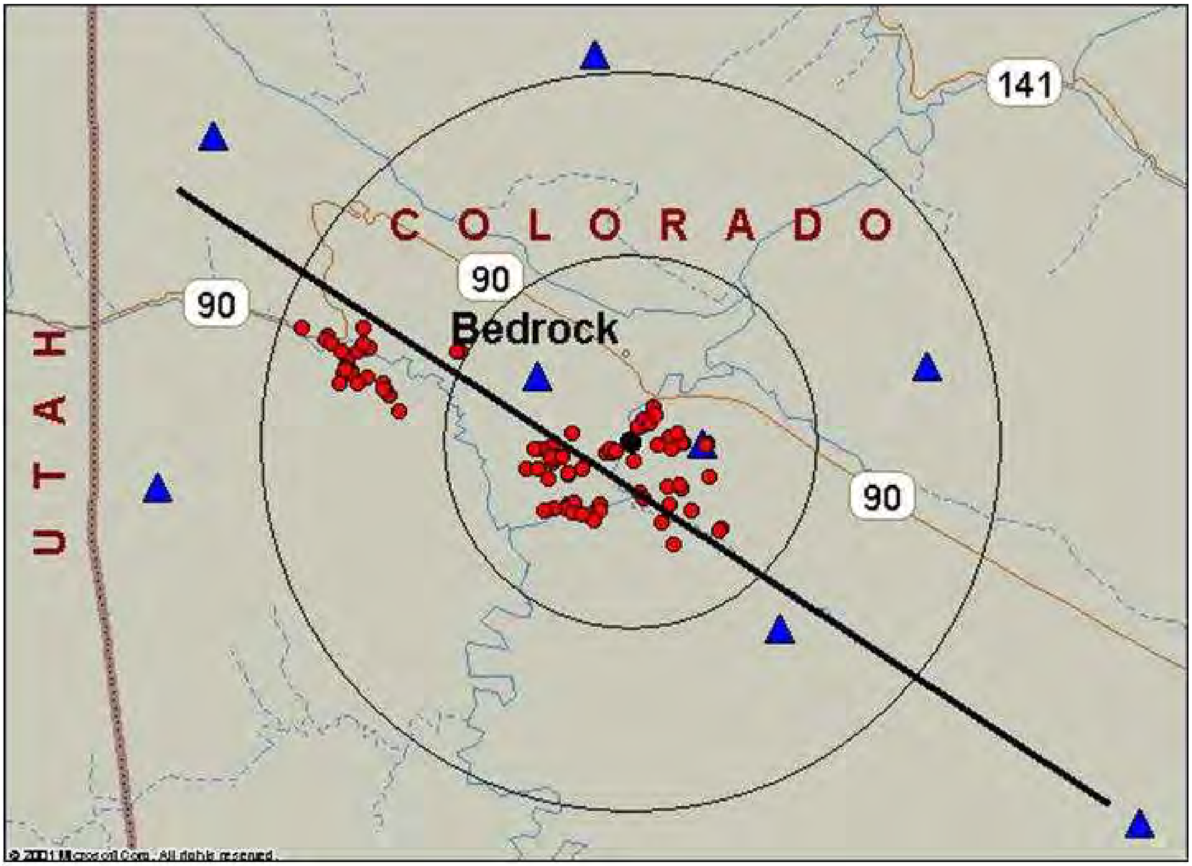


***Figure 9. Seismicity located during 2001 by PVSN using one-dimensional velocity model; 83 events plotted. Injection well is solid (black) circle. Approximate strike of Wray Mesa fault system (Bremkamp and Harr, 1988) shown as solid line. Some PVSN seismogram sites shown in filled (blue) triangles. Concentric circles are 5-km and 10km radii centered on injection well.***

As expected, **Figure 10** shows that the 2001 events locate within the two groupings defined by previous year events. The figure also shows two dashed lines; these lines run N55$^{o}$W, the implied strike of the main faults of the Wray Mesa Fault System. The dashed lines are not intended to overlay faults, but are markers of the fault system's principal strike direction. As discussed in last year's annual report, the relocated epicenters and the shapes of the seismic clouds align well with the strike of the fault system.

The group 8 km northwest of the well first appeared in 1997. We believe that the paucity of events

