

**TECHNICAL SERVICE CENTER
Denver, Colorado**

Technical Memorandum No. D8330-2001-007

**2000 Status Report-Paradox Valley Seismic Network
Paradox Valley Project
Southwestern Colorado**

Prepared by

Ken Mahrer
Lisa Block
Jon Ake

U.S. Department of the Interior
Bureau of Reclamation



April 2001

RECLAMATION'S MISSION

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

DEPARTMENT OF THE INTERIOR'S MISSION

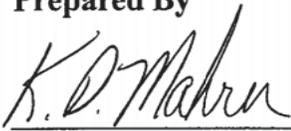
As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. Administration.

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

Technical Memorandum No. D8330-2001-007

**2000 Status Report-Paradox Valley Seismic Network
Paradox Valley Unit
Southwestern Colorado**

Prepared By

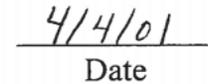


Ken Mahrer
Geophysicist


Date

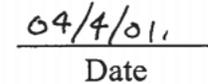


Lisa Block
Geophysicist


Date



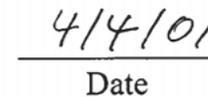
Jon Ake
Seismologist


Date

Peer Review



Ute Vetter
Geophysicist


Date

1.0 Introduction

This report provides a summary of the calendar year 2000 seismological observations from 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. The objective of the PVU is the removal and deep-injection well disposal of Paradox Valley brine prior to it entering the Dolores River. The objective of the seismic monitoring program is to (1) record, evaluate, and catalog waveforms from seismic events in and around Paradox Valley; (2) locate the sources of local seismic events; (3) determine source mechanics (e.g., focal mechanisms) of the events when feasible; and (4) identify and evaluate any relationships between seismicity, geology, tectonics, subsurface brine movement and location, and injection parameters. In order, the following sections discuss instrumentation, well operations, analysis, observations, and conclusions.

2.0 Instrumentation

PVSN provides seismograph coverage for roughly 5500 km² of the Colorado Plateau centered on the intersection of the Dolores River and Paradox Valley (**Figure 1**). PVSN was installed in late 1983 and has operated continuously since that time. The station designations used in **Figure 1**, station names, locations, elevations, and operational parameters are given in **Table 1**. During much of 2000 the network consisted of 14 stations (**Figure 1**) with station PV08 turned off. PV08 returned to service in October, giving the network 15 stations. Within the limits of terrain accessibility and radio telemetry linkage, the network is loosely arranged in two concentric rings of stations centered on the brine injection well. The outer ring has a diameter of 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 component seismometers. The Davis Mesa and Nyswonger Mesa stations (PV11 and PV16, respectively), operate three-component seismometers, recording vertical, east-west, and north-south motion. A third 3-component station is planned for 2001. The seismometers at all

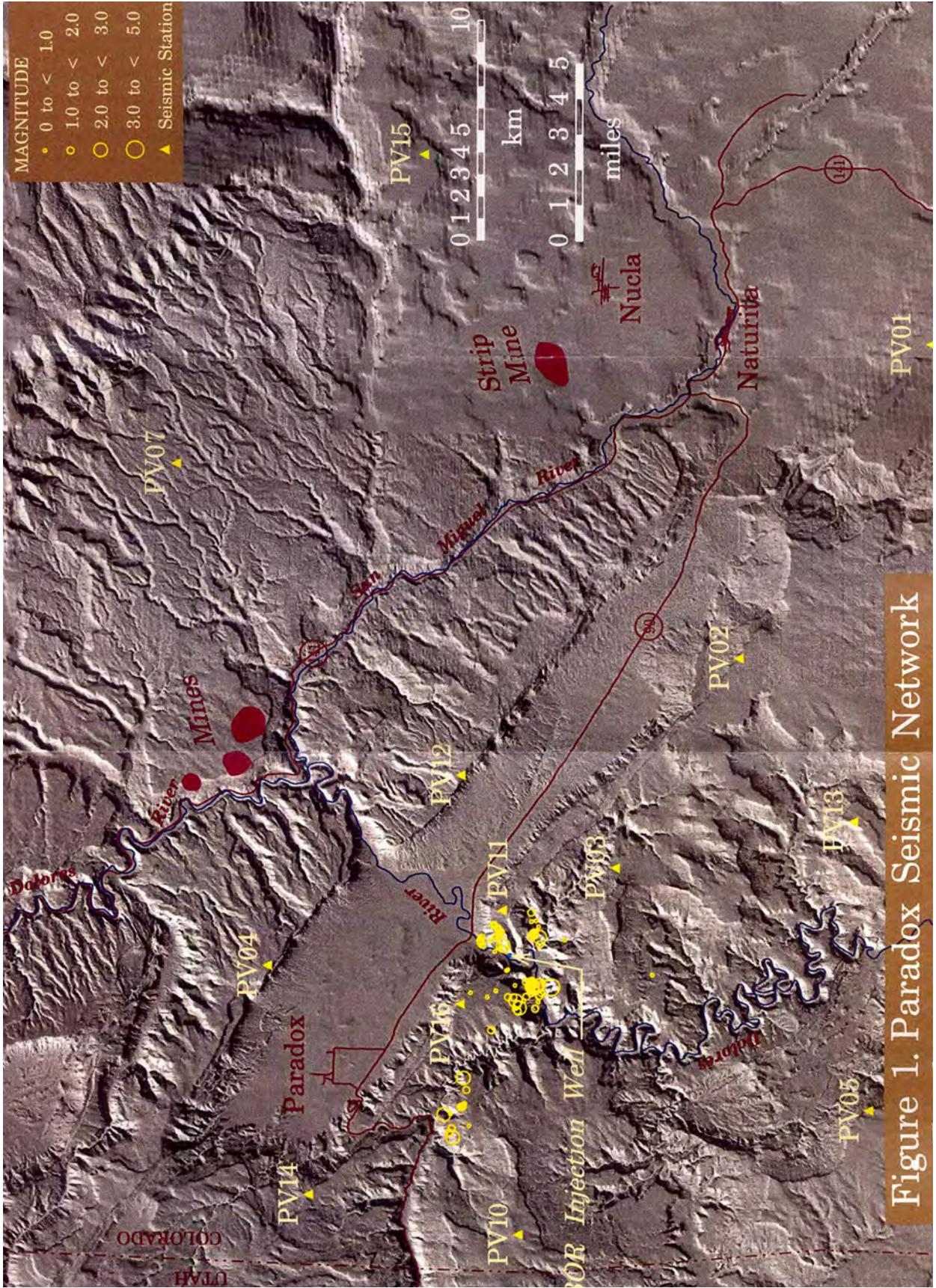


Figure 1. Paradox Seismic Network

sites are Teledyne Geotech Model S-13's, a high-quality, reliable, ground velocity measuring instrument with flat velocity 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 the field amplifiers is set to minimize long-period noise (see **Table 1**).

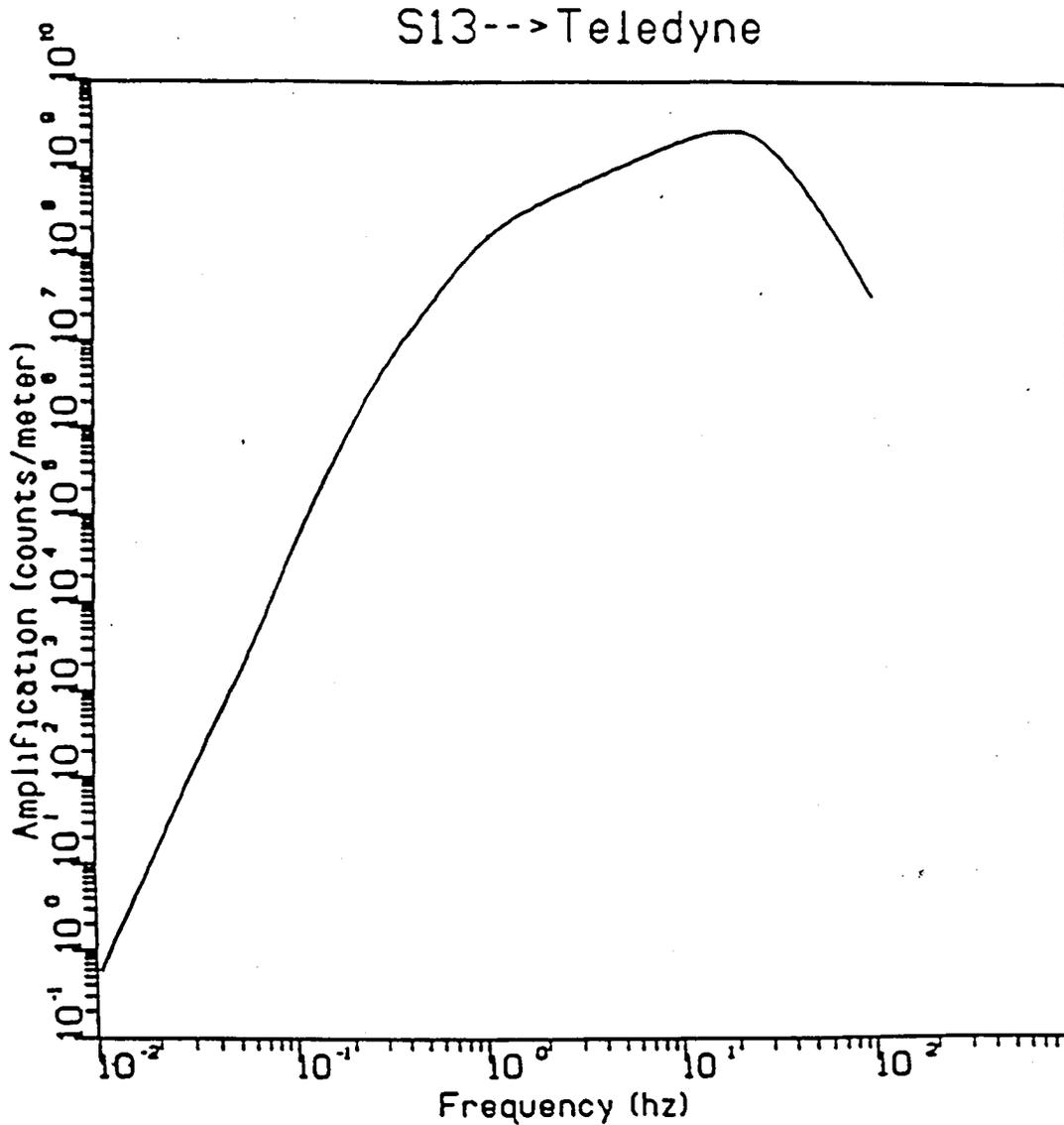


Figure 2. Typical response of a vertical-component Teledyne Geotech S13 seismometer associated electronics and digital recording used at PVSN sites. Nominal gain of 48 db for curve displayed, Teledyne Geotech model 42.5 amplifier/VCO and model 4612 discriminator. Damping is 0.71 of critical.

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	38.59	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 well is 1540 m above msl. Station PV08 is outside the boundaries of Figure 1.

2.1 Telemetry Upgrade: Analog to Digital. In October of 2000, Reclamation upgraded a portion of the data telemetry path from an analog to digital system. The analog system had experienced numerous problems most of which resulted in either lost data or seriously reduced signal-to-noise.

The digital system upgrade has solved most of these problems. In addition to changes in data transmission, the conversion included adapting and refining the Earthworm data acquisition, event detection and data archiving software system originally developed by the US Geological Survey and used in their seismic arrays.

Prior to October 2000 each seismometer site telemetered a continuous analog radio signal to Nucla, CO where these data were combined (i.e., multiplexed) and transmitted via a complex chain of telephone lines and microwave links through Colorado (i.e, through Grand Junction, Montrose, and Loveland) to Reclamation's seismic computing facility at the Denver Federal Center (DFC) in Lakewood, CO. At the DFC, a computer system demultiplexed, digitized, and processed the data through event detection software. When potential earthquake signals were detected, the software wrote a data file of the buffered data stream. The software also classified the event (e.g., local, regional, or teleseismic) and computed a preliminary event location (i.e., a hypocenter). Subsequently, a project seismologist reviewed all automated results and reevaluated all events near the Paradox injection well.

