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1999 Status Report-Paradox Valley Seismic Network
Paradox Valley Project
Southwestern Colorado

Prepared by

Jon Ake
Ken Mahrer
Lisa Block

U.S. Department of the Interior
Bureau of Reclamation

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Geophysics, Paleohydrology, and Seismotectonics Group

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Prepared By

Jon Ake
Seismologist — April 18, 2000 Date

Ken Mahrer
Geophysicist — Apr 18, 2000 Date

Lisa Block
Geophysicist — April 18, 2000 Date

Peer Review

Ute Vetter
Geophysicist — April 19, 2000 Date

1.0 Introduction

This report provides a brief summary of seismological observations from the Paradox Valley Seismic Network (PVSN) for the 1999 calendar year. The objective of the seismic monitoring program is to (1) record and evaluate seismic events in the region surrounding Paradox Valley, with a specific focus on the immediate vicinity of the injection well; (2) provide locations of the local seismic events; (3) determine focal mechanisms of the events when feasible; and (4) identify and evaluate any relationships between seismicity, geology, subsurface brine location, and injection parameters. In order, the following sections will discuss operations, analysis, observations, and conclusions.

2.0 Operations

The PVSN provides seismographic coverage for a roughly 5500 km^2 region of the Colorado Plateau centered on the intersection of the Dolores River and Paradox Valley (**Figure 1**). The PVSN was installed in late 1983 and has operated continuously since that time. During 1999 the network consisted of 15 stations (**Figure 1**) with characteristics summarized in **Table 1**. The network is arranged in two concentric rings of stations centered on the brine injection well location. The outer ring has a diameter of approximately 80 km.

Each station of the PVSN consists of a seismometer, amplifier, voltage control oscillator (VCO), low power telemetry radio, and broadcast tower with antenna. All systems are powered by solar-recharged batteries. Thirteen of the stations operational during 1999 were equipped with single component, vertical motion seismometers. The Davis Mesa and Nyswonger Mesa stations (PV11 and PV16, respectively) were operated as three component sites with vertical, east-west, and north-south oriented seismometers. The seismometers at all 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. The amplifiers and VCO's at all sites are also manufactured by Teledyne Geotech (model 4250). The pass band of the field amplifiers has been set to minimize long-period noise. The characteristics of the field instrumentation are summarized in **Table 1** and shown schematically in **Figure 2**.