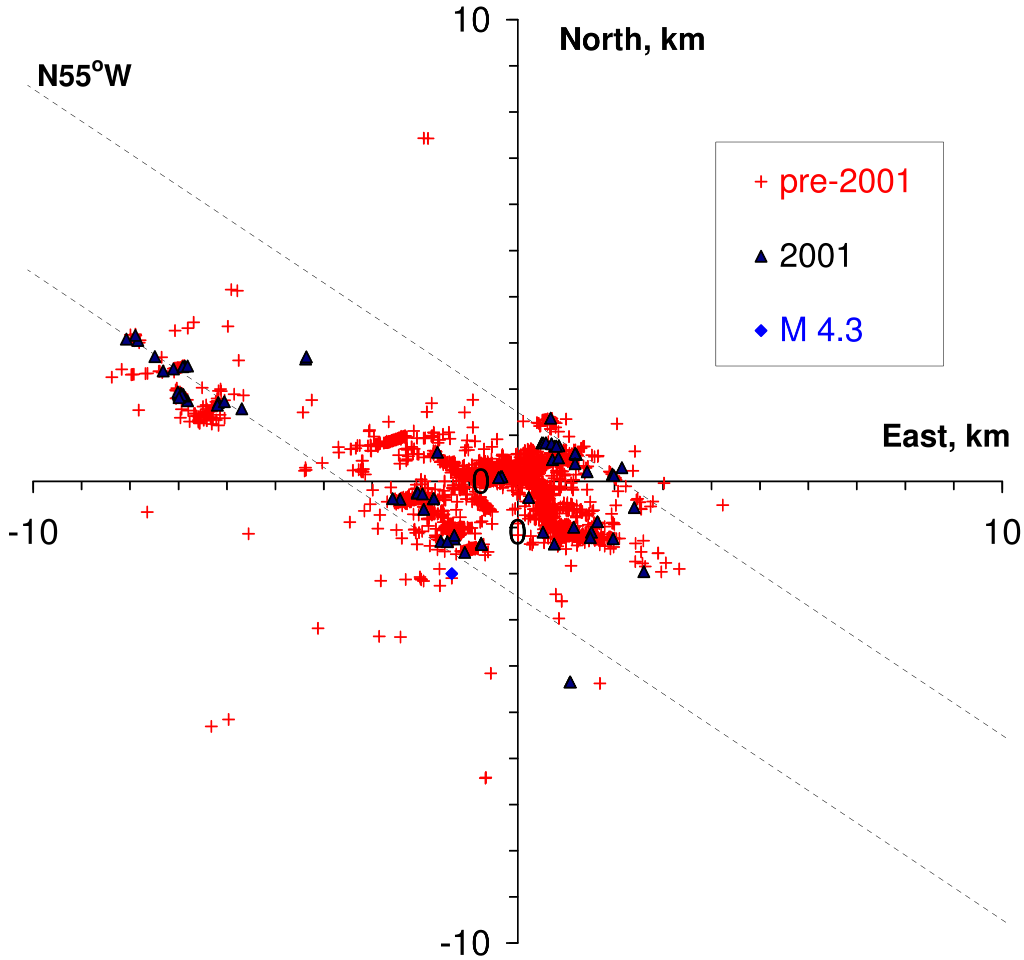


***Figure 10. PVU-induced earthquake epicenters for 2001 and years 1998-2000. All epicenters are relocated from one-dimensional model. Axes are centered on the PVU injection well. Dash lines run N55°W, the implied strike of Wray Mesa Fault system.***

between the two groups, which has been maintained for almost 4 years, indicates the zones communicate hydrologically by a conduit of fluid, probably through the Wray Mesa fault system. The solid line in **Figure 9** shows a line corresponding to one element the fault system based on Bremkamp and Harr (1988) and aligns well with the relation between the northwest group and the wellbore.

Complementing **Figures 9** and **10**, **Figure 11** 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) interpretation and speculation. Projected on the cross section are all events from 1991 through the end of 2001

**Figure 11** shows a number of features. First it shows two vertical groupings of events: one in the Precambrian near the injection well and one starting in the Leadville and rising through the salt about 1.5 km southwest of well. Most likely the second grouping is the actual location of the fault Bremkamp and Harr (1988) speculated to lie about 1.5 km west. **Figure 11** 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 11** 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, with the total number of events substantially less than in previous years, about 28 of the 81 (relocated) events or 35% were 4.8 km or deeper. Note that since the Precambrian shallows to the southwest, these numbers represent minimum number of events in the Precambrian.

**Figure 11** shows earthquake locations for 2001 as with previous years (Ake et al., 1999; Ake et al., 2000; Mahrer et al., 2001) suggest that these events occur primarily over a depth interval of 3.5 to 5.5 km relative to the wellhead. Much of the activity is centered on the depth interval of the perforations of the injection well. It needs to be recognized that the range of depths computed using the initial, one-dimensional velocity model may be representative of the true range of depths or the results may be controlled by the uncertainty in depth determination arising from using a small number of vertical-component stations with a poorly constrained velocity model.