In contrast, the new system removes the complex analog link between Nucla and the DFC and replaces it with a single digital telephone link, analogous to an Internet link, directly from Nucla to the DFC. Continuous analog signals from each seismometer site are still received at Nucla. However, these signals are now digitized at the Nucla site and transmitted as digital data directly to the DFC. At DFC the data are event detected using Earthworm with the system classifying, locating, and archiving the detected events for subsequent reanalysis. Beside being much more reliable, the new digital link between Nucla and Lakewood has substantially reduced noise contamination in the data, improving event locations.

2.2 Performance. During 2000, the network and telemetry system, including both systems, operated at approximately 80% efficiency. Efficiency is the total number of operational data channel days divided by the total number of potential channel days (i.e., $6570 = 365 \text{ days} \times 18 \text{ data channels}$). This 2000 efficiency is slightly below previous years', which averaged approximately 90%. In addition to minor, but not unexpected data outages due to lightning strikes, weak batteries, etc., the system witnessed an unprecedented level of telephone line problems resulting in sporadic

down time for both individual stations and the full network. However, because of the robust nature of the network deployment, some or all of the network was online, detecting and locating earthquakes in the Paradox Valley during all but approximately 10 days of the year. With the new digital system, the telephone line linkage and microwave link problems have now been eliminated.

3.0 Well Operations

Figure 3 shows a plan view and a north-viewing cross-section depth profile of the PVU injection

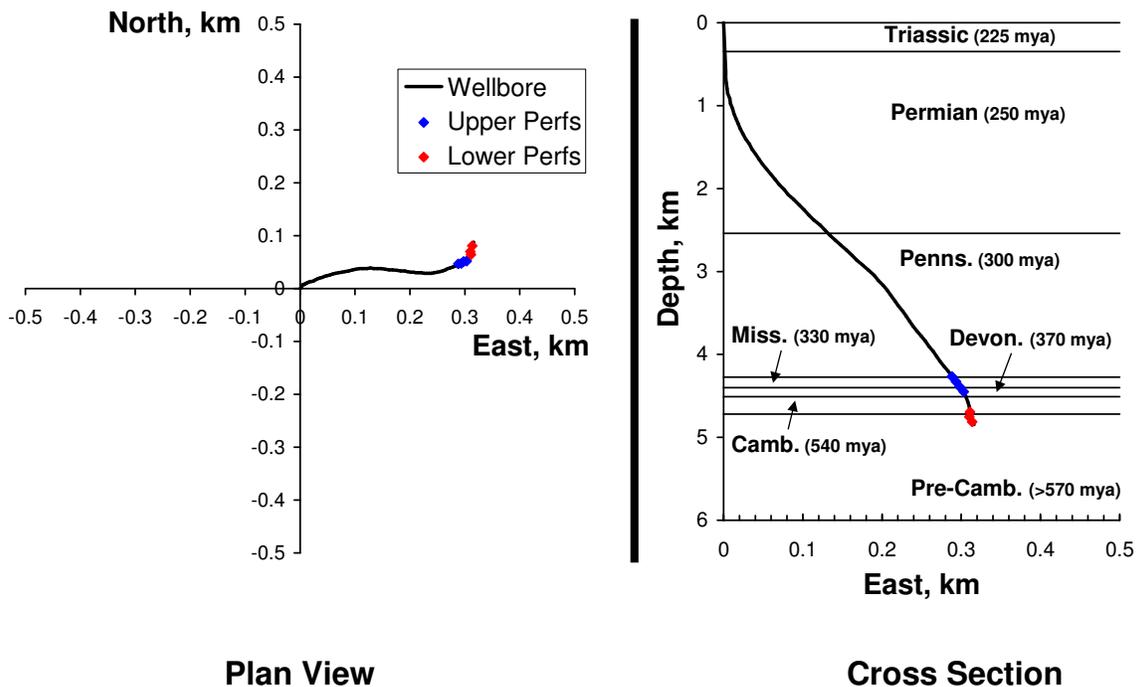


Figure 3. Wellbore Profile Showing Well-Log Determined Stratigraphic Units and Well Casing Perforation Intervals

well. The plan view, whose origin represents the wellhead, shows the well drifts approximately 0.3 km to the east and slightly to the north over its 4.8+ km depth. The cross section in **Figure 3** shows an exaggerated view of 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 interval is the Mississippian-aged limestone, the Leadville formation.

During 2000, PVU pumped approximately 112 million gallons of injectate (70% Paradox Valley Brine plus 30% Dolores River fresh water). This compares to 150 million gallons during 1999 and 167 million gallons during 1998. The reduced injectate volume was a result of operational modifications following the M 4.3 earthquake on May 27, 2000. (This earthquake is discussed later in this report.)

Prior to the May 27th event, the injectate was pumped at approximately 340 gal/min with a surface pressure of 4800+ psi. Immediately following the event, the well was shut in (i.e., pumping was terminated) for 28 days. During the shut-in period, the pumping strategy and its effect on seismicity were evaluated and a new strategy, expected to reduce the seismicity, was recommended. On June 23rd pumping resumed at a rate of approximately 220 gal/min. During the shut-in, the surface pressure dropped to approximately 1200 psi. With the resumed pumping, surface pressure climbed from approximately 1200 psi to 4300 psi (new normal operational value) over the next 3 weeks. Reducing the injection rate was an attempt to reduce the seismicity and mitigate the potential for large events. (The details leading to the change in pumping strategy are discussed below.) Based on the 6 months of seismicity following resumed injection, the new strategy seems to have reduced both the rate at which the seismic events are created and, hence, the inferred probability of creating larger or felt events.

During 2000, there were four shut-in periods in addition to the May 28th shut-in: 12/21/99 to 1/7/00, 1/16/00 to 1/17/00, 1/29/00 to 2/01/00, and 12/19/00 to 1/07/01. These periods are important beyond operational maintenance. The seismic data show that following a shut-in, the rate of seismicity in the near-wellbore region (i.e., about 2 km from the wellbore) is greatly reduced.

4.0 Analysis

4.1 Magnitude Calculation. In general, the size of an earthquake can be calculated using a variety of methods. In most cases calculating magnitude for local seismic events follow a procedure

calibrated for local conditions. For PVSN, the magnitudes are computed from the duration of the recorded signal. This scale is called the duration or coda magnitude and is denoted M_D .

As noted above the first stations at PVSN were installed in 1983. Prior to 1983, local events could only be recorded by large-scale, remote seismic arrays run by the US Geological Survey or the University of Utah. Very few local events were recorded prior to 1983, thus, a new signal duration-magnitude relation for PVSN had to be developed. Because of the paucity of events, the new relation was developed and calibrated using events from a region of western Colorado broader than Paradox Valley and the injection well vicinity. The relationship yields reasonable results for events with local magnitudes between 1.0 and ~ 2.3 , when compared to local magnitudes computed by the US Geological Survey National Earthquake Information Center and the University of Utah's. Uncertainty in magnitudes for local events is assumed to be approximately ± 0.5 magnitude units. For events larger than moment magnitude ~ 2.3 (a magnitude scale denoted by M and assumed equivalent to local magnitude in this range), the PVSN coda magnitudes have not been tested to assure accuracy. Additional magnitude determination studies will be pursued as the project proceeds.

4.2 Preliminary Event Location Method. Accurately locating earthquakes requires (1) carefully 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 described above, experienced seismologists manually pick the phase arrival times in all local earthquakes. 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, primary or P-wave arrival time picks are obtained from all stations with acceptable signal-to-noise ratios. However, secondary or S-wave arrival times are picked only from the three-component stations PV11 at Davis Mesa and PV16 at Nyswonger Mesa and from the closest single-component station to the injection well, PV03 at Wild Steer (see **Figure 1**). Although S-wave arrival times are very important to the analysis, only 3 stations are used because the close proximity of the sources and stations and the complexity of local geology facilitate easily mispicking S-wave phases and mis-locating the events. This is especially true when trying to pick S-wave arrivals from stations with only verti-

cal-component instrumentation.

Preliminary determination of earthquake locations uses a flat, one-dimensional, layered earth velocity model and the computer program SPONG (Malone and Weaver, 1986). The velocity profile of the one-dimensional crustal model is summarized in **Table 2**. The P-wave velocities were developed using Wong and Simon's (1981) results as an initial model, to which refraction survey results and sonic logs were added. The refraction interpretation used local mining explosions and sonic velocity logs obtained during injection well drilling. The S-wave velocities in this model were computed from the P-wave velocities assuming a Poisson's ratio = 0.25 or, equivalently, $V_p/V_s = 1.732$. Additional studies to upgrade the velocity model and increase event location accuracy using seismic tomography have been conducted and are briefly summarized below.

In addition to the earthquake signals, seismic networks also record non-seismic events. These include thunder, lightning strikes, landslides, low-flying aircraft, seismic (e.g., oil) exploration surveys, and other cultural noise, especially mine blasts. The discrimination of earthquake signals from these noise sources requires experience and consistency in processing. Ten years of examining waveform data from PVSN plus knowing the locations of established mining operations facilitates differentiating local earthquakes from mining explosions. Blasts are routinely monitored from a distributed area around Uravan, as far away as Paonia and Rifle, and from a strip mine west of Nucla (see **Figure 1**). The local explosion sources have distinct waveform characteristics (e.g., impulsive or very abrupt P-wave arrivals, unusually weak S-phase arrivals, and enhanced surface wave arrivals for small magnitude events) that are easily identified by experienced observers. There are no known explosion sources in the vicinity of the injection well that could produce blasts that could be misidentified as earthquakes.

5.0 Observations

Prior to injection at PVU, the Paradox Valley region witnessed on average one or two recordable events per year (EnviroCorp, 1995; Ake and others, 1996). From the injection tests in 1991 through 1999, the region has witnessed more than 3400 events. Hence, we can safely infer that virtually all the year 2000 events discussed below were induced by the PVU injection.

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

5.1 Event Production Rates. During 2000, 306 earthquakes were located within 8 km of the Paradox Valley brine injection well. This is a substantial reduction in induced events compared to the 1142 in 1999 and 1165 in 1998. **Figure 4** compares the cumulative annual event production for 1998, 1999, and 2000. **Figure 5** shows a histogram comparing the 1998, 1999, and 2000 monthly event production rates. **Figures 4 and 5** emphasize how dramatically event production was reduced during 2000.

For 1998, 1999, and 2000, the average daily event production rates were 3.15, 3.14, and 0.85 events per day, respectively. **Figures 6 and 7** look more closely at the 2000 data and show the daily seismic event production rates for 2000 plotted with average daily injection rate and average daily wellhead pressure, respectively. The 2000 data show 130 events occurred on or before the

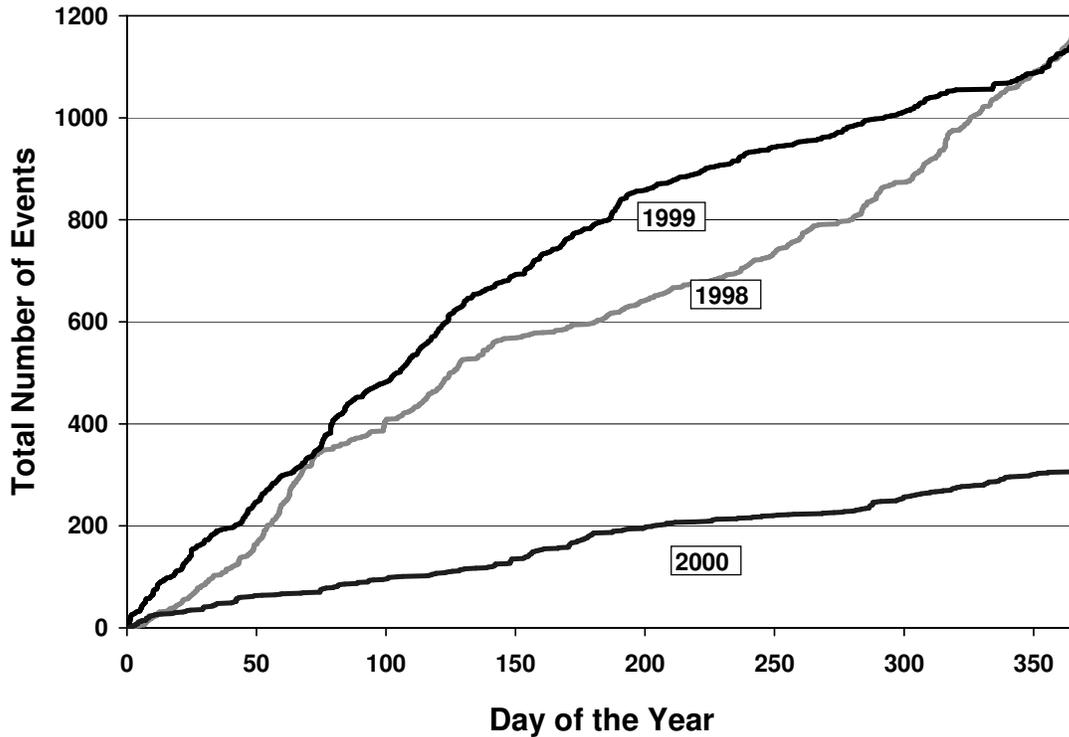


Figure 4. Total Number of Seismic Events by Year.