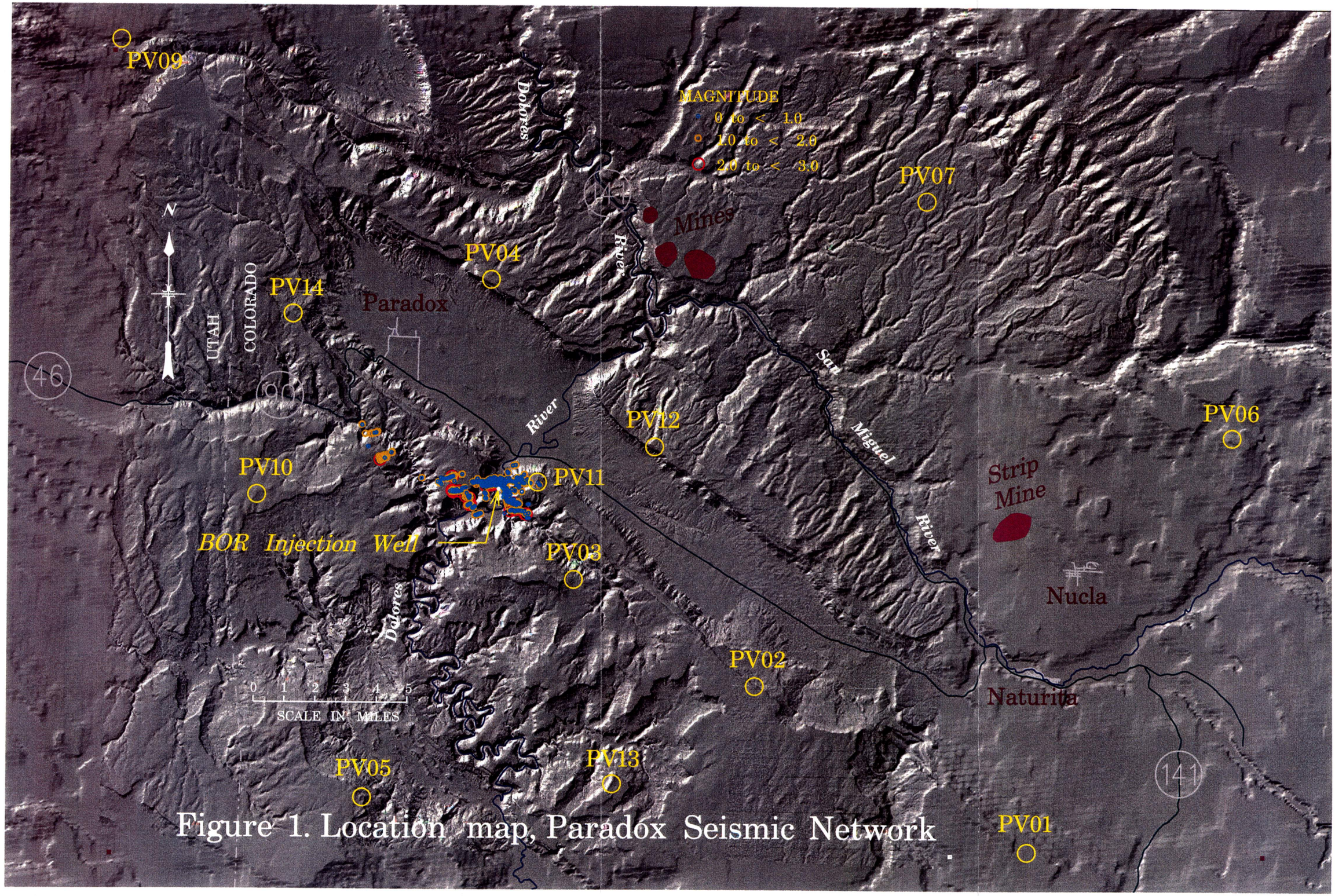

Figure 1. Location map, Paradox Seismic Network

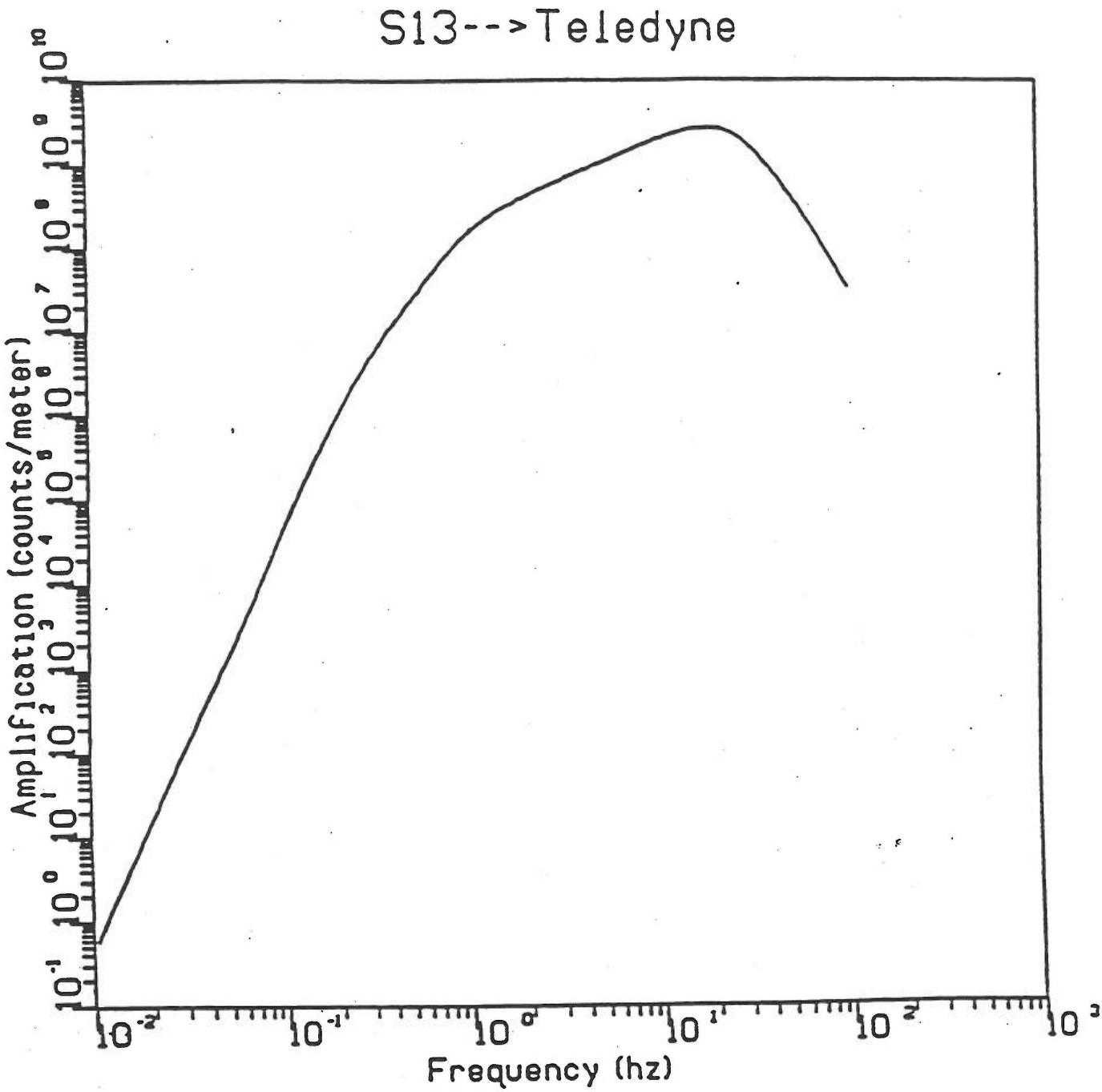

Figure 2. Typical response for PVSN station with a vertical-component Teledyne Geotech S13 seismometer and associated electronics and digital recording. Nominal gain of 48 db for curve displayed, Teledyne Geotech model 42.5 amplifier/VCO and model 4612 discriminator. Damping value of 0.71 of critical.

Table 1: PVSN Instrument Locations and Characteristics

Station Designation	Station Name	Latitude	Longitude	Elev (m)	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
PV06	Coal Canyon	38.33	108.46	2274	6/83	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 with respect to msl, the surface elevation of the well is 1549m. Gains are as operated during 1999. Station PV08 is outside the boundaries of Figure 1. Station PV15 is not shown on Figure 1 for clarity as it has nearly the same location as PV06.

From each seismometer site, a continuous analog signal is radio telemetered to Nucla, CO where the site data are multiplexed and transmitted via telephone lines and microwave links to the U.S. Bureau of Reclamation seismic computing facility at the Denver Federal Center (DFC). At the DFC, the data are demultiplexed, digitized, and fed through an event detection algorithm. When potential earthquake signals are detected by the algorithm, a data file of the buffered data stream is written. Additional automated data processing is then performed and event classification and preliminary event locations are computed. Subsequently, project seismologists review all automated results and all local earthquakes are re-analyzed.

During 1999, the network operated satisfactorily. Minor, but not unexpected, data outages due to lightning strikes and telephone circuit problems resulted in individual stations being down on a sporadic basis. However, the network was online, capable of detecting and locating earthquakes in the Paradox Valley every day of the year. The operational efficiency of the network (i.e., total number of operational station days/total number of potential instrument days) was approximately 90%.

3.0 Analysis

In general, the size of an earthquake can be computed using one of a variety of calculation methods. In most cases magnitude calculations for local seismic events follow a general procedure that has been calibrated for local conditions. The magnitudes of the events recorded by the PVSN are computed based on the total time duration of the recorded signal. This scale is called the duration or coda magnitude and is denoted $\mathbf{M_D}$. Since prior to 1983, very few events had been recorded in the Paradox Valley area, the relationship between signal duration and magnitude used at PVSN had to be developed and calibrated using events from a broader region of western Colorado. The relationship yields reasonable results for events with local magnitudes between 1.0 and ~2.3, when compared to local magnitudes computed by the National Earthquake Information Center and the University of Utah. Uncertainty in magnitudes for local events is assumed to be approximately +/- 0.5 magnitude units. For events larger than moment magnitude ~2.3 (denoted by **M**, a magnitude scale assumed equivalent to local magnitude in this range), the duration-based magnitudes have not been adequately tested to assure accuracy. Additional magnitude determination studies will be pursued as the project proceeds.

The accurate determination of earthquake location requires careful identification and measurement of arrival times of specific phases in the recorded signals, appropriate array geometry, and a valid velocity model of the region through which the signals travel. As described above, all local earthquakes were manually picked by experienced seismologists to minimize uncertainty in phase identification and arrival time. A minimum of four arrival times from at least three stations was imposed as a requirement to locate an event. Primary or P-wave readings were obtained for all operational stations with acceptable signal-to-noise ratios, secondary or S-wave readings were used only from the three-component stations at Davis Mesa (PV11), and Nyswonger Mesa (PV16), and for the closest single-component station to the injection well at Wild Steer (PV03) (see **Figure 1**).

Preliminary earthquake locations are obtained using a one-dimensional, layered earth velocity model and the computer program SPONG (Malone and Weaver, 1986). The one-dimensional crustal velocity model is summarized in **Table 2**. The P-wave portion of this model was developed using the results from previous studies in the area as an initial model (Wong and Simon, 1981), with the addition of mining explosions in the area as known sources for refraction surveys, and on analyses of sonic velocity logs obtained during drilling of the injection well. The S-wave velocities in this model were computed from the P-wave velocities assuming a Poisson's ratio of 0.25 (equivalent to a Vp/Vs of 1.732). Additional studies to increase event location accuracy using seismic tomography are currently being conducted and are briefly summarized in Section 4.