**6.5 Earthquake Recurrence. Figures 12** and **13** show cumulative recurrence curves for earth-

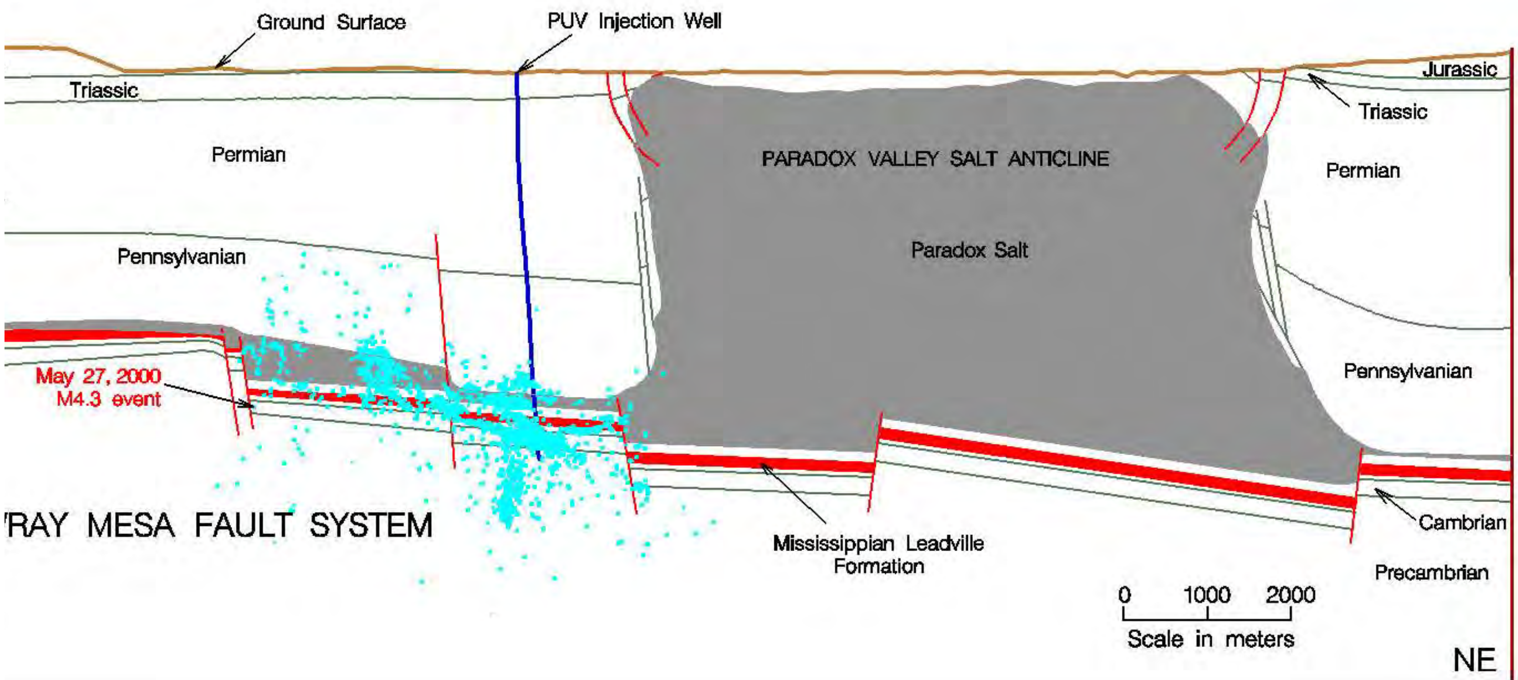


***Figure 11. Cross section of Paradox Valley and bordering region through PVU injection well and normal to strike of the valley. Projected on to cross section are all seismic events 1991 through 2001.***

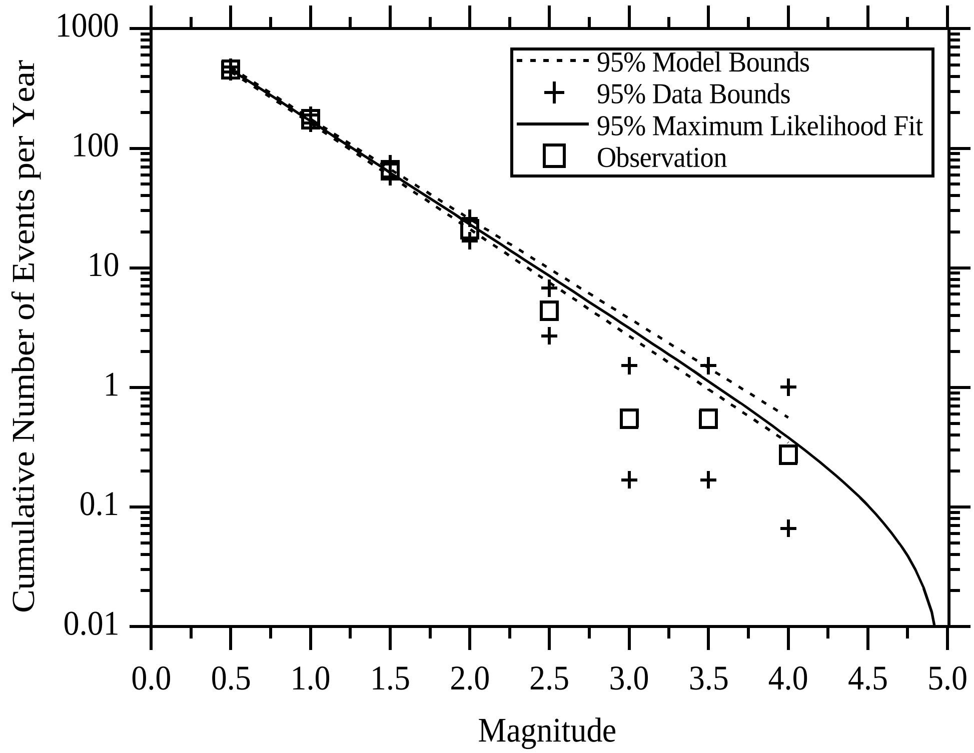


***Figure 12. Cumulative recurrence curve for earthquakes located by the PVSN near the brine injection well from 1996 through June, 2000. Maximum likelihood fit and 95% confidence bounds indicated. The computed "b-value" is 0.86. A maximum magnitude of 5.0 was assumed for the calculations.***

quakes for the 345-gpm injection period, 1996 to late June, 2000, and the 230-gpm injection, late June 2000 through the end of 2001, respectively. The figures begin at $\mathbf{M_D}$ 0.5 since the data suggest this is the lower detection/location threshold (i.e., below $\mathbf{M_D}$ 0.5 ground motion is small and event detection is incomplete.) The (fitted) slope of the recurrence curves (known at the "*b*-value") are 0.78 for the 230-gpm time period and 0.86 for the 345-gpm period. The b-value relates the change in the number of earthquakes with a unit change in magnitude. In Figures 12 and 13 we annualized the data so the b-values here relate the change in the number of earthquakes *per year* with a unit change in magnitude. In 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.

The b-values in **Figures 12** and **13** are consistent with observations of earthquake recurrence