May 27 event, 37 occurred during the shut-in from May 28 through June 22, and 139 occurred from June 23 through the end of the year. This breaks down to 0.9 events per day prior to the May 27 event, and 0.72 after the event. After pumping was resumed at the reduced rate, seismic event production reduced 20%.

5.2 Event Magnitudes. As noted above, the seismic event production in 2000 was substantially less than earlier years. This results from both the 5 shut-in periods and the reduced pumping rates following the May 27th event. Similarly, in 2000, fewer larger magnitude events were observed. **Figure 8** shows the event magnitude distribution for 1998, 1999, and 2000. Because it is hard to see the distribution for events M_D 2.0 and larger, we've add an insert to the figure. Examining these data more closely shows that during 1998 8.0% of the events were larger than M_D 1.5. During 1999, 8.7% were larger than M_D 1.5. During 2000, prior to and including the May 27th event, 8.5% were larger than M_D 1.5. Note that despite the reduced rate of event production in 2000, the pre-May 27 proclivity to produce larger events is relatively the same as 1998 and 1999. However,

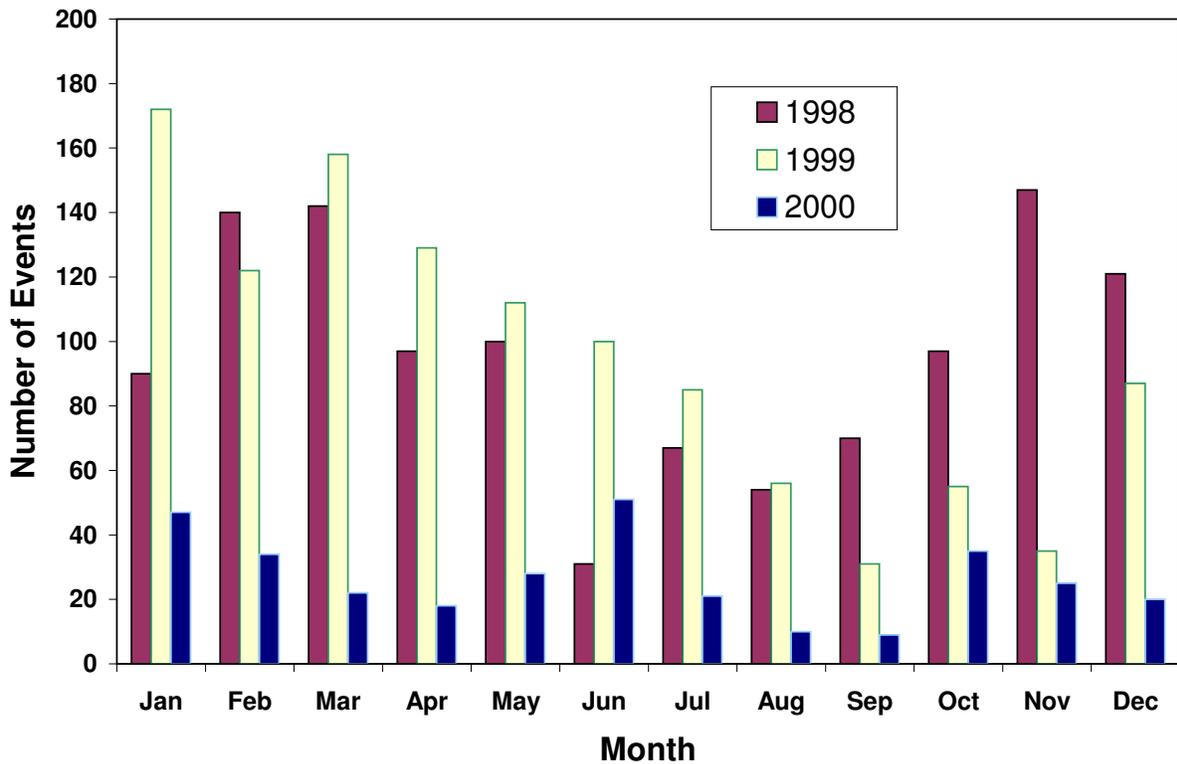


Figure 5. Annual Seismic Event Production by Month

after pumping was resumed at a reduced rate, following the May 27th event, only 5.5% were larger than M_D 1.5. This 6 month period shows a 30% reduction compared to the 1998, 1999, and pre-May 27 data. These data show that pumping at a lower rate reduced the proclivity for both producing events and producing larger events.

5.3 Felt Events. Between 1991 and the end of 2000 more than 3,700 events have been attributed to project operations. Of these, more than 99% are imperceptible (i.e., $< M_D$ 2.6) to people at the surface and can only be detected by the local seismic network. From 1991 to 1996 no events were reported felt at the surface. Between 1996 and the end of 2000 12 events were reported felt; during that same period, 17 events M_D 2.5 or greater were recorded. Of these recorded events, 3 occurred in 1998, 7 in 1999 and 4 in 2000. Of the 2000 events only 1 occurred after May 27.

5.4 May 27 Event. To date the largest event induced by injection at PVU was M 4.3 on May 27, 2000 at approximately 4 PM local time. This event was felt by nearby residents of the Paradox

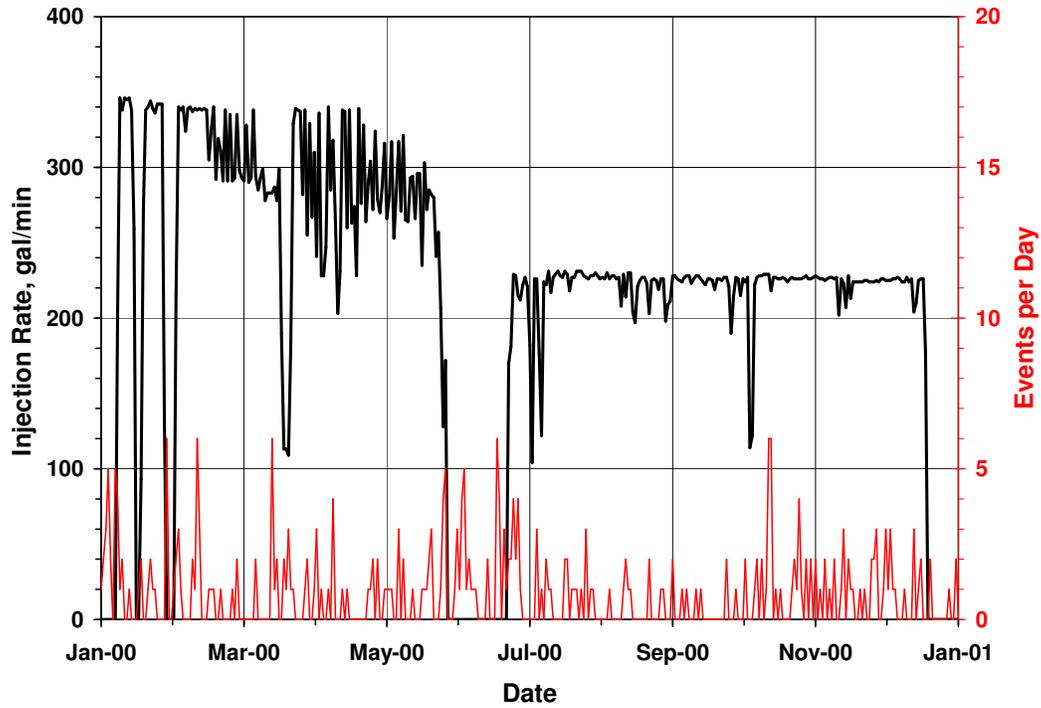


Figure 6. Average Daily Injection Rate (black) and Seismic Events per Day (red) for Year 2000

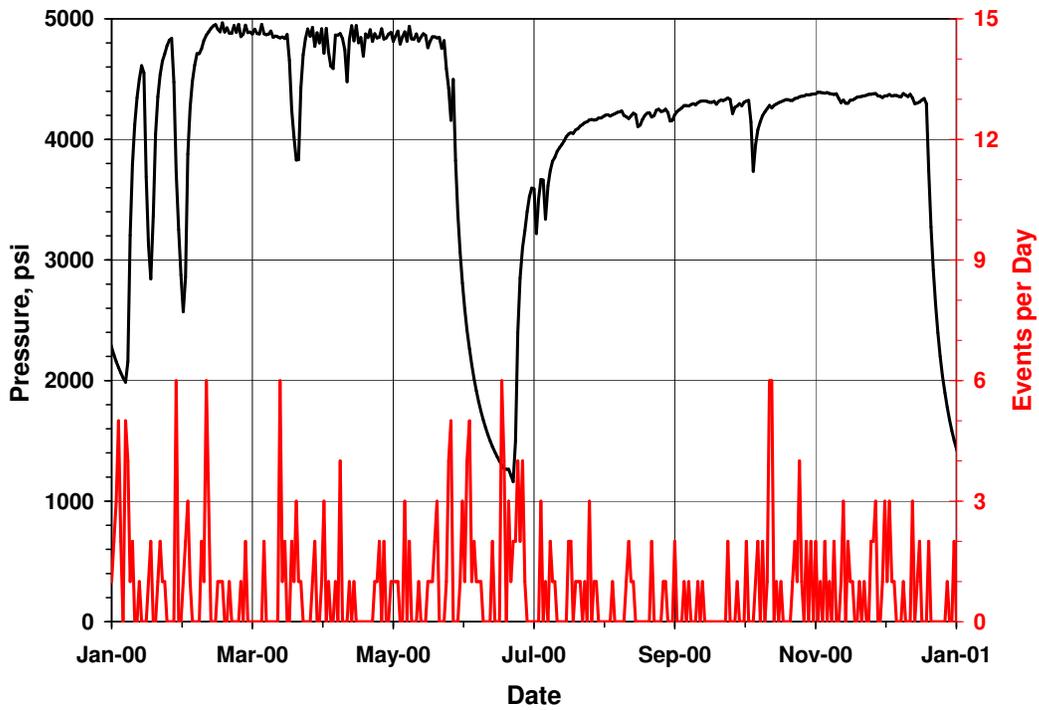


Figure 7. Wellhead Pressure (black) and Seismic Events Per Day (red) for Year 2000