In addition to the earthquake signals, seismic networks also record non-seismic events, which include thunder, lighting strikes, landslides, and cultural noise, especially mining activities. The discrimination of earthquake signals from these unwanted noise sources requires experience and consistency in processing. Based upon 10 years of examining waveform data from the PVSN plus the known locations of mines in the Paradox Valley area, the differentiation of local earthquakes from mining explosions within the network is robust. Blasts are routinely monitored from a distributed area around Uravan and from a strip mine located west of Nucla (see **Figure 1**). These explosion sources have diagnostic waveform characteristics (impulsive P-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.

Table 2: PVSN Velocity Model

Depth (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
Note: Depth indicated is relative to datum of +1850 m above mean sea level.		

4.0 Observations

During 1999, 1142 earthquakes were located within 7 km of the Paradox Valley brine injection well. Based upon the almost total lack of observed seismicity prior to injection and previous observations (EnviroCorp, 1995; Ake and others, 1996), we infer these events to be associated with the injection process. Five events with $M_D > 2.5$ were recorded during 1999. The largest events in 1999 were two M_D 2.8 events that occurred on June 3 and July 30. Both the U. S. Geological Survey and University of Utah Seismograph stations estimated moment magnitudes (M)

for these events between 3.0 and 3.5. Both of these events were felt by nearby residents of the Paradox Valley. The earthquakes associated with the brine injection well during 1999 are shown in plan view on **Figure 3**. These events range in duration-based magnitude from -0.5 to 2.8. The error in locating events generally decreases with increasing magnitude since identifying the P and S-phases in the smaller events is compromised by a reduced signal-to-noise ratio. As a result, most of our conclusions for this data set are based on events with $\mathbf{M_D} > 0.8$.

Note in **Figure 3** that the spatial distribution of the seismicity recorded in 1999 is contained within an elongated envelope with the long axis of the envelope running approximately EW and extending about 4 km from the injection well. This elongated shape is consistent with the spatial distribution of events observed previously (Ake and Mahrer, 1999). The persistent spatial distribution of events suggests that the occurrence of triggered 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 1998 a second group of events were located approximately 6-7 km to the northwest of the well, outside the primary envelope of seismicity. These events have been the most distant from the well observed to date. This region continued to be a source of earthquakes during 1999 (see **Figure 3**). **Figure 4** summarizes the depth distribution of earthquakes near the well with $\mathbf{M_D} > 0.8$ located during 1999. The range of depths observed in 1999 is generally similar to that observed in previous reporting periods with one exception. A substantial number of events with depths greater than 6 km was observed during 1999. These events are clearly within the Precambrian basement rocks. The preliminary earthquake locations displayed in **Figures 3** and **4** suggest that seismic slip occurred primarily over an interval of 4 to 6.5 km depth 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.

Figure 5 is a recurrence curve for all the earthquakes located during 1999 near the brine injection

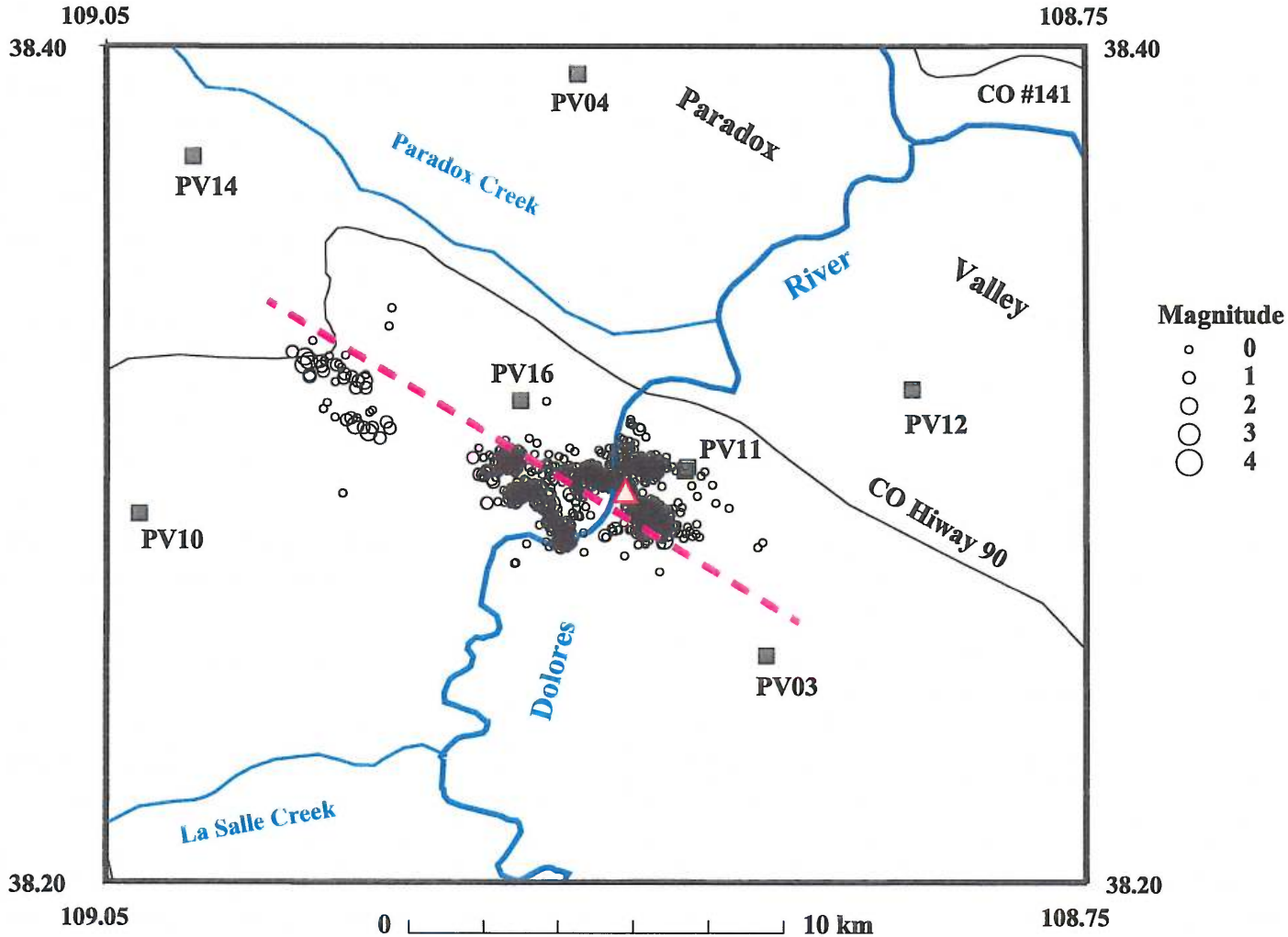

Figure 3. Seismicity located during 1999 by the PVSN using one-dimensional velocity model, 1142 events plotted. Location of injection well shown by triangle. Approximate location and orientation of one element of the Wray Mesa fault system (from Bremkamp and Harr, 1988) shown in magenta. Location of seismograph stations indicated by filled squares.