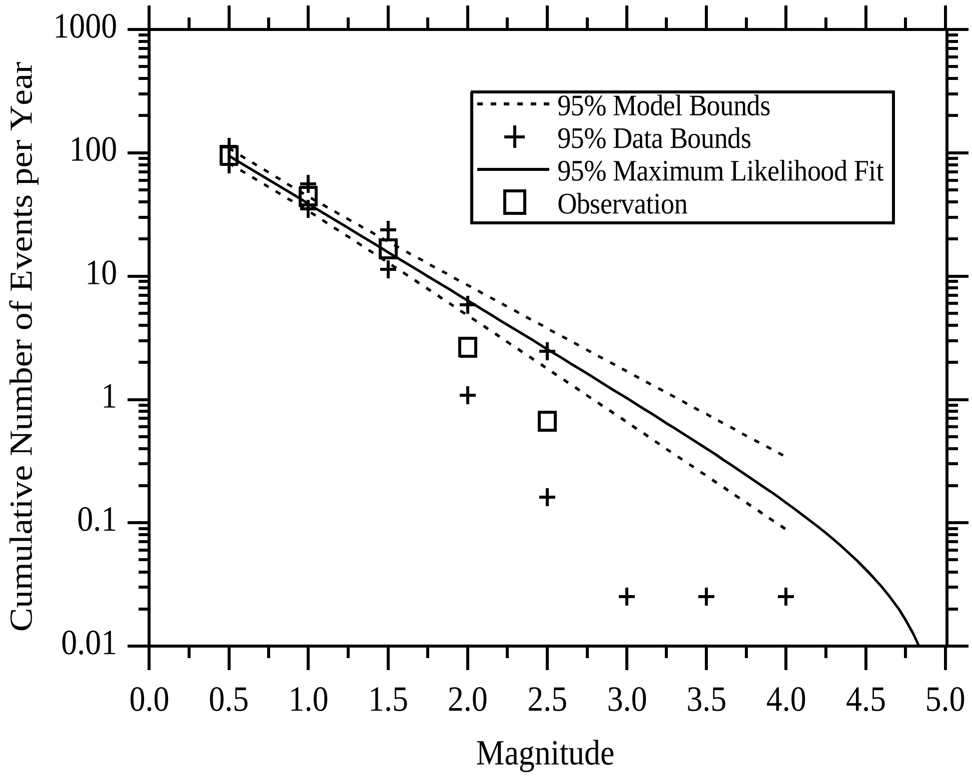


***Figure 13. Cumulative recurrence curve for earthquakes located by the PVSN near the brine injection well for June 2000 through the end of 2001. Maximum likelihood fit and 95% confidence bounds indicated. The computed "b-value" is 0.78. A maximum magnitude of 5.0 was assumed for the calculations.***

within the seismically inactive Colorado Plateau (Wong and others, 1996; LaForge, 1996). The similarity of *b*-values to other studies in the Colorado Plateau support the concept that the induced earthquakes at the Paradox site is due primarily to the release of tectonic shear-stress. This observation agrees with our source (i.e., focal mechanism) studies of the PVSN data discussed in the next section.

**6.6 Focal Mechanism.** The waveforms of the 2001 data are consistent with previous years', indicating that the focal mechanics of the 2001 seismicity is most likely the same as previous years. Hence we did not feel a need to calculate new fault plane solutions. For completeness we repeat our statements from last year's report.

P-wave first motion observations are used to construct focal mechanisms for evaluating potential fault planes and characteristics of the *in situ* tectonic stress field. Using earthquakes with strong first motions and occurring over a range of locations, we constructed 75 focal mechanisms. As with previous observations, the results are dominated by strike-slip faulting on west-northwest trending, steeply dipping fault planes. However, several events with oblique strike-slip-normal mechanisms were observed. **Figure 14** shows a Rose diagram of the fault plane angles of the 75 focal mechanisms. The Pressure (or P) axes and Tension (or T) axes for these events are shown in Rose diagram form in **Figure 15**. The T-axis direction is a consistent northeast direction and the P-axes are oriented northwest (~N 51$^{o}$W). No difference in spatial distribution of focal mechanism types is evident throughout PVSN's entire data set.

**6.7 Earthquake Mode.** The previous two sections present data supporting the conclusion that the source mechanics of the PVU earthquakes is shear slippage across existing faults and fractures. However, the injection at PVU must create volume for emplacing the injectate and therefore creates and opens tensile fractures (i.e., hydraulic fractures). 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 fracture opening or aperture is on the order of a few millimeters, at most, and therefore the (new) surface area of a fracture is on the order of 10's of square centimeters, or less. Fractures this size radiate minimal seismic energy. At the surface, this radiation is well below the detection level of any seismometers. In addition this radiation is in the frequency band of a few 100 Hz to a couple 1,000 Hz. Seismometers, as used at PVSN, are designed to operate at frequencies below a few 10's of Hz and lower. Hence, we can safely say that all the ground motion recorded by PVSN is due to seismic shear events, not tensile openings.

**6.8 Seismic Modeling.** To facilitate evaluation of the potential relationship of seismicity to reservoir and fluid transport characteristics, a significant effort was made to obtain the best earthquake locations possible. This effort consisted of two parts. The first was the development of a three-dimensional velocity model for the Paradox Valley area using a progressive, three-dimensional velocity-hypocenter inversion (Block, 1991). A data set consisting of 682 earthquakes with $\mathbf{M_D}$ greater than 0.7 and good signal-to-noise ratios was used in the inversion. The second step of the