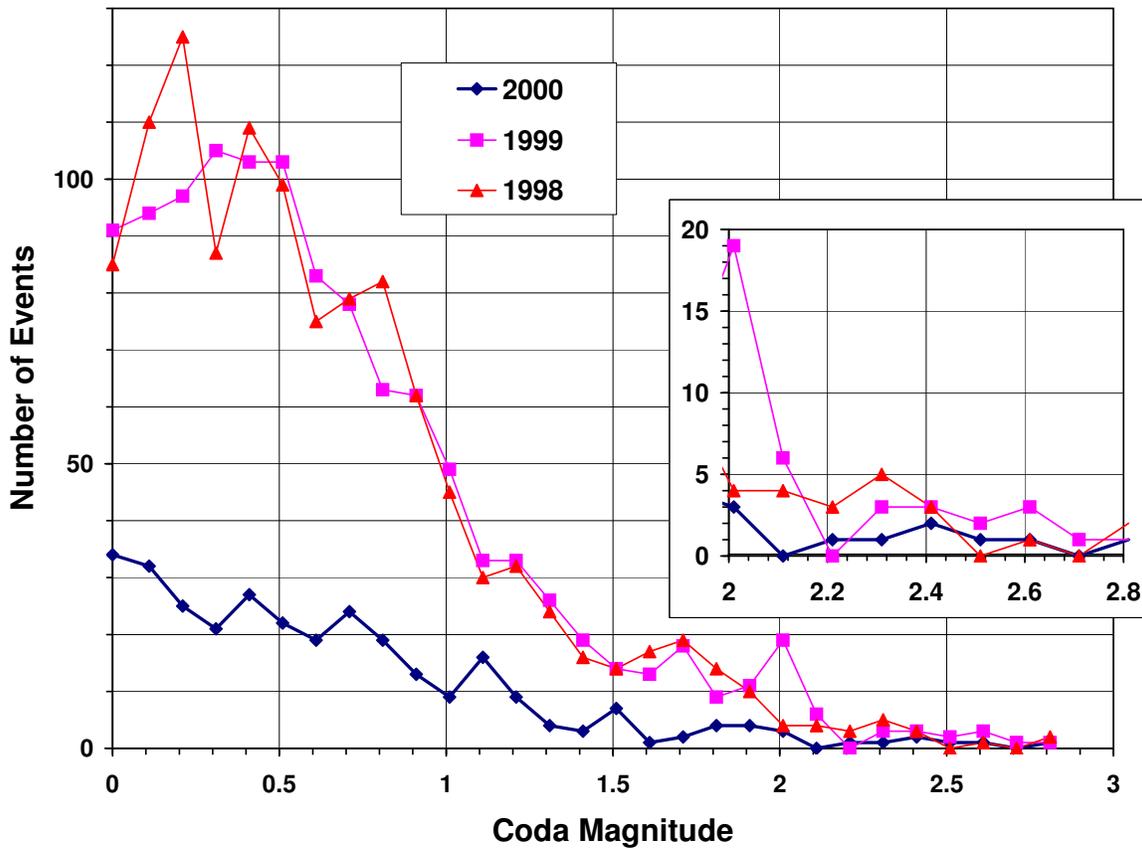


Figure 8. Population Distribution of Seismic Event Magnitudes by Year. Insert shows blowup of larger magnitudes.

Valley. Due to telephone data circuit problems, many of the stations of PVSN were not available at the time of this event. However enough information was salvaged to locate the event about 2 km west and 2.6 km south of the wellbore at a depth of approximately 4.1 km below the surface. Immediately following the event, injection was terminated and the wellhead was shut-in. The well was shut down for 26 days with pumping resuming on June 23. During the shut-in period alternative operational schemes were discussed. As noted in this report, the new schedule reduced injection rate and, hence, wellhead pressure.

Figure 9 shows the distribution of number of days versus average daily injection rate. These data show two sharp peaks. The peak in the vicinity of 350 gal/min was the injection rate using 3 pumps and was the normal injection rate from 1996 until the May 27th event. The peak at approximately 230 gal/min is the injection rate with 2 pumps operating. This is the injection rate used

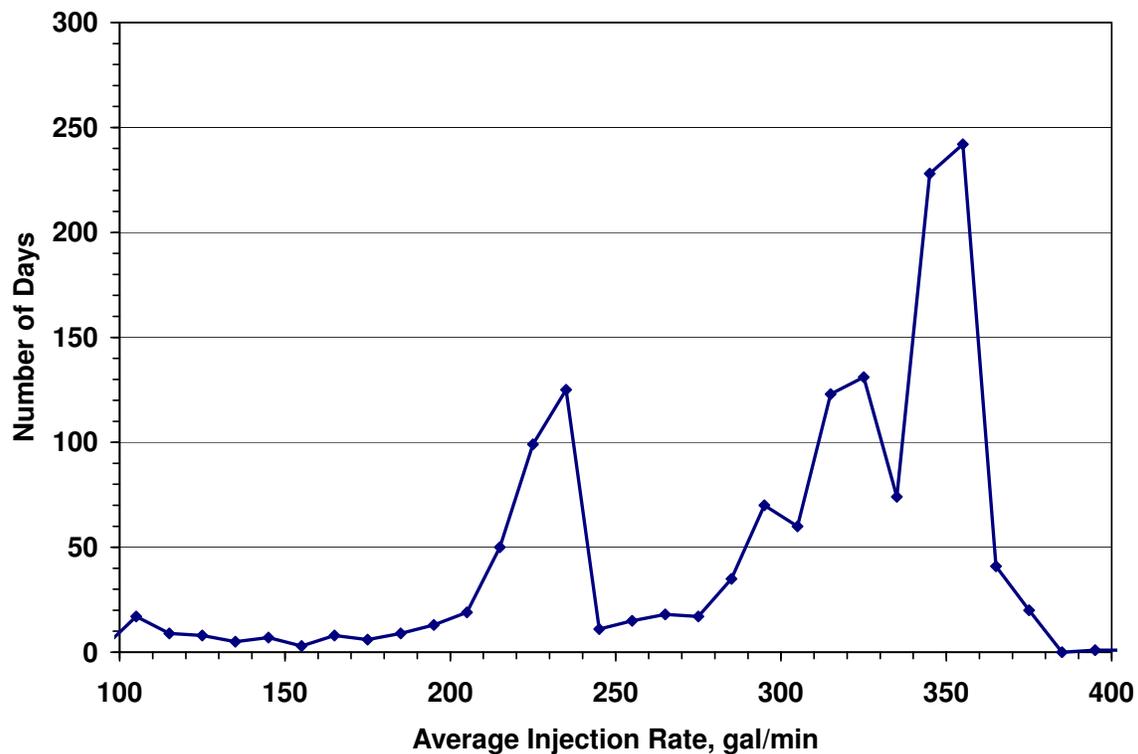


Figure 9. Daily Injection Rate Distribution for Years 1996-2000

after pumping resumed on June 23rd. With this rate change and **Figure 10**, the events per day as a function of average daily injection rate, we can predict that the rate of seismic event production should decrease 2 to 5-fold.

Similarly, consider **Figure 11**. Here event-wellbore horizontal distance versus time of occurrence and wellhead pressure versus time are plotted. These data show that following well shut-in (i.e., during resulting wellhead pressure drops), the number of events within a two kilometers radius (i.e., “the near wellbore”) drops off dramatically. However, **Figure 11** shows that when pumping resumes using 3 pumps, the near-wellbore quickly becomes seismically active. In contrast, when pumping resumes using 2 pumps, the near-wellbore region remains seismically quiet. The data in **Figures 9-11** show that from the end of June through the end of December the reduced pumping substantially reduced seismic production at PVU.

5. 5 Event Locations. **Figure 12** shows a plan view (i.e., epicenters) of the 306 earthquakes asso-

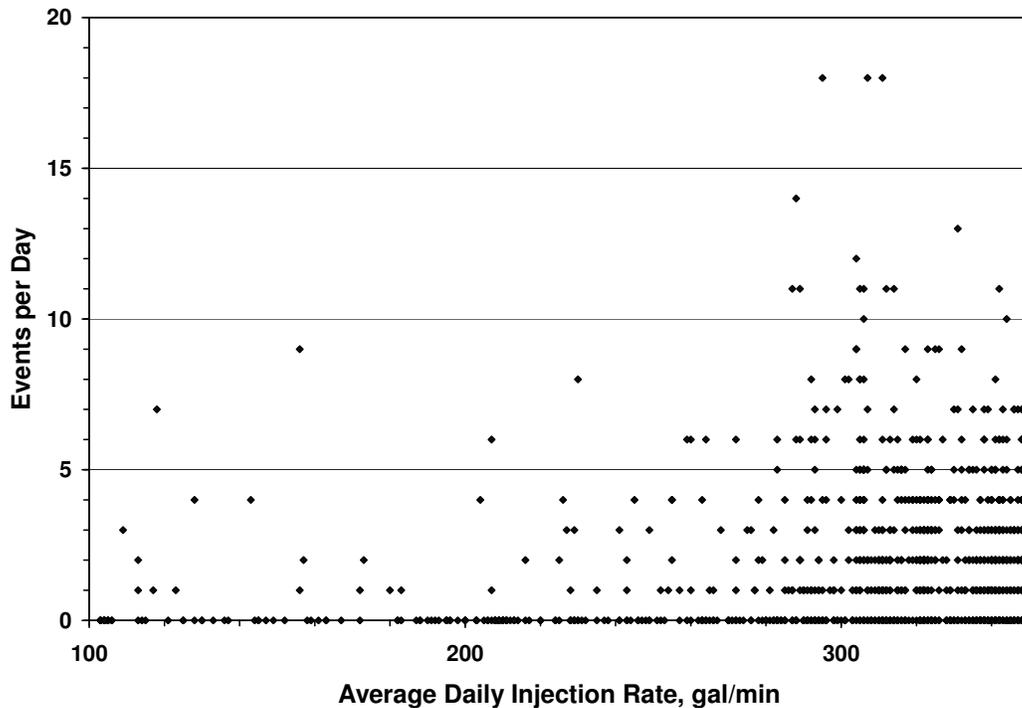


Figure 10. Events per Day versus Average Daily Injection Rate for 1996 through May 27, 2000

ciated with the injection during 2000. The magnitudes of these events range from M_D -0.5 to M_D 4.3. 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-phase arrivals. As a result, most of our conclusions for this data set are based on larger or events with $M_D > 0.8$.

Figure 12 shows that the spatial distribution of the seismicity recorded in 2000 is contained within two groups. The first and most populated grouping, surrounds the injection wellhead in an elongated envelope whose long axis runs approximately EW and extends about 4 km from the well. The second grouping, which is discussed below, is centered about 8 km to the northwest of the wellhead. **Figure 13**, a comparison of the epicenters for 1998, 1999, and 2000, shows that for 2000, both the I-modal grouping and the elongated shape of well-centered group are very similar to 1998's and 1999's (Ake and Mahrer, 1999; Ake et al., 2000).

Since the well-centered envelope of the 2000 seismicity overlays those of previous years, the

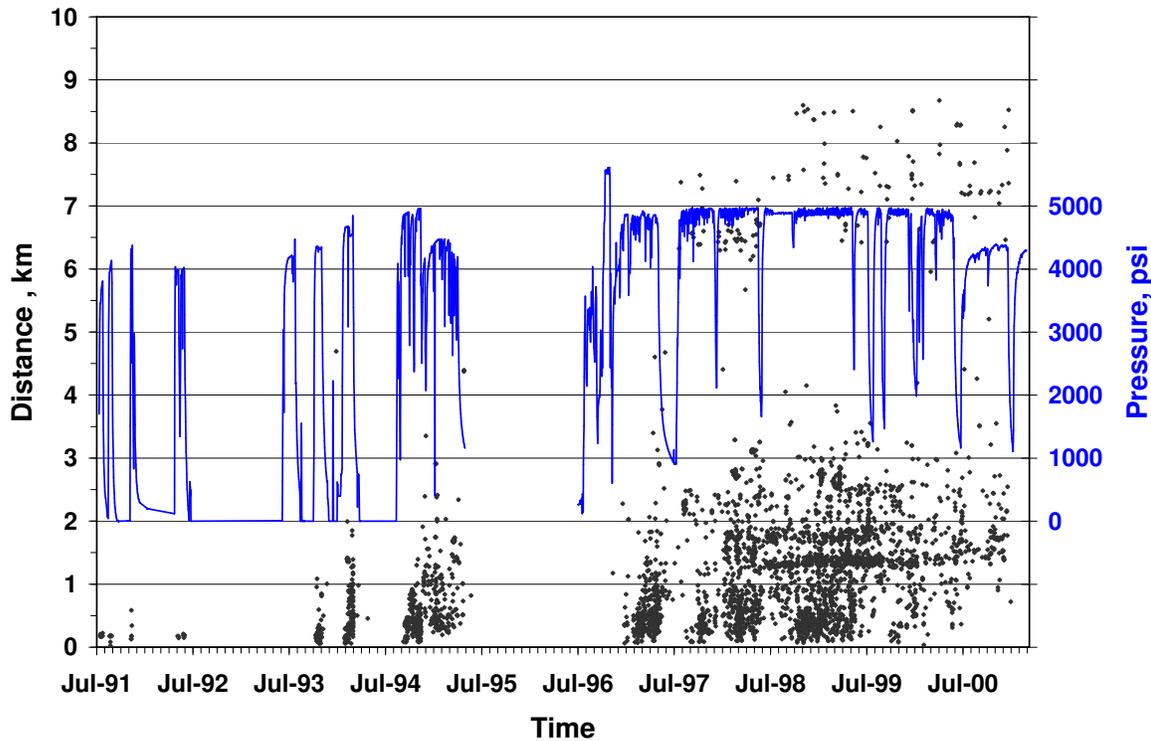


Figure 11. Event-Well (Horizontal) Distance and Wellhead Pressure versus Time for 1991-2000

extent of the injectate envelope may be expanding very slowly and much of the volume occupied by the 2000 injectate may lie within this seismicity envelope. That is, rock fracturing caused by the injectate (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 deterministic crustal attributes (e.g., stress, preexisting faults, planes or zones of weakness, etc.) and is not a random process.