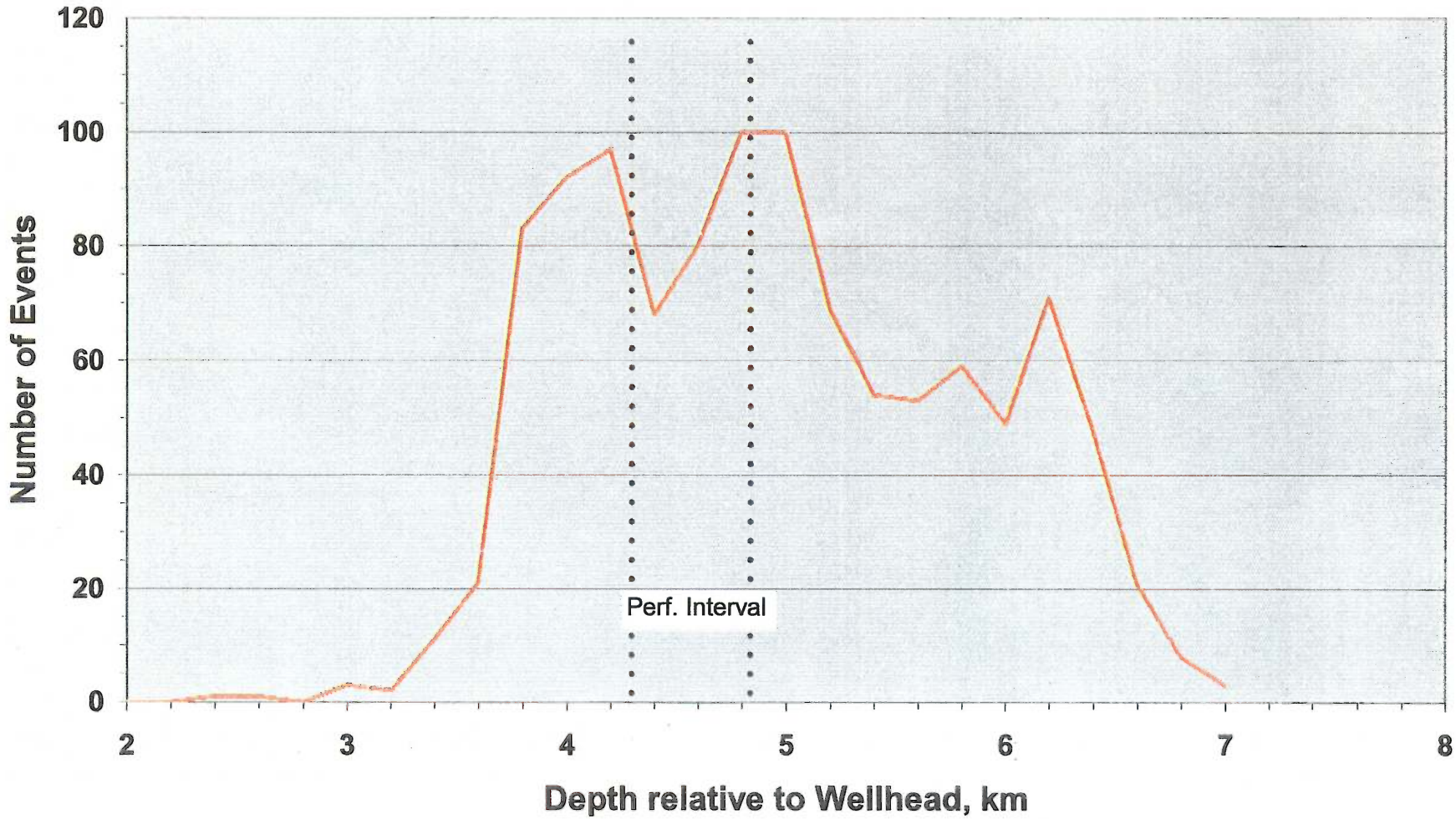

Figure 4. Seismic event depth distribution based on one-dimensional velocity model for near-wellbore events during 1999.

well. **Figure 5** suggests that, as operated during 1999, the detection/location threshold for the PVSN was approximately M_D 0.7. Below this threshold magnitude, events are incompletely recorded by the network. The slope of the recurrence curve (the "*b*-value") is 0.81. 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 (c.f. 0.87 in 1998). 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.

The cumulative number of earthquakes observed during 1997, 1998, 1999 and early 2000 is illustrated on **Figure 6**. The average number of events per day recorded by the network during 1999 was 3.1 with a variability of 0 to 18 events per day, with 33 days having no events and 13 days having 10 events or more. Daily average injection pressure and injection rate for the brine injection well are plotted with number of events per day on **Figures 7** and **8**. Injection was halted entirely for 5 days for routine maintenance during May 1999 (the period of highest sustained flows in the Dolores River). Following the occurrence of the felt event of June 3, discussions regarding potential changes in well operations were held. Based upon the observation that the number of earthquakes declined substantially following prolonged periods with no injection during previous years, well operations were altered to require a minimum of two shut-in periods of at least twenty days per year. The change in the absolute number of events per day and slope of the cumulative number of events curve can be seen in **Figures 6** and **7**. The slope of the cumulative frequency curve decreased in late 1999 and has remained lower during the first quarter of 2000.

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 1999 earthquakes with strong first motions and occurring over a range of locations, 85 focal mechanisms were constructed. As with previous observations, the results are dominated by strike-slip faulting on west-northwest trending, steeply dipping fault planes. A Rose diagram of the fault plane angles of the 85 focal mechanisms developed using 1999 data is shown on **Figure**