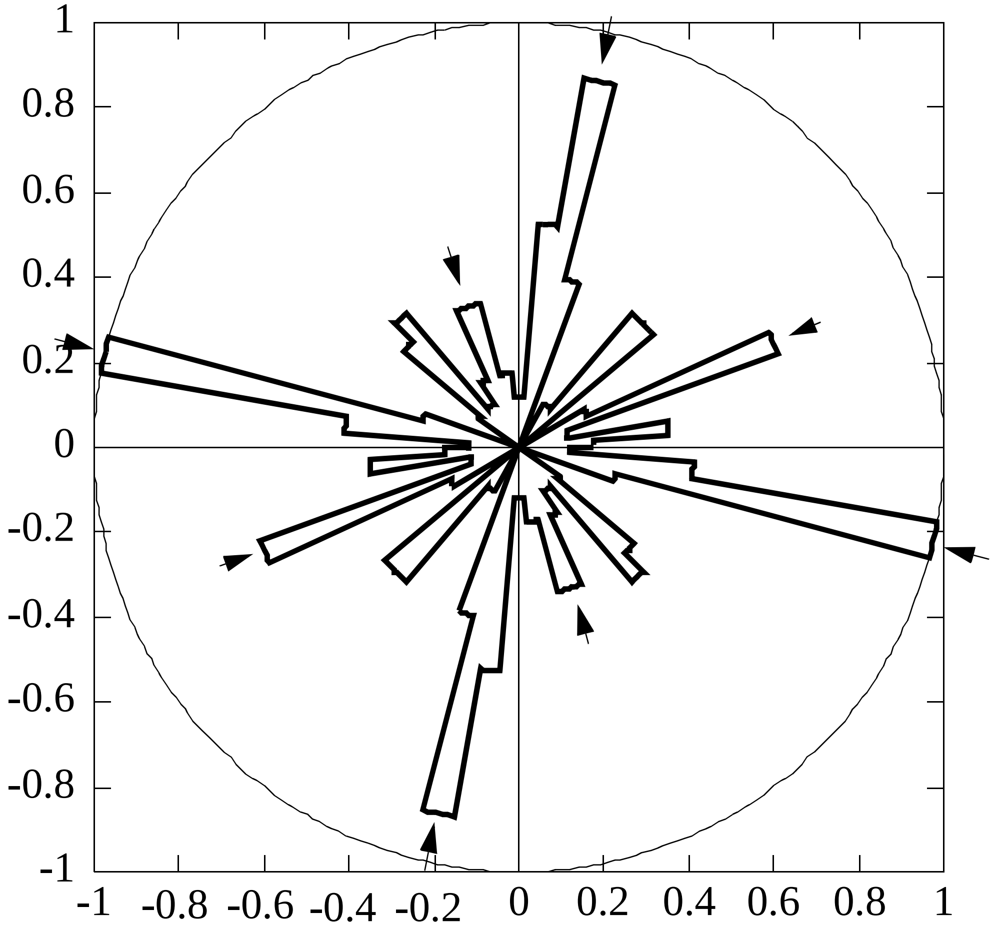


***Figure14. Rose diagram of fault plane directions from 75 focal mechanisms recorded in 2000. For comparison, paired arrows indicate directions from 1999 data analysis. The strike of the Paradox Valley is approximately N 55ºW.***

process was to perform a relative relocation of as many earthquakes as possible (i.e., clean wave-forms with strong signal-to-noise ratios) using the three-dimensional velocity model developed in the first step of the process. (Waldhauser and others, 1999). Approximately 95% of the events recorded between 1991 and 2001 had sufficient signal-to-noise ratios to be included in the relative relocation. Utilization of the three-dimensional velocity model resulted in an approximately 14% reduction in arrival-time root-mean-square (rms) residuals (observed minus theoretical travel times) relative to the one-dimensional model. The relative relocation procedure resulted in more than a 90% reduction in rms residual of arrival time differences relative to the three-dimensional results. The final earthquake epicenters for 1991 through 2001 are shown in **Figure 16**. The figure

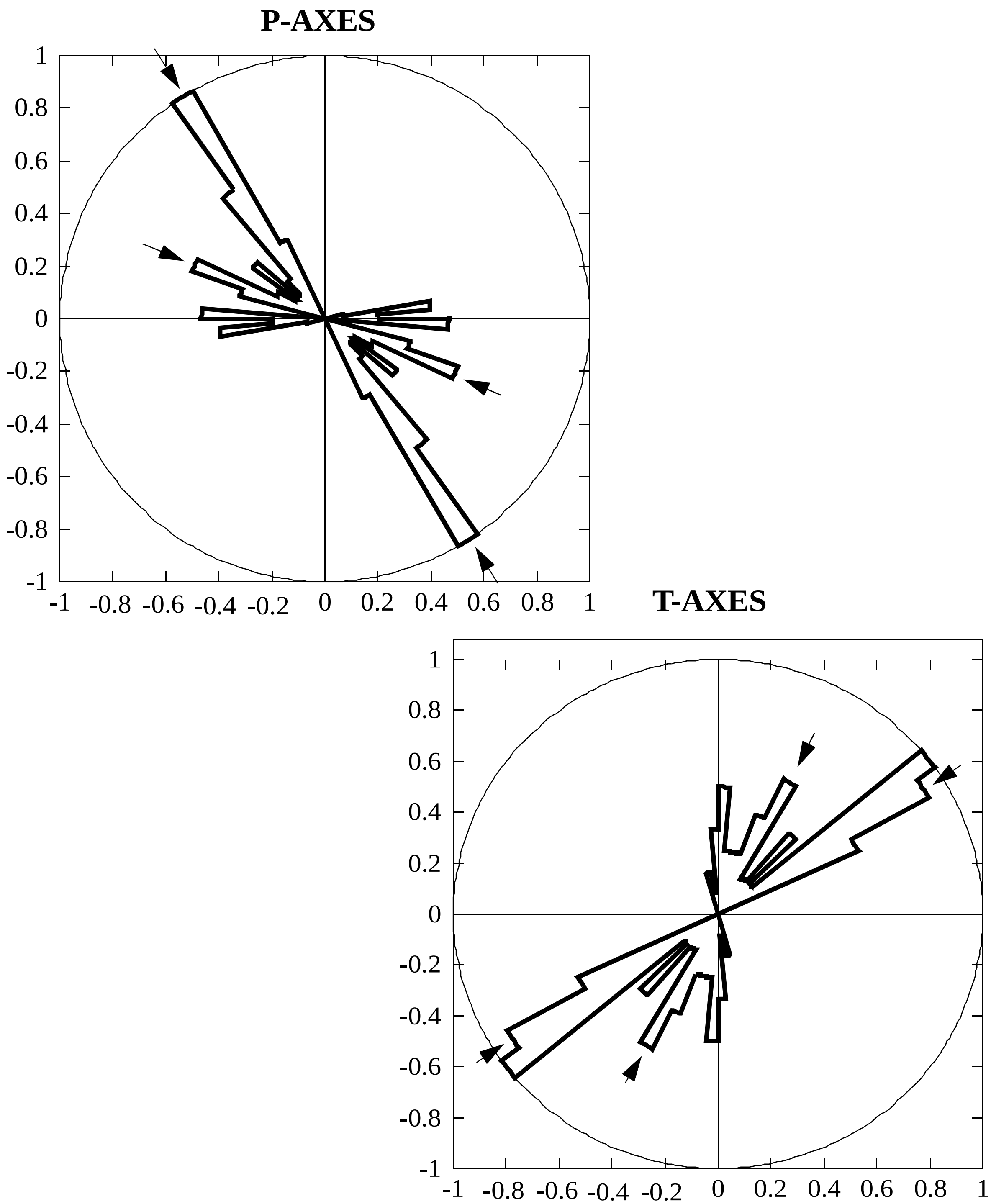


***Figure 15. Rose diagram of P-axis directions and T-axis directions from 75 focal mechanisms obtained during 2000 from the PVSN, southwestern Colorado. Paired arrows show directions from 1999 data analysis. The strike of the Paradox Valley is approximately N 55ºW.***

shows a pullout, close-up with the event location symbol size minimized to emphasize the linear features in these data (discussed below).