During late 1997 a second group of events began approximately 8 km to the northwest of the well, outside the primary (i.e., well-centered) seismicity envelope. This group contains the furthest induced events from the well observed to date. During 2000, induced earthquakes continued in this region (see **Figures 12** and **13**).

Complementing **Figures 12** and **13**, **Figure 14** summarizes the depth distribution history of near

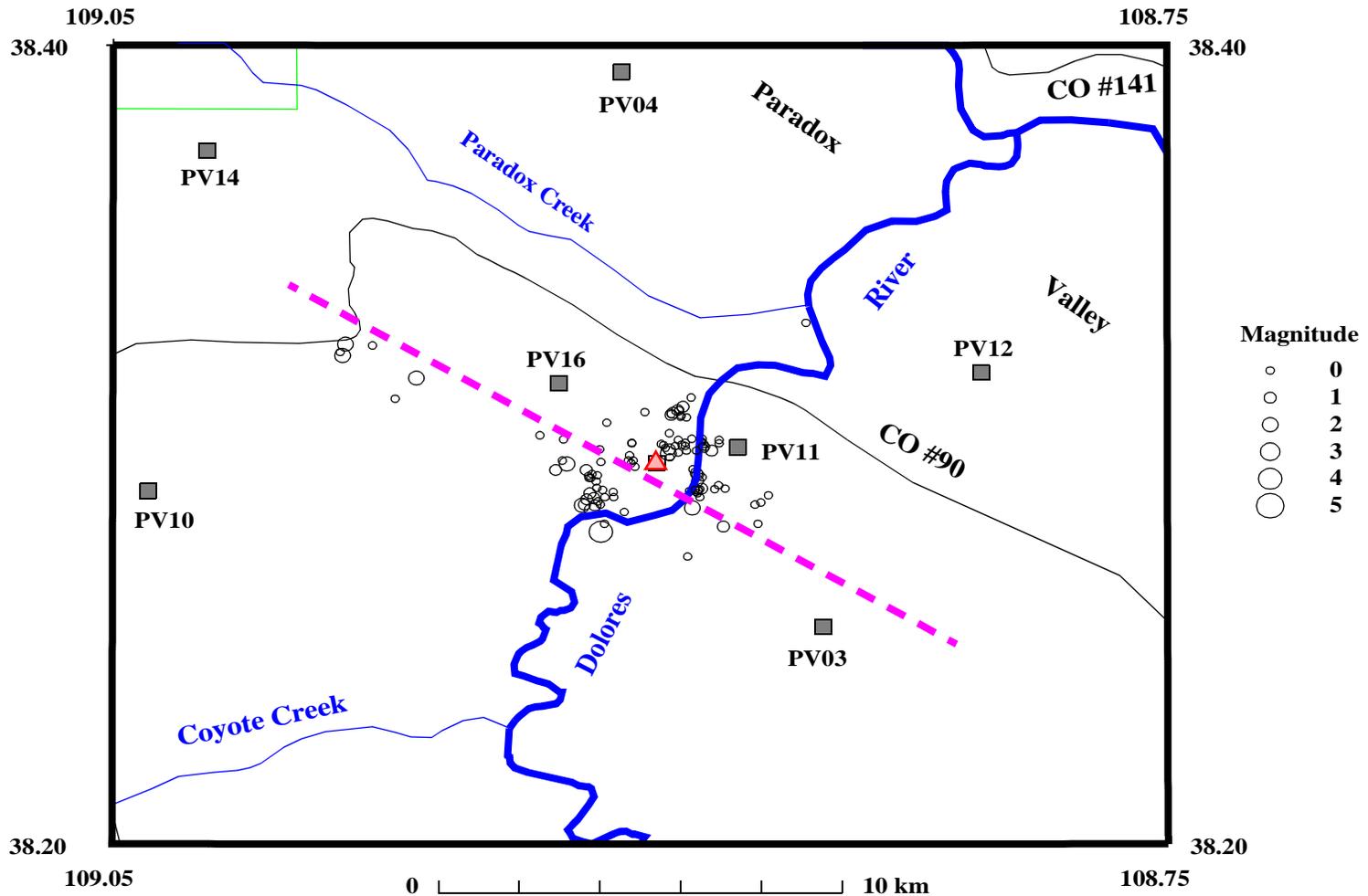


Figure 12. Seismicity located during 2000 by the PVSN using one-dimensional velocity model, 309 events plotted. Location of injection well shown by triangle. Approximate location and orientation of one element of the Wray Mesa fault system (from Bremkamp and Harr, 1988) shown in magenta. Location of seismograph stations indicated by filled squares.

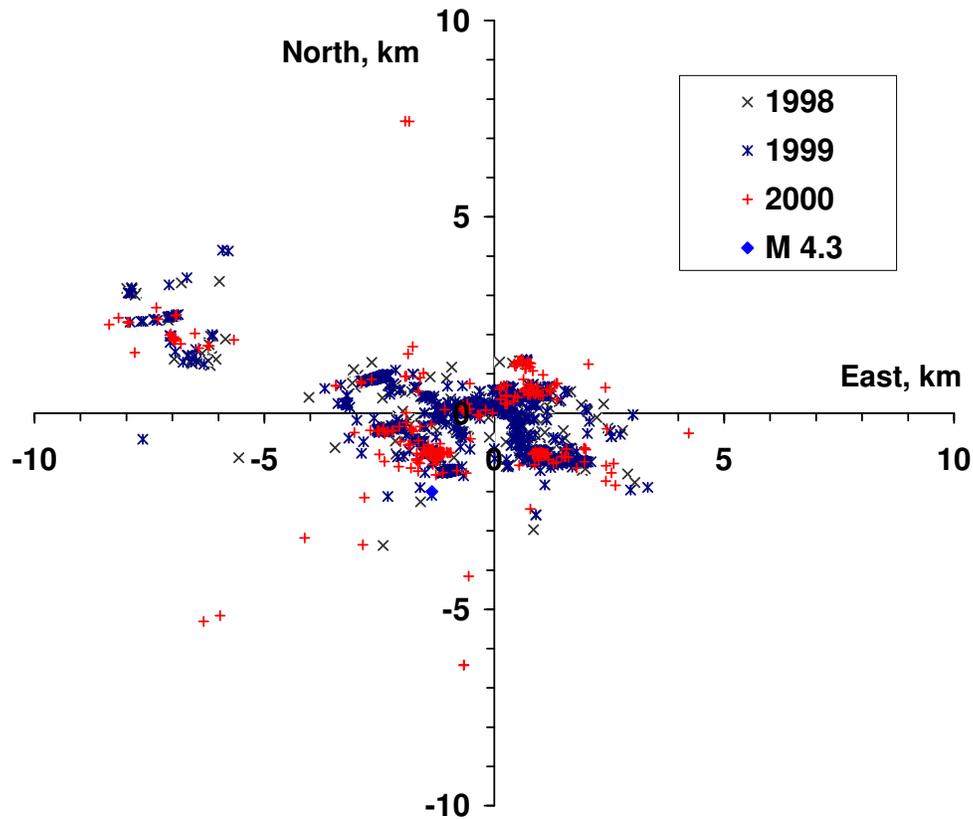


Figure 13. Epicenters by Year for 1998-2000 and Approximate Location of May 27, 2000, M 4.3 Event

wellbore events since continuous pumping began in 1996 and includes year 2000 earthquakes. The figure also shows the surface pressure history and a superimposed geologic (stratigraphic) column at the wellbore. In this figure, the “near-wellbore” region is defined as the region bounded by a cylinder whose axis is the wellbore and whose radius is 2 km. Note that the range of depths observed in 2000 is generally similar to previous years: between 3.5 and 5.5 km.

Figure 14 shows a substantial number of events within the Precambrian basement rocks (i.e. below 4.8 km). In these data, approximately 18% of the 1998 events were in the Precambrian. During 1999, 24% were in the Precambrian. In 2000, before the May 27th M 4.3 event, 30% of the events were in the Precambrian. This seems to indicate an increasing proclivity for deeper events. However, after the resumption of pumping in late June, only 16% percent of the events were in the Precambrian. The reduced pumping strategy in late June was invoked, in part, to

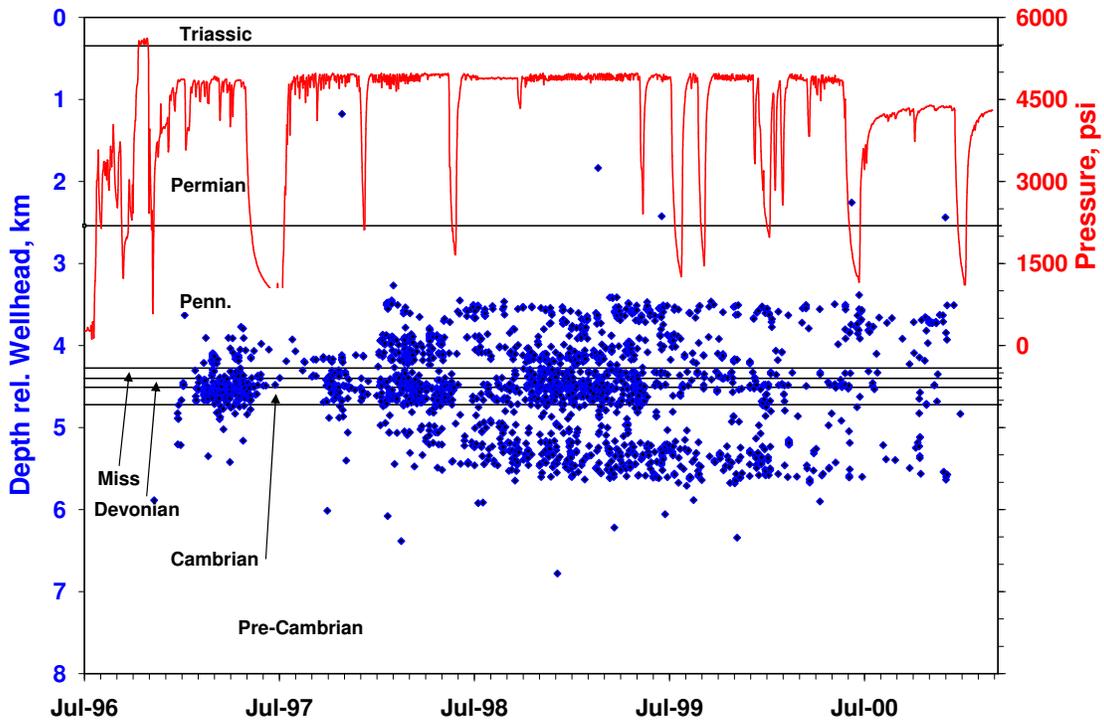


Figure 14. Depth of Near Wellbore Events (distance < 2 km) and Wellhead Pressure-Time History for Continuous Pumping, 1996-2000

reduce the probability of large events. As discussed below, the Precambrian is viewed as having the potential for the larger events. However, as can best be determined (see next paragraph), these data indicate that the reduced pumping strategy is reducing the probability of inducing events in the Precambrian.