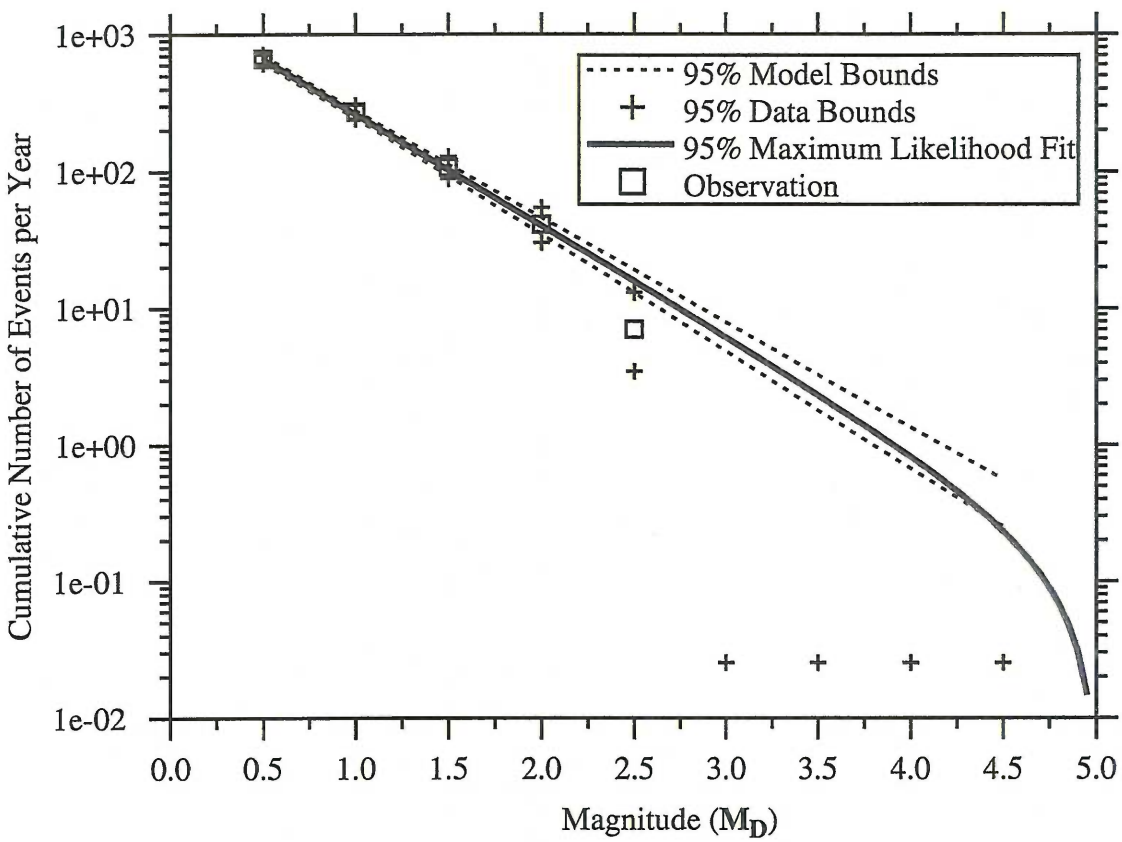

Figure 5. Cumulative recurrence curve for earthquakes located by the PVSN near the brine injection well during 1999. Maximum likelihood fit and 95% confidence bounds indicated. The computed "*b*-value" for 1999 is 0.81. A maximum magnitude of 5.0 was assumed for the calculations.

9. The Pressure (or P) axes and Tension (or T) axes for these events are shown in Rose diagram form in **Figure 10**. The T-axis direction is a consistent northeast direction and the P-axes are oriented northwest (~N 51°W). No difference in spatial distribution of focal mechanism types was evident within the 1999 data set. The results are very similar to the 1998 observations.

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

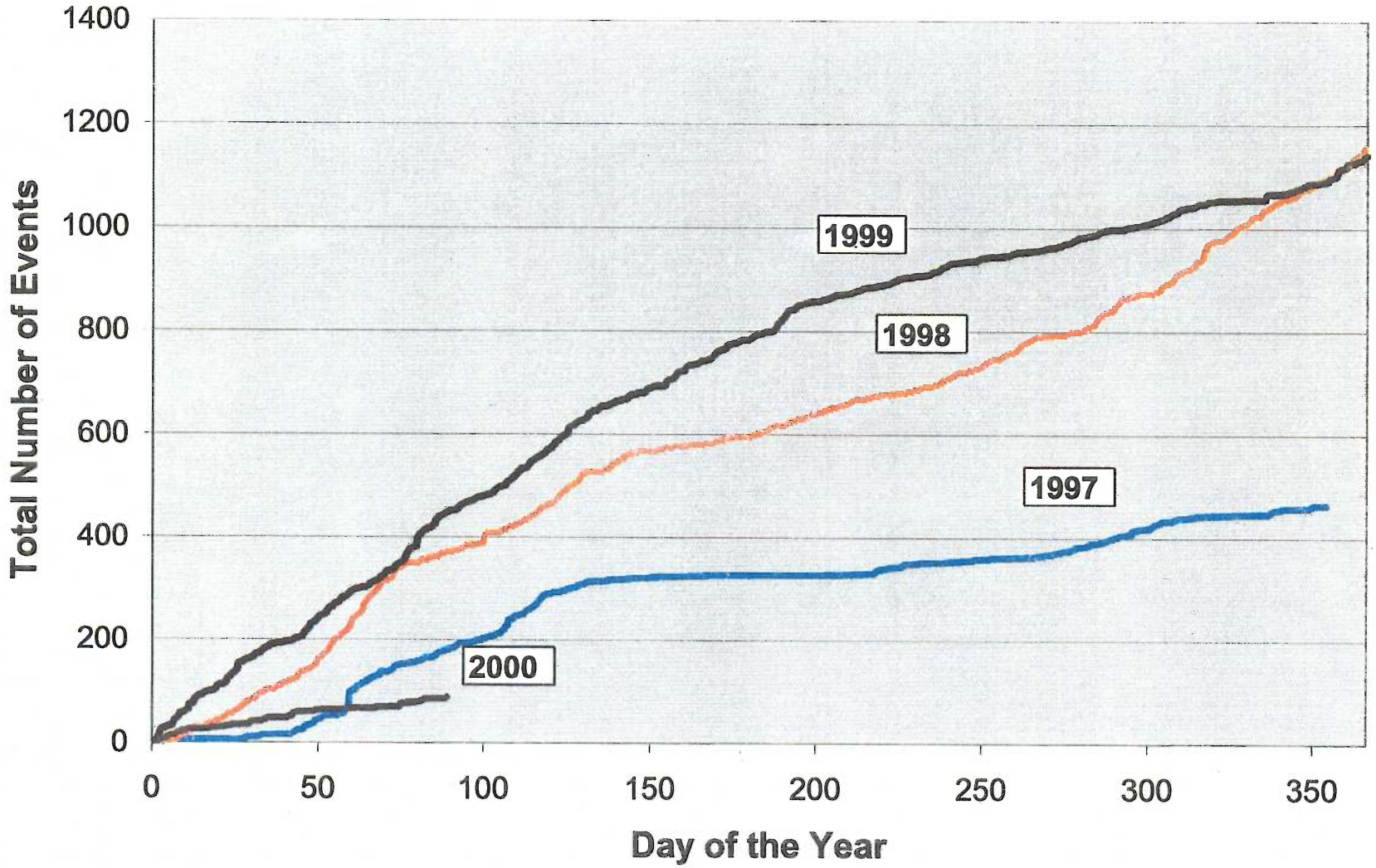

Figure 6. Cumulative number of seismic events versus time for each year of continuous pumping.