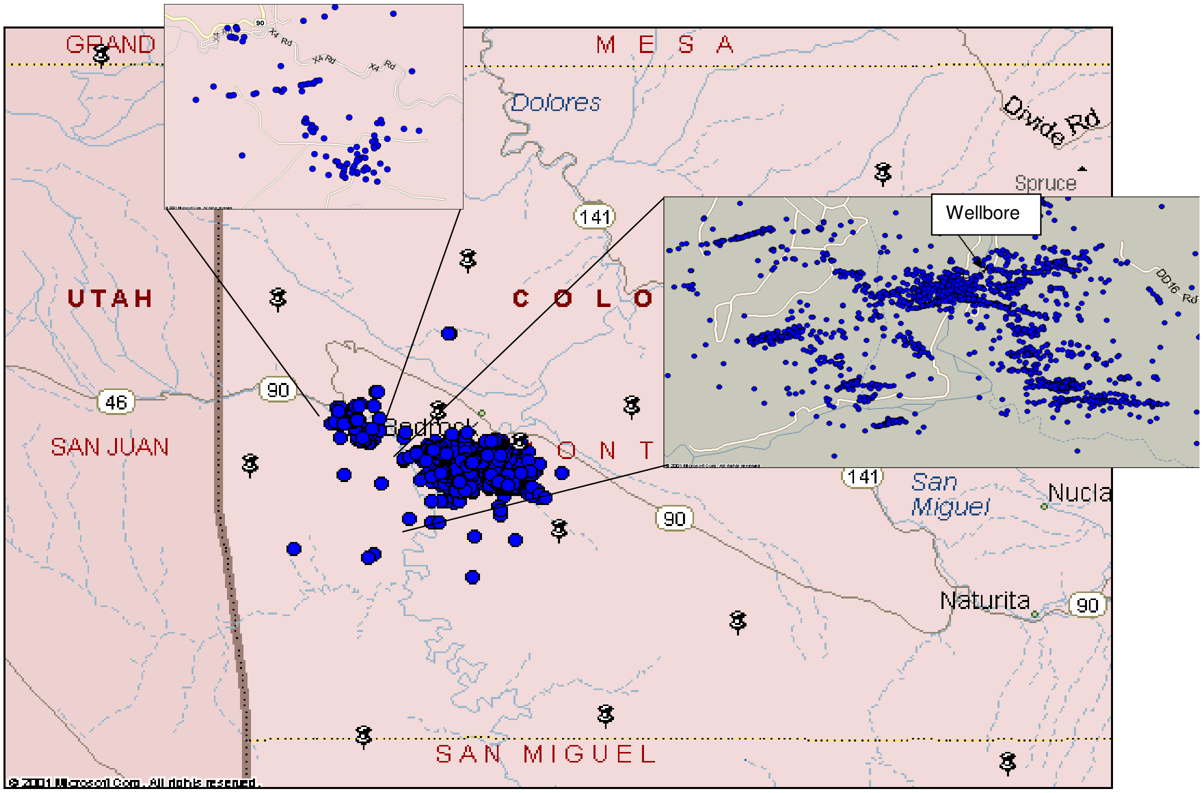


***Figure 16. Relocated seismic event locations from 1991 through 2001. Insert shows relative location of PVU injection well.***

As discussed in previous annual reports (e.g., Ake et al., 2000; Mahrer et al., 2001), the loci of relocated earthquakes are consistent with the interpretation that most of the tectonic stress release takes place along (existing) linear features with orientations consistent with either the two sets of focal mechanism results (set 1: N81W and N9E; set 2: N21W and N69E) or the two sets of fractures observed in the oriented core samples (primary: N69W and N74W; secondary: N38W and N42W; Ake and Mahrer, 1999). Very little seismicity appears to be occurring along the planes consistent with the Wray Mesa fault system as defined by Bremkamp and Harr (1988). The strike of the Wray Mesa fault system was estimated to be ~N55$^o$W by Bremkamp and Harr (1988). It is likely that these features are the most through going structures in the area. We believe this behavior suggests fluid is being preferentially carried along these steep planes with a northwest strike (elements of the Wray Mesa system). Opening of these planes will require the least energy as they are oriented normal to the least principal stress direction (as inferred from T-axes of the focal mechanisms, see **Figure 15**).

## 7.0 Modeling Rock Properties

As noted earlier, the 2001 seismicity overlays the extent or zone defined by previous years' seismicity. From this we can reasonably assume that the extent of the injectate envelope is expanding very slowly and much of the volume occupied by the 2001 inject may lie within this seismicity envelope. That is, rock fracturing caused by the inject (i.e., newly created and separated rock surfaces) is probably occurring within the well-centered zone defined by the seismic envelope of previous years. The persistent spatial distribution of events suggests that the occurrence of induced earthquakes at this site (and hence fluid migration) is controlled by physical attributes, like stress, preexisting faults, planes or zones of weakness, etc., and is not a random process.

Supporting this are the results from BORFRAC, a computer code used by Envirocorp (1995) to synthesize injection data and fit the synthetics to real injection data from the 1991-1995 injection test sequence. BORFRAC synthesizes the data by modeling the well and formation and their response to high-pressure injection. In the initial BORFRAC model, Envirocorp assumed traditional hydraulic fracturing: single vertical fracturing divided into two wings, each extending from opposite sides of the well at the depth of the casing perforations. This model assumes that the injectate follows the fracture wings and diffuses into the formation through the native permeability of the fracture walls. This type of model predicts seismic locations confined to a very narrow elliptical envelope centered on the well and whose semi-major axial plane overlays the wings of the fracture. From the seismic data which showed a diffused network of locations, they interpreted a network of injectate flow paths in the Leadville Formation. Envirocorp upgraded the BORFRAC model from a single fracture to a network of fractures. Using the network model BOR-

FRAC gave better agreement between the model data and wellbore injection data.