The earthquake locations displayed in **Figures 12-14** suggest that seismic slip occurred primarily over a near-wellbore 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 perforates 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. This problem is presently being studied.

5.6 Earthquake Recurrence. **Figure 15** is a cumulative recurrence curve for earthquakes located during 2000. The figure begins at M_D 0.5 since previous results suggest that value is the lower

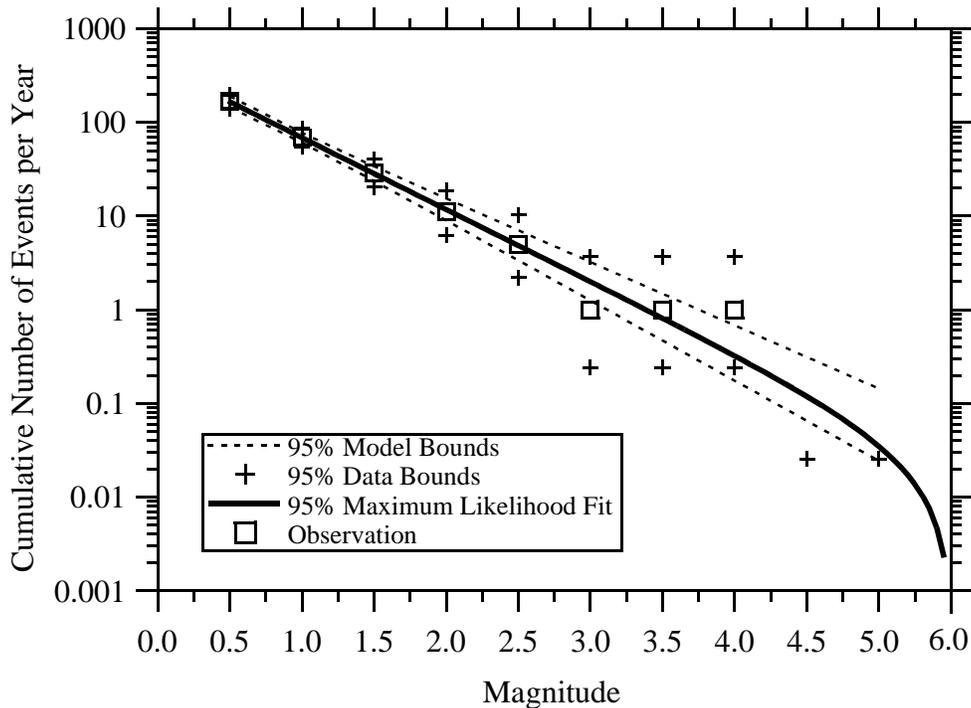


Figure 15. Cumulative recurrence curve for earthquakes located by the PVSN near the brine injection well during 2000. Maximum likelihood fit and 95% confidence bounds indicated. The computed “ b -value” for 2000 is 0.766. A maximum magnitude of 5.5 was assumed for the calculations.

detection/location threshold. Below this threshold magnitude, events are incompletely recorded by the network. The slope of the recurrence curve (the “ b -value”) is 0.766. This value is consistent with other observations of earthquake recurrence within the seismically inactive Colorado Plateau (Wong and others, 1996; LaForge, 1996) and with previous observation periods (cf., 0.87 in 1998 and 0.81 in 1999). This similarity in b -values to other studies in the Colorado Plateau suggests the occurrence of earthquakes at the Paradox site is due primarily to the release of existing tectonic shear-stress rather than from tensile fracturing associated with the brine injection process.

5.7 Focal Mechanism. The use of P-wave first motion observations to construct focal mechanisms is an established technique to evaluate potential fault planes and characteristics of the in situ tectonic stress field. Using a subset of year 2000 earthquakes with strong first motions and occurring over a range of locations, 75 focal mechanisms were constructed. 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. A Rose diagram of the fault plane angles of the 75 focal mechanisms developed using 2000 data is shown on **Figure 16**. The Pressure (or P) axes and Tension (or T) axes for these events are shown in Rose diagram form in **Figure 17**. The T-axis direction is a consistent north-east direction and the P-axes are oriented northwest ($\sim N 51^\circ W$). No difference in spatial distribution of focal mechanism types was evident within the 2000 data set. The results are very similar to the 1998 and 1999 observations.

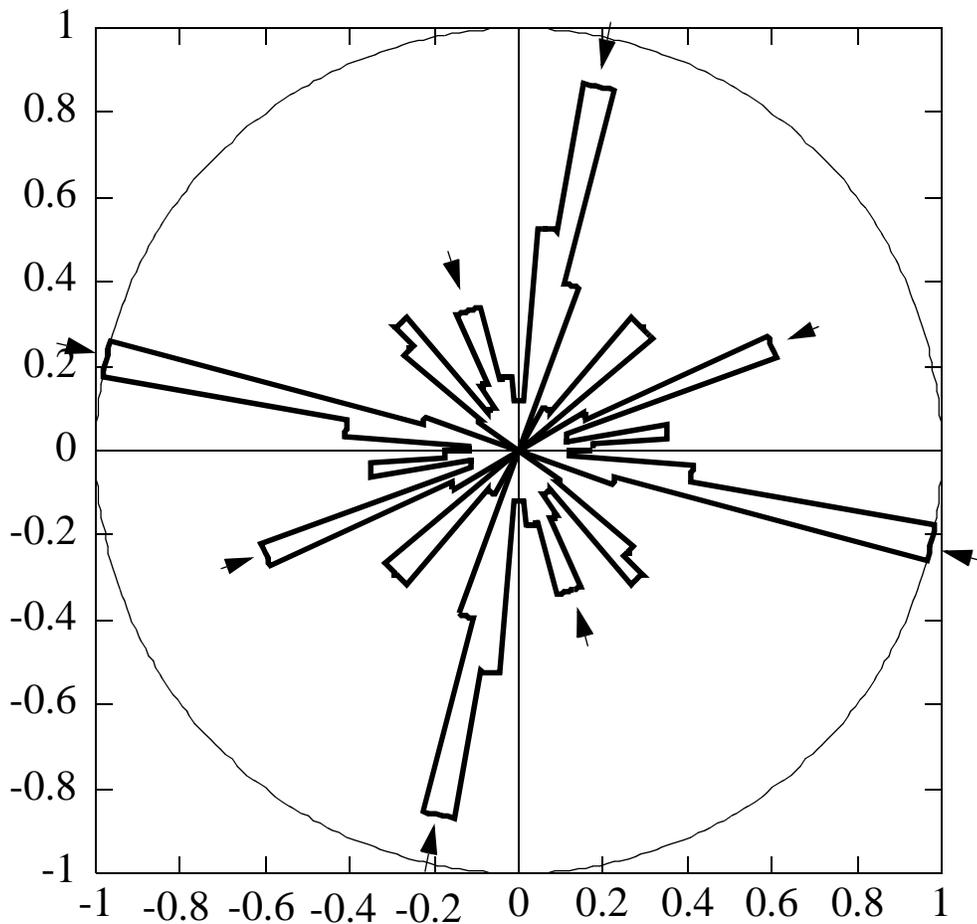


Figure 16. Rose diagram of fault plane directions from 75 focal mechanisms obtained during 2000 from the PVSN, southwestern Colorado. Paired arrows indicate directions from 1999 data analysis. The strike of the Paradox Valley is approximately $N 55^\circ W$.

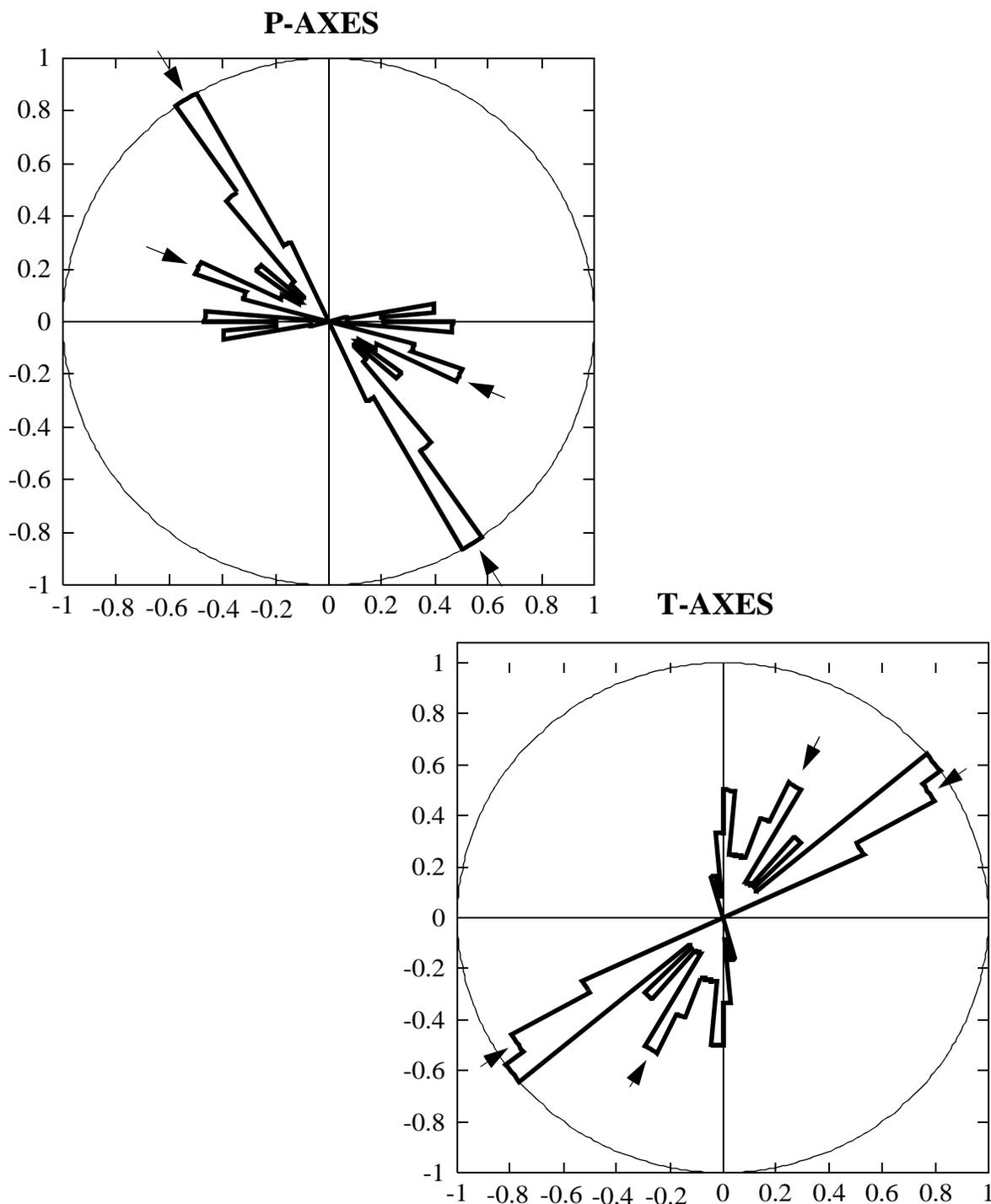


Figure 17. Rose diagram of P-axis directions and T-axis directions from 75 focal mechanisms obtained during 2000 from the PVSN, southwestern Colorado. Paired arrows show directions from 1999 data analysis. The strike of the Paradox Valley is approximately N 55°W.