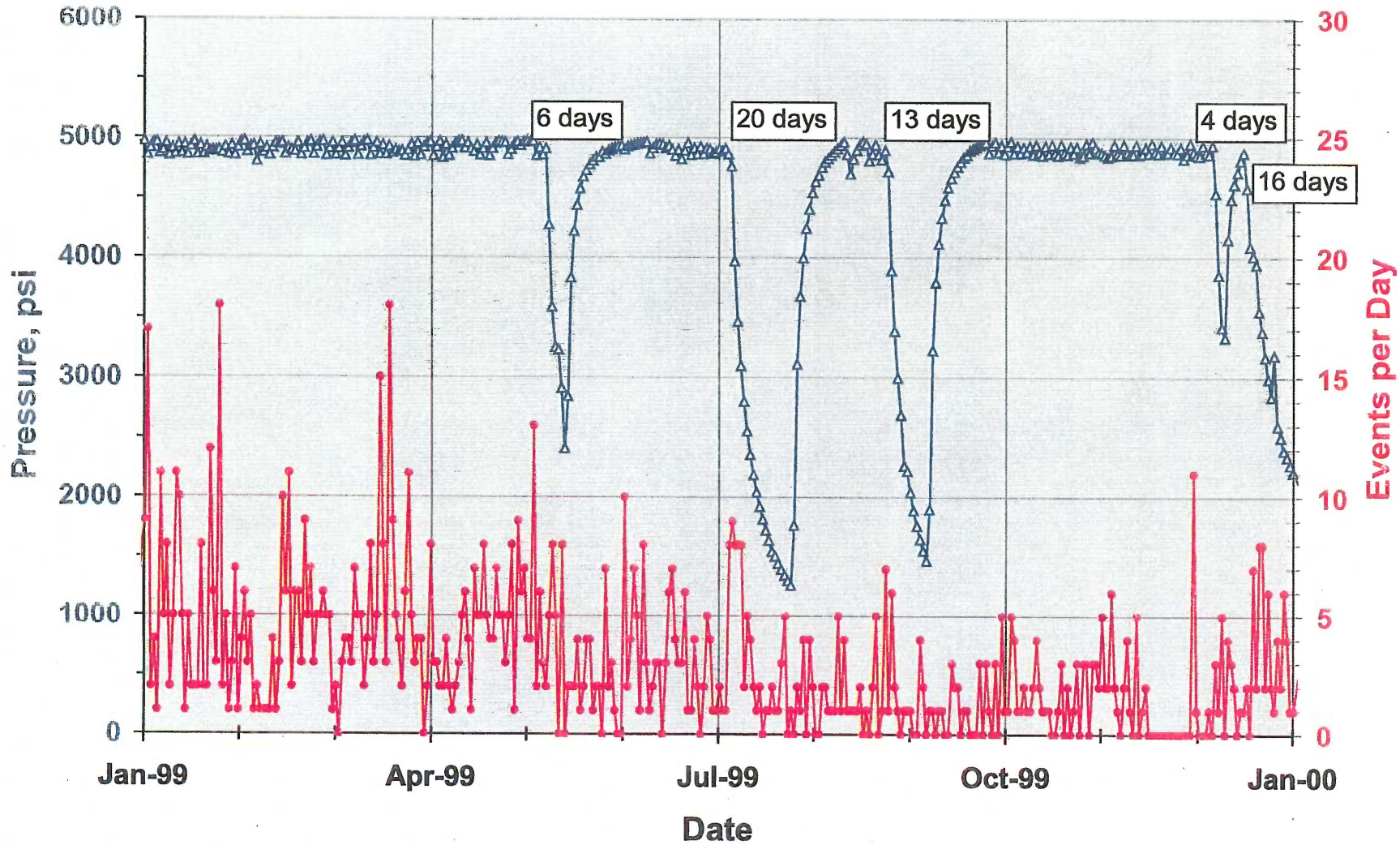

Figure 7. Wellhead injection pressure (blue) and number of seismic events per day (red) versus time for 1999. Sharp dips in pressure indicate shut down days with number of days shut down in boxes.

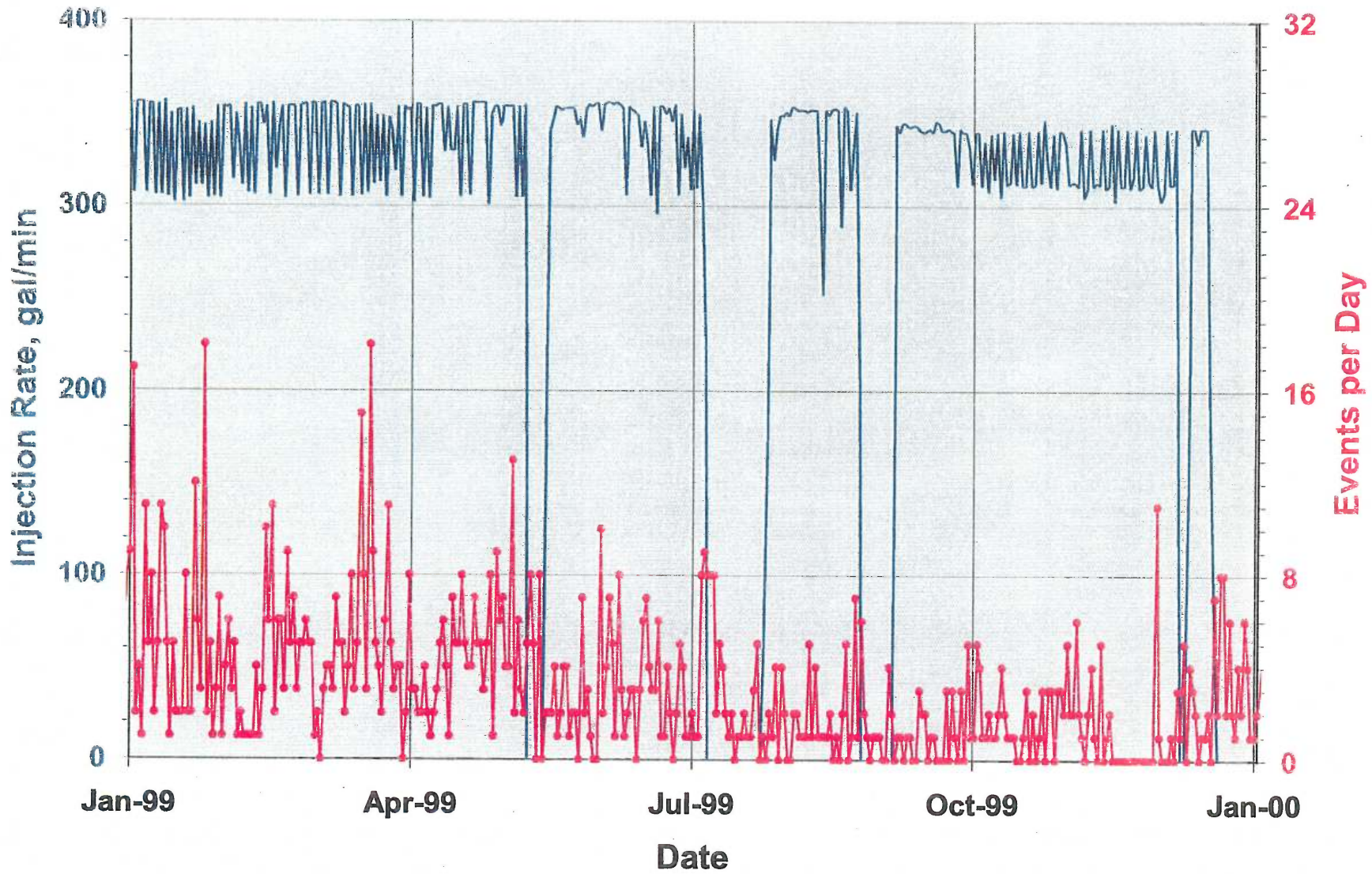

Figure 8. Average brine injection rate (blue) and number of seismic events per day (red) for 1999.