**7.1 Seismicity, Fault Properties, and Injectate Volume.** Since project inception in 1991, PVU has injected ~3.3 billion liters (~865 million gallons) or ~3.3 million cubic meters of injectate. In response to the greater than 11,000 psi pressure, at the injection depth the injectate is compressed to ~93% of its surface volume or about 3 million cubic meters. This volume of fluid must occupy existing space or create new space. It is very likely that at 4.8 km (16,000 ft) depth not very much open space exists. The question then is where *in situ* is injected fluid being stored, in existing space (e.g., faults, old fractures and joints, or existing pores), in new space (e.g., new fractures), or a combination of both? To evaluate the existing-space hypothesis, we considered existing faults and the possibility of opening these faults.

Consider **Figure 17**, a close-up of **Figure 16**. **Figure 17** shows linear groupings of seismic events. As an upper bound on available fracture and fault storage volume, we interpreted these groupings as corresponding to faults or fractures of the Wray Mesa system that have been reached (i.e., seismically activated) by injectate. Note the two major groupings, near the well and northwest of the well. Considering the northwest trend of the Wray Mesa fault system, it is likely that a northwestern fault runs from the well group to the northwestern group. Based on this map and implied local faults of Bremkamp and Harr (1988), we tallied approximately 30 km of fault length. We then assumed that the faults averaged about 0.5 km height, the height of the Leadville formation. To accommodate the full injectate volume would require opening these faults and fractures 193 mm (7.61 in). This opening is unrealistic in a rock mass at this depth with PVU's injectate and its pressures. Based on recovered cores from hydraulic fracture experiments in the oil and gas industry, we expect the fault openings to be a few millimeters.

If we assume that the 30 km of faults and fractures have openings between 1 and 5 millimeters, then, at any time, only a few percent of the injectate volume can be stored in these faults and fractures. This means that the injectate either has created new fractures or its has diffused into the pore spaces of the rock mass. Considering the new fracture scenario, we calculated the length of new fracture needed, assuming 0.5 km high fractures. The amount of new fracture is on the order of a few thousand kilometers. Clearly this is not possible. Hence the only logical scenario is that

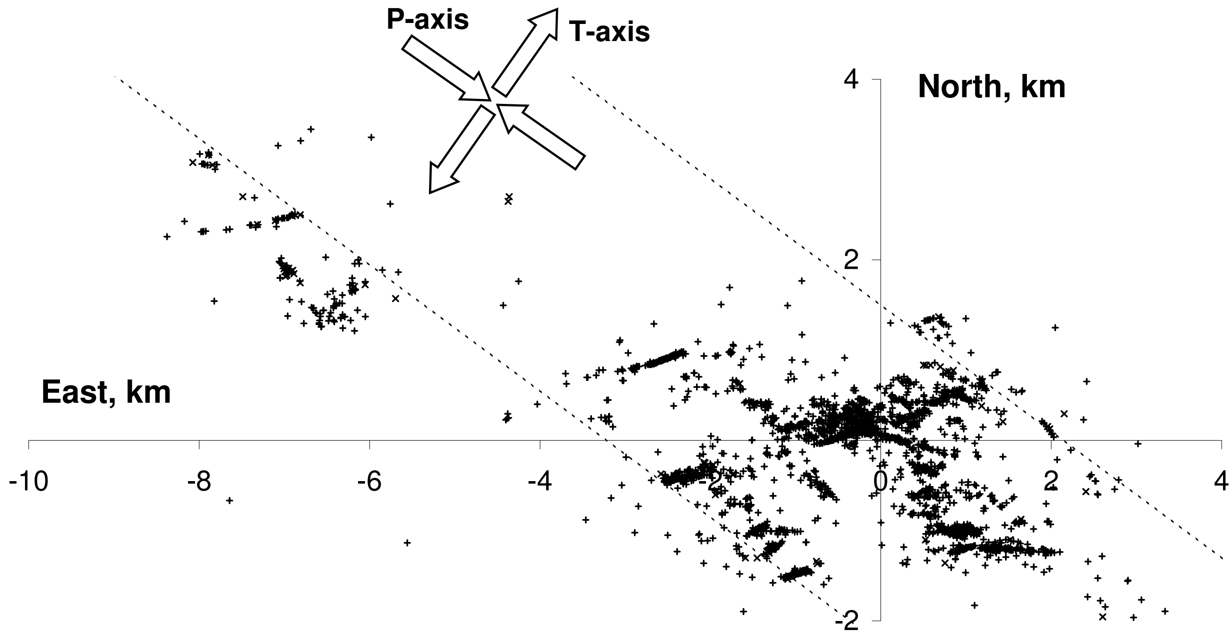


***Figure 17. Close up of relocated seismic epicenters. Axis is center on injection well. Dashed lines run N55$^o$W, the assumed strike of the Wray Mesa Fault system. Linear groupings of epicenters show (implied) seismically-activated faults and (pre-existing) fractures.***

more that 95% of the injectate has diffused into the rock mass.

**7.2 Seismicity and Effective Porosity**. It is mostly likely that the injectate migration is through diffusion into the rock mass. The seismicity has allowed us to study an aspect of diffusion, specifically the effective porosity of the rock mass.

As a first estimate for porosity we modeled the fluid volume as a vertical cylinder 2.0 km high and growing radially. We assumed 2.0 km height since that is the maximum vertical extent of most of the seismicity. **Figure 18** shows the results of this modeling. The figures shows a number of features. First, the scatter data are the horizontal distance of the seismicity from the wellbore as a function of time. This shows the growth of the two seismic zones: the one surrounding the well and the one ~8.5 km to the northwest. For the model diffusion model discussed below we only consider the zone surrounding the well. Next we've plotted the radius of the growing cylinder based on the injected volume, again, as a function of time. Here we modeled five porosities; in decreasing porosities these are 0.05%, 0.01%, 0.005%, 0.0025%, and 0.001%. From smallest to largest, these porosities span a factor of 50.