5.7 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 M_D greater than 0.7 and good signal-to-noise ratios was used in the inversion. The second step of the process was to perform 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 of the process. (Waldhauser and others, 1999). Approximately 95% of the events recorded between 1991 and 2000 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 2000 are shown in **Figure 18**. The figure shows a pullout, close-up with the event location symbol size minimized to emphasize the linear features in these data (discussed below).

Figure 19 shows a series of 3-dimension cross sections of the relocated earthquakes. **Figure 19a** is a view looking north; **Figure 19b** is looking west, **Figure 19c** is looking northwest (i.e., along the strike of Paradox Valley); and **Figure 19d** is looking southwest (i.e., normal to the strike of Paradox Valley). In these figures the nearly vertical, heavy line is the wellbore profile with the wellhead located at coordinate point (0,0,0). **Figure 19** shows distinct vertical or near vertical linear hypocenter groups including those events in the Precambrian (i.e., below 4.8 km). As noted below, the orientation of these linear groupings is consistent with the orientations of both the individual earthquake focal mechanisms and the oriented (wellbore) core fractures. **Figure 19** also shows that the majority of the events near the well occur at depths between the top of the primary injection horizon (4.3 km, the Mississippi-aged Leadville Formation) and the bottom of the well. The seismicity shallows to the northwest in agreement with the inferred shallowing of the Leadville Formation in that direction (Bremkamp and Harr, 1988). A significant number of earth-

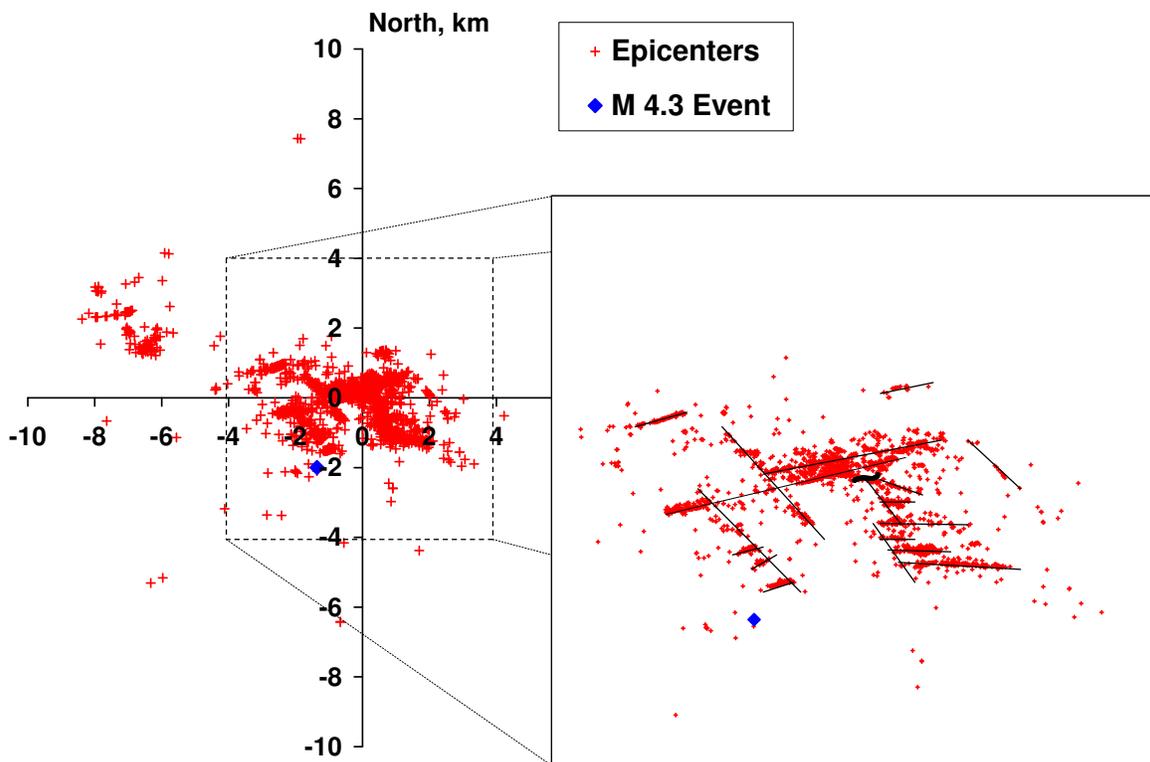


Figure 18. Epicenters from 1991-2000 Seismic Data. Axes are centered on injection wellhead.

quakes appear to be unambiguously located below the bottom of the well in the Precambrian basement rocks.

As discussed in the 1999 annual report (Ake et al., 2000), the loci of relocated earthquakes in 2000 (**Figures 18 and 19**) are consistent with the interpretation that most of the tectonic stress release takes place along 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 \sim N55°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