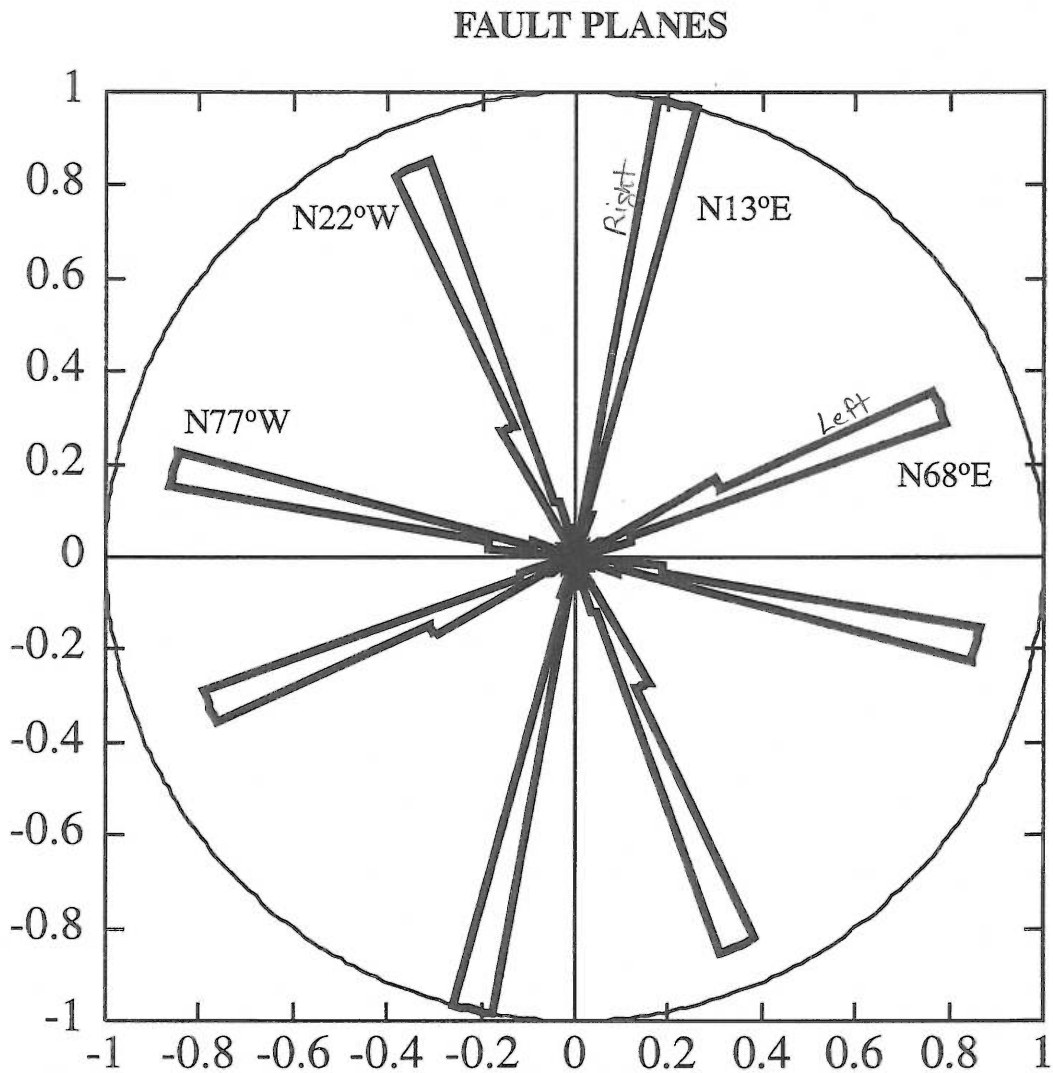

Figure 9. Rose diagram of fault plane directions from 85 focal mechanisms obtained during 1999 from the PVSN, southwestern Colorado. The strike of the Paradox Valley is approximately N 55°W.