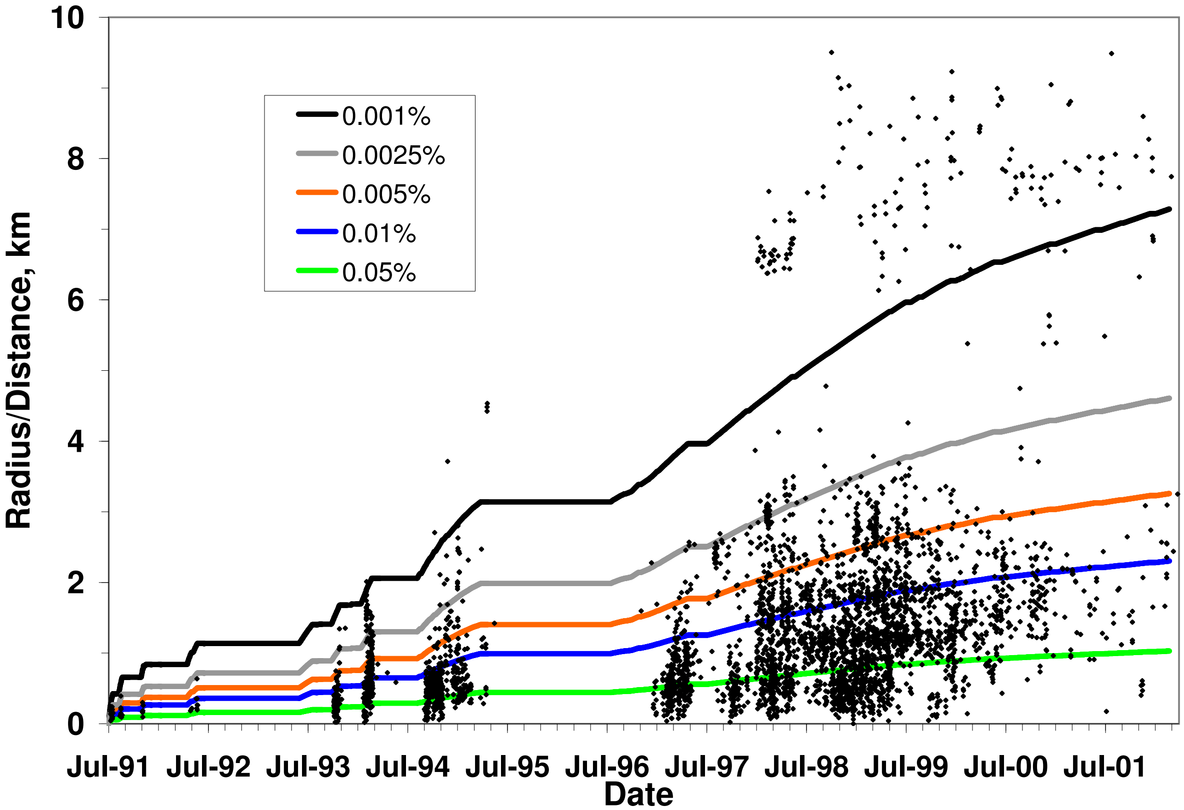


***Figure 18. Horizontal distance of seismic event from the injection well versus time event occurred and the (calculated) extent or radius of an expanding cylinder of injectate for 5 rock porosities versus time. Injectate radius model used injected volume and assumed a fixed 2 km height***

Based in the pre-2000 seismic expansion rate in **Figure 18**, the porosity models suggest a porosity between 0.005% and 0.0025%. In 2000 with the inception of more shut downs and the reduced injection rate in late June, the growth of seismic zone is greatly curtailed and the model no longer fits the seismic zone expansion. This may mean that with overall reduced injection, the injectate is not being forced to move as quickly, but instead diffuses into the existing region defined by the extent of the seismicity. Using this scenario, a fixed region defined by the extent of seismicity, we assumed a seismogenic volume of about 30 cubic km. With an injected volume of about 0.003 cubic km (i.e., 3 million cubic meters), this gives a porosity of 0.01%. This second value of porosity is not the same as our first, but, given the impreciseness of these models, they agree reasonably well. For comparison, when Envirocorp (1995) ran its BORFRAC reservoir model to simulate the performance of the injection well and the Leadville formation, it used 0.05% porosity.

## 8.0 Conclusions

The general objectives of recording, analyzing, and interpreting seismicity in the Paradox Valley region was successfully carried out during 2001. The seismic data showed that the adjustment to the PVU injection schedule in 2001 continued to reduce the level of seismicity. Relevant observations from this reporting period include:

(1) The ~80 microearthquakes of 2001 located in the two seismogenic zones defined by previous years' microearthquake locations;

(2) As in previous years, the frequency of occurrence of observed earthquakes reduced following periods of cessation of brine injection and following a long-term reduction in injection rate;

(3) Induced earthquakes continued to occur approximately 6-8 km northwest of the injection well with a gap between those events and the event cloud surrounding the injection well;

(4) The spatial patterns of observed seismicity seem to follow the Wray Mesa fault and fracture system and are consistent with relevant tectonic stress characteristics, as manifested by strike-slip faulting on northwest-southeast planes with northeast trending T-axes, relative to earlier observations;

(5) The seismic data from the 10 years of monitoring injection seem to indicate that a threshold for microseismic production occurs between the reduced 230 gpm injection and the previous 345 gpm injection. Staying below this threshold seems to mitigate the number of events produced per year and the annual likelihood of larger events. However, mitigation is not elimination. Although the annual probability of larger events seems to be reduced, larger events are still probable.

## 9.0 Accomplishments

In April 2001, we presented a professional poster (Block et al., 2001) describing the seismicity recorded by PVSN, its analysis and its interpretation at the 2001 Annual Spring Meeting of the Seismological Society of America. The presentation was very well received.

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