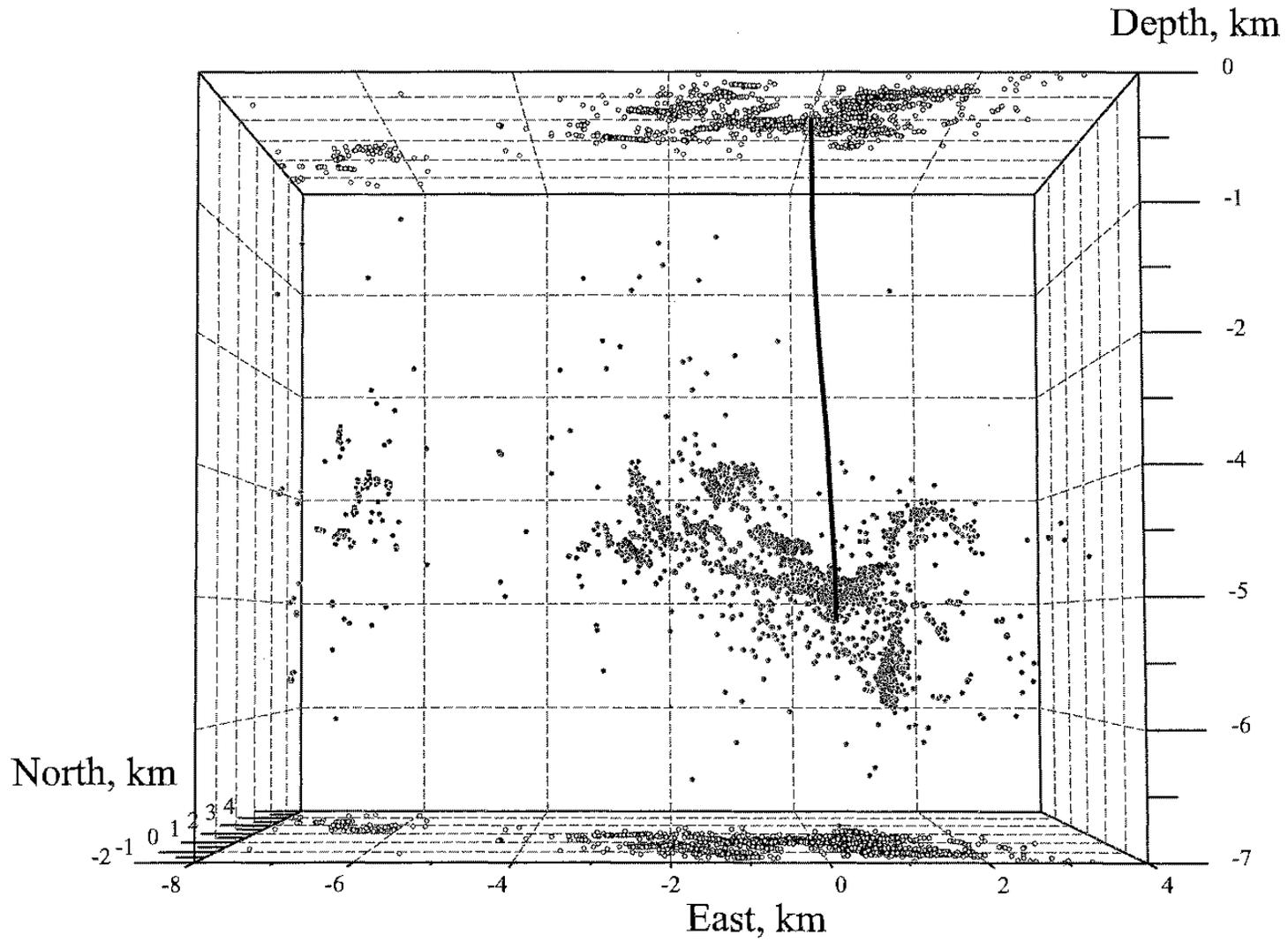


Figure 19a. Hypocenters viewed looking north. Heavy line is wellbore

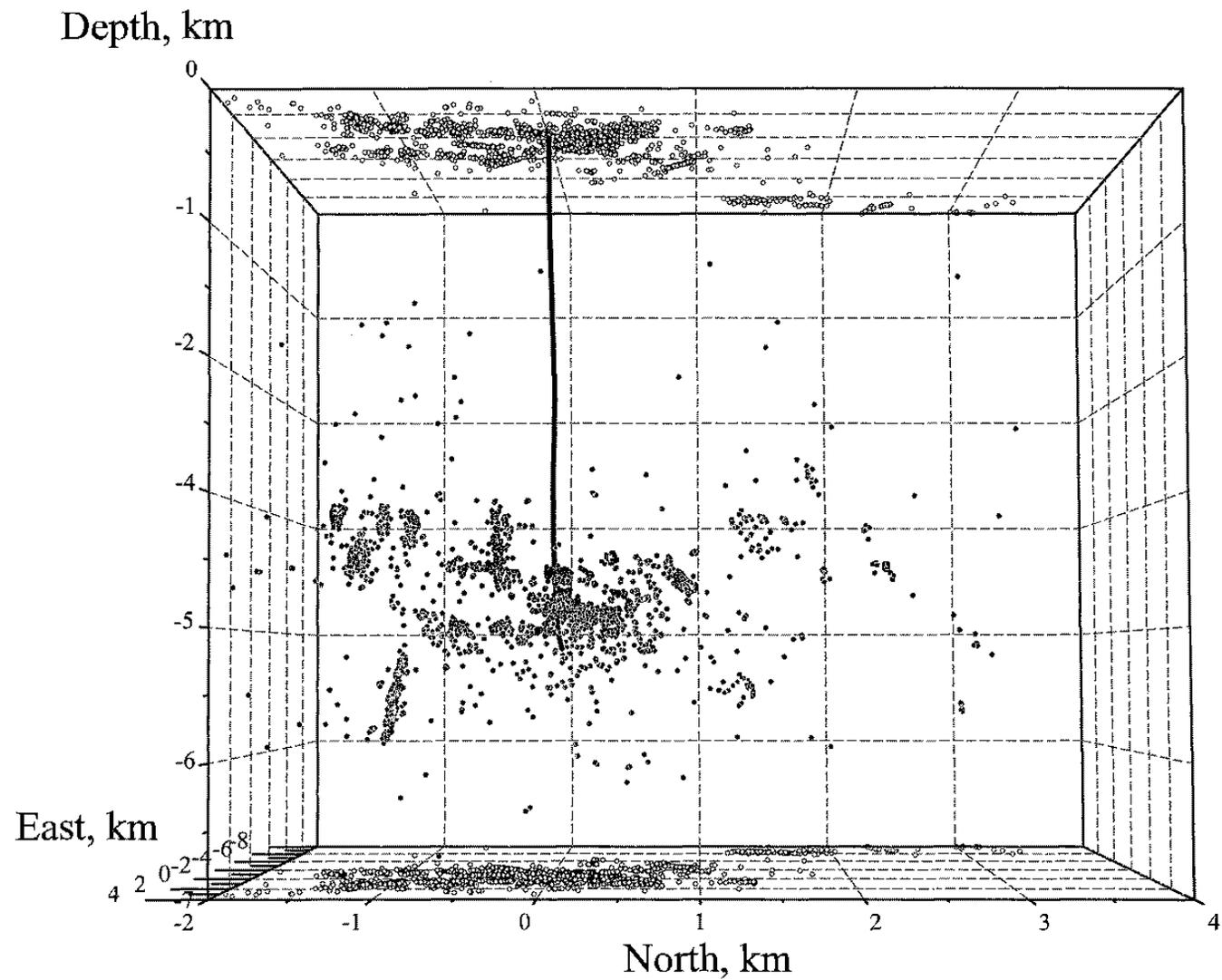


Figure 19b. Hypocenters viewed looking west. Heavy line is wellbore

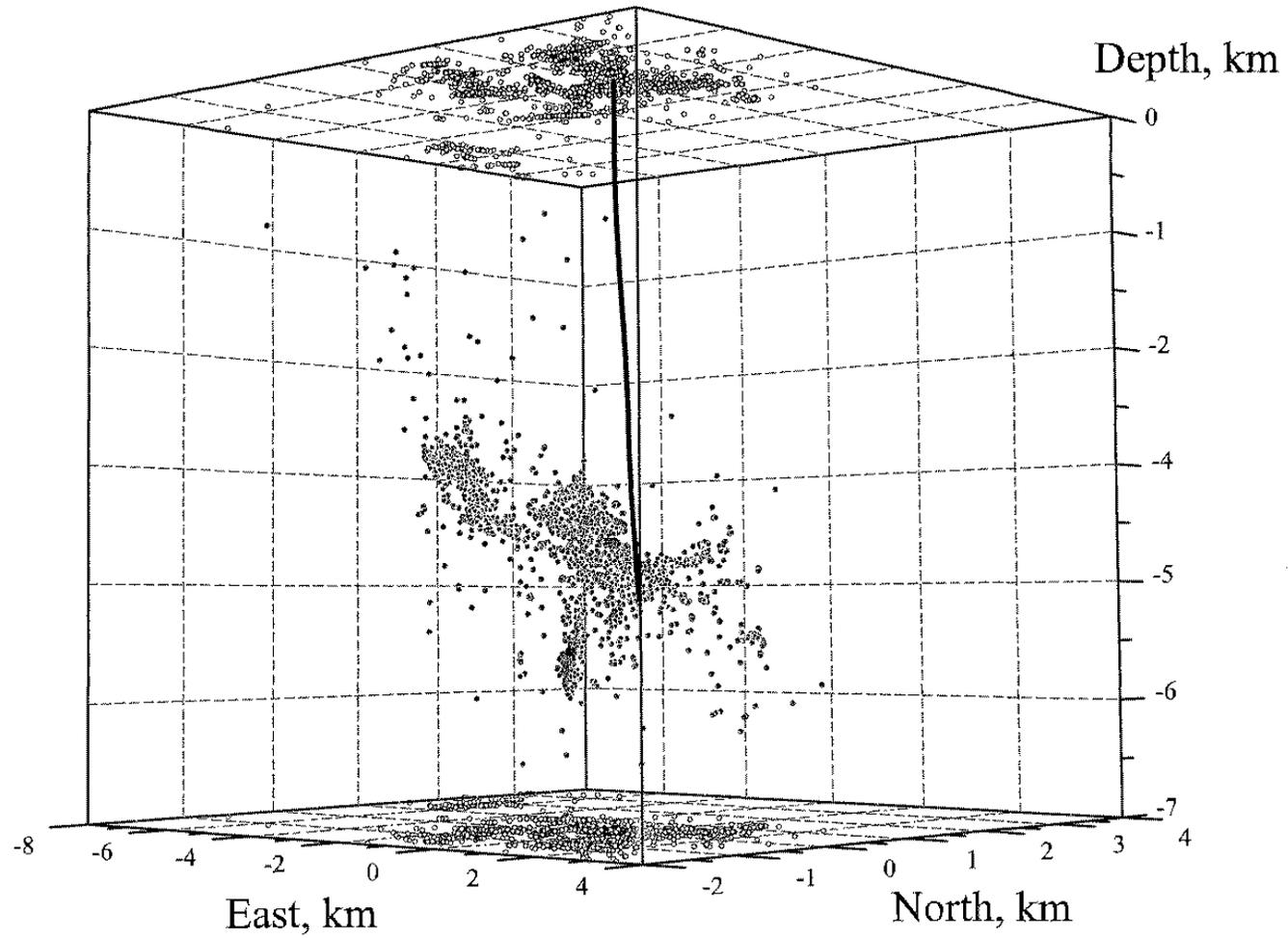


Figure 19c. Hypocenters viewed looking northwest -- along strike of Paradox Valley. Heavy line is wellbore

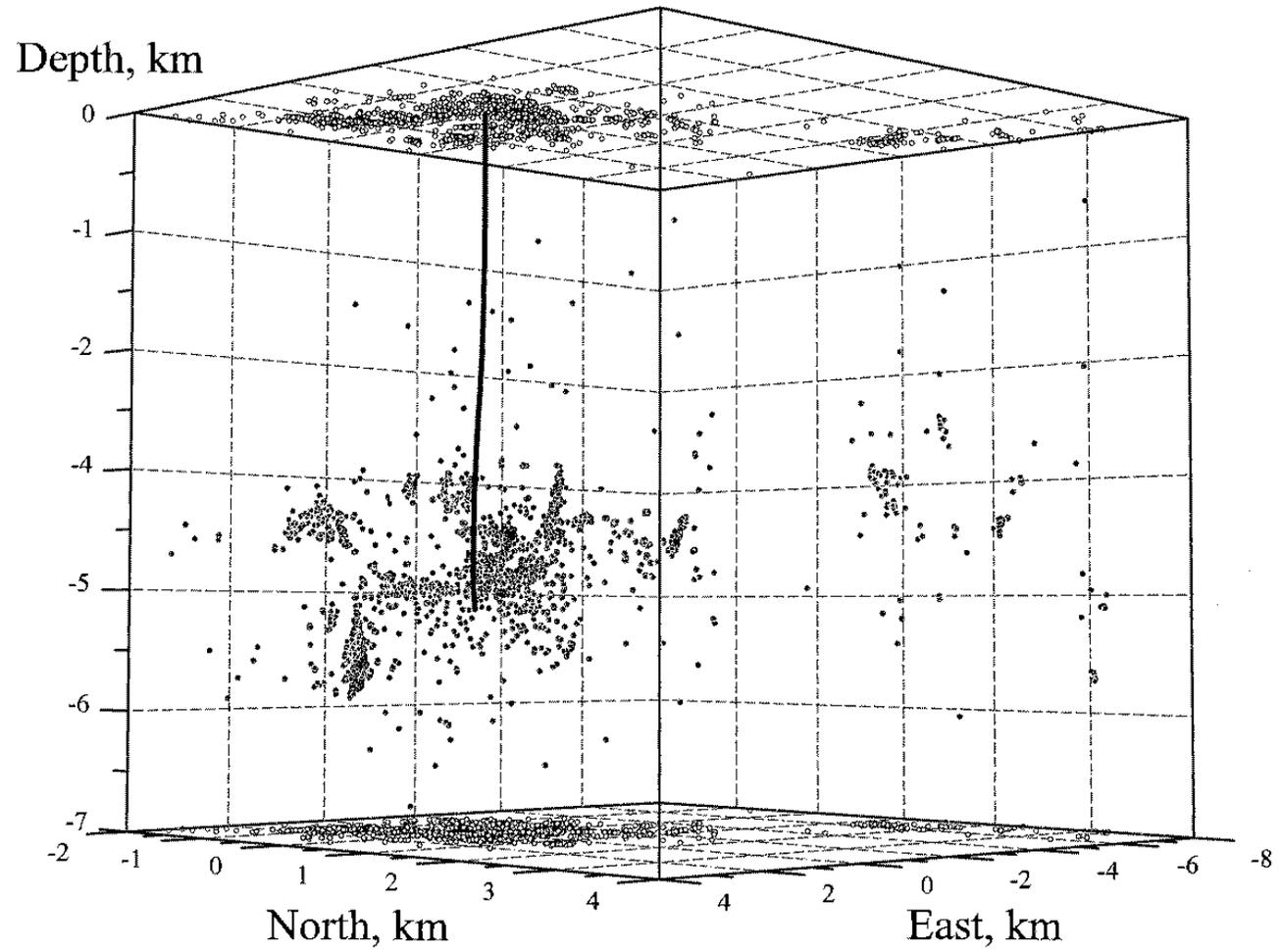


Figure 19d. Hypocenters viewed looking southwest -- across strike of Paradox Valley. Heavy line is wellbore

(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 17**).

6.0 Conclusions

The general objective of recording and analyzing seismicity in the Paradox Valley region was successfully carried out during 2000. In addition, analysis of the seismic data was successfully used to adjust the PVU injection well schedule to reduce the level of seismicity and the probability of larger events. Relevant observations from this reporting period include: (1) the location of more than 300 microearthquakes in an elongated zone surrounding the Paradox brine injection well; (2) a pronounced reduction in frequency of occurrence of observed earthquakes following periods of cessation of brine injection and following a long-term reduction in injection rate; (3) the continuing occurrence of earthquakes approximately 6-8 km northwest of the injection well; (4) the consistent spatial patterns of observed seismicity and relevant tectonic stress characteristics (as manifested by strike-slip faulting on northwest-southeast planes with northeast trending T-axes) relative to earlier observations.

7.0 References

- Ake, J. P., D. R. H. O'Connell, L. Block, and U. Vetter, 1996. Summary report, Paradox Valley Seismic Network, Paradox Valley Project, southwestern Colorado (*draft*): Seismotectonic Report 96-9, U. S. Bureau of Reclamation, Seismotectonic and Geophysics Group, Denver, CO, 89 pp.
- Ake, J., and K. Mahrer, 1999. 1998 Status report-Paradox Valley Seismic Network, Paradox Valley Project, southwestern Colorado: Technical Memorandum No. D8330-99-016, U. S. Bureau of Reclamation, Seismotectonics and Geophysics Group, Denver, CO, 18 pp.
- Ake, J., K. Mahrer, and L. Block, 2000. 1999 Status report-Paradox Valley Seismic Network, Paradox Valley Project, southwestern Colorado: Technical Memorandum No. D8330-2000-012,

- U. S. Bureau of Reclamation, Seismotectonics and Geophysics Group, Denver, CO, 23 pp.
- Block, L. V., 1991. Joint hypocenter-velocity inversion of local earthquake arrival time data in two geothermal regions: Ph. D. Dissertation, Massachusetts Institute of Technology, 448 pp.
- Bremkamp, W., and C. L. Harr, 1988. Area of least resistance to fluid movement and pressure rise, Paradox Valley Unit, Salt Brine Injection Project, Bedrock, Colorado: Final unpublished report to the U.S. Bureau of Reclamation, Denver, CO., 39 pp.
- EnviroCorp, 1995. Report of evaluation of injection testing for Paradox Valley Injection Test No. 1: EnviroCorp Project Report No. 10Y673: Final report prepared for the U.S. Bureau of Reclamation by EnviroCorp Services and Technology, Inc., Houston TX, 26 pp.
- LaForge, R. L., 1996. Seismic hazard assessment for Navajo Dam, Navajo Indian Irrigation Project, New Mexico: Seismotectonic Report No. 96-11, U. S. Bureau of Reclamation, Seismotectonics and Geophysics Group, Denver, CO, 34 pp.
- Malone, S., and C. Weaver, 1986. Informal memorandum describing earthquake location program SPONG: University of Washington Geophysics Program, Seattle, WA, 10 pp.
- Waldhauser, F., W. L. Ellsworth, and A. Cole, 1999. Slip-parallel seismic lineations on the northern Hayward Fault, California: *Geophysical Research Letters*, **26**, No. 23, p. 3525-3528.
- Wong, I. G., and R. B. Simon, 1981. Low-level historical and contemporary seismicity in the Paradox Basin, Utah and its tectonic implications: Rocky Mountain Association of Geologists-1981 Field Conference Guidebook, p. 169-185.
- Wong, I. G., S. Olig, and J. D. J. Bott, 1996. Earthquake potential and seismic hazards in the Paradox Basin, southeastern Utah: *in* Geology and Resources of the Paradox Basin, 1996 Special Symposium, A. C. Huffman, W. R. Lund, and L. H. Godwin [eds.], Utah Geological Association and Four Corners Geological Society Guidebook No. 25, p 251-264.