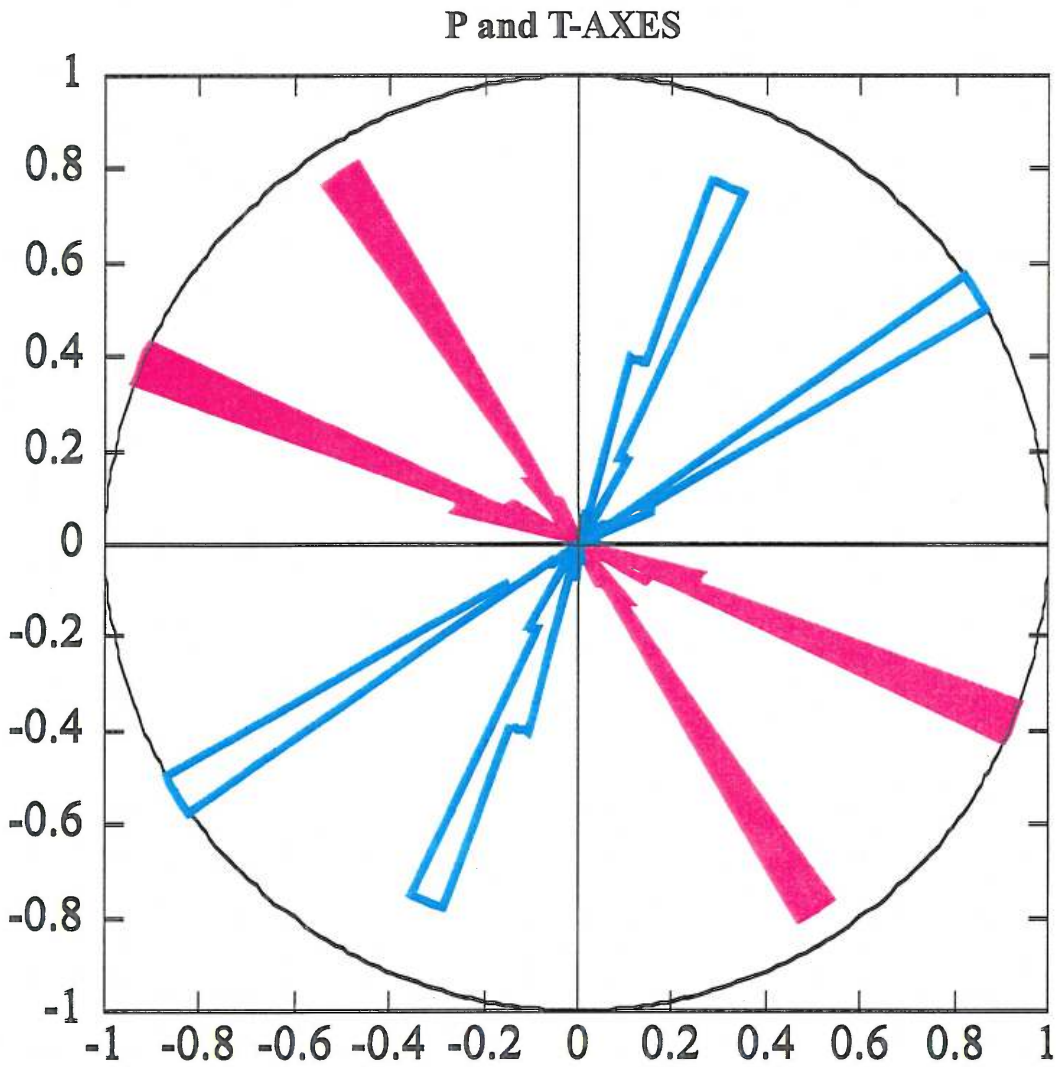

Figure 10. Rose diagram of P-axis directions (shown in magenta) and T-axis directions (shown in cyan) from 85 focal mechanisms obtained during 1999 from the PVSN, south-western Colorado. The strike of the Paradox Valley is approximately N 55°W.

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 a larger set of the earthquakes using the three-dimensional velocity model developed in the first step of the process. (Waldhauser and others, 1999). 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. A subset of the earthquakes located using the relative relocation procedure is shown in **Figure 12** (compare to **Figure 3**, preliminary locations obtained using the one-dimensional velocity model). A cross section of the relocated earthquakes is shown in **Figure 13**. The majority of the events near the well occur in depth between the top of the primary injection horizon (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. A significant number of earthquakes appear to be unambiguously located below the bottom of the well in the Precambrian basement rocks.

The relocated earthquakes shown on **Figure 12** strongly suggest that most of the tectonic stress release is taking place along linear features with orientations consistent with either the focal mechanism results or fractures observed in the oriented core sample. 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°W by Bremkamp and Harr (1988). It is likely that these features are the most through going structures in the area. We interpret this behavior to suggest fluid is being preferentially carried along these steep planes with a northwest strike (elements of 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 10**).

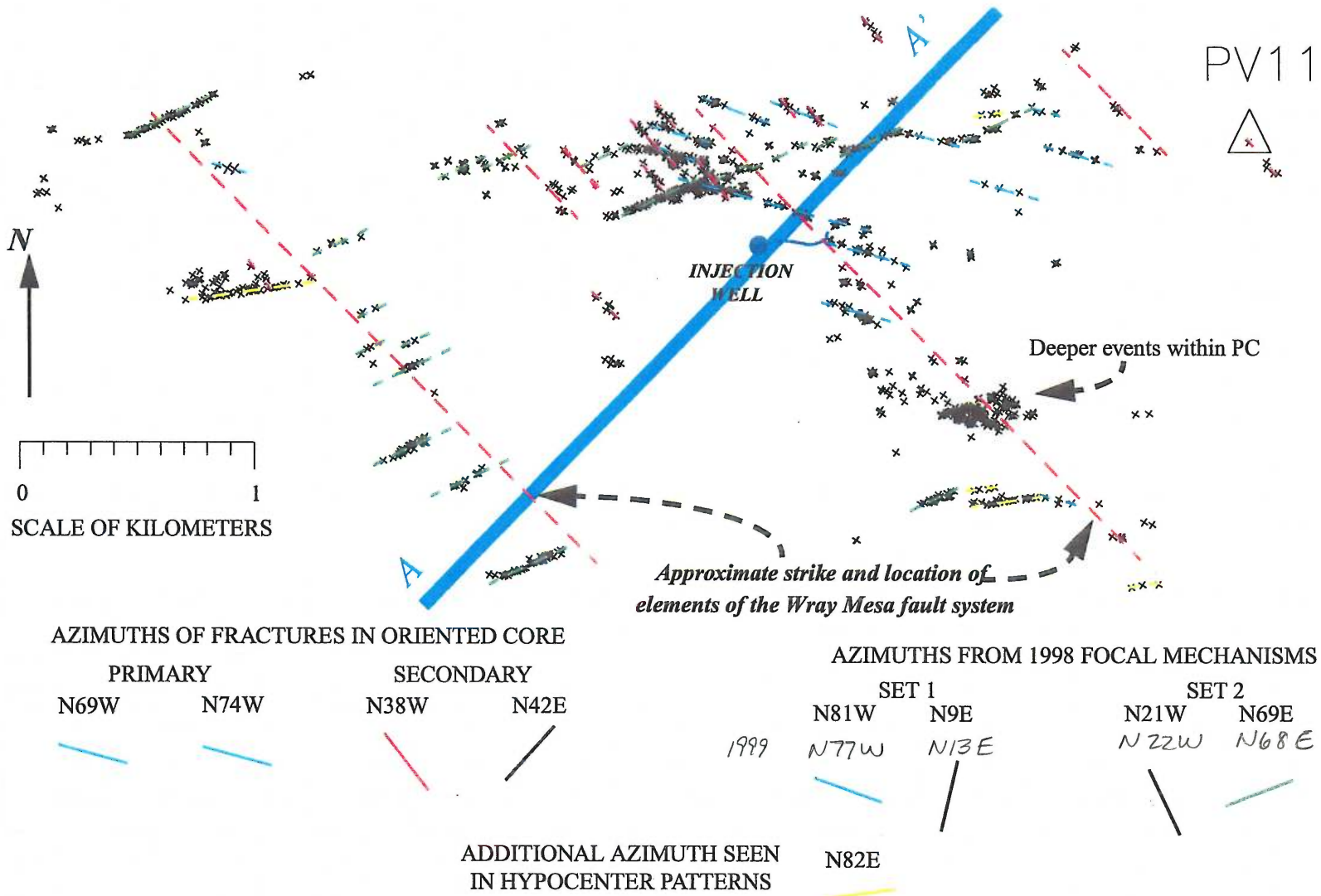

Figure 12. Earthquakes (1991-1999) relocated using 3-D velocity model and relative relocation technique. Azimuths of fractures from oriented core and focal mechanisms indicated by color. Longer dashed red lines indicate average orientation of core and Wray Mesa faults (from Bremkamp and Harr, 1988). Surface location of well indicated by blue dot, deviation by blue line. Location of section shown in Figure 13 indicated by heavy cyan line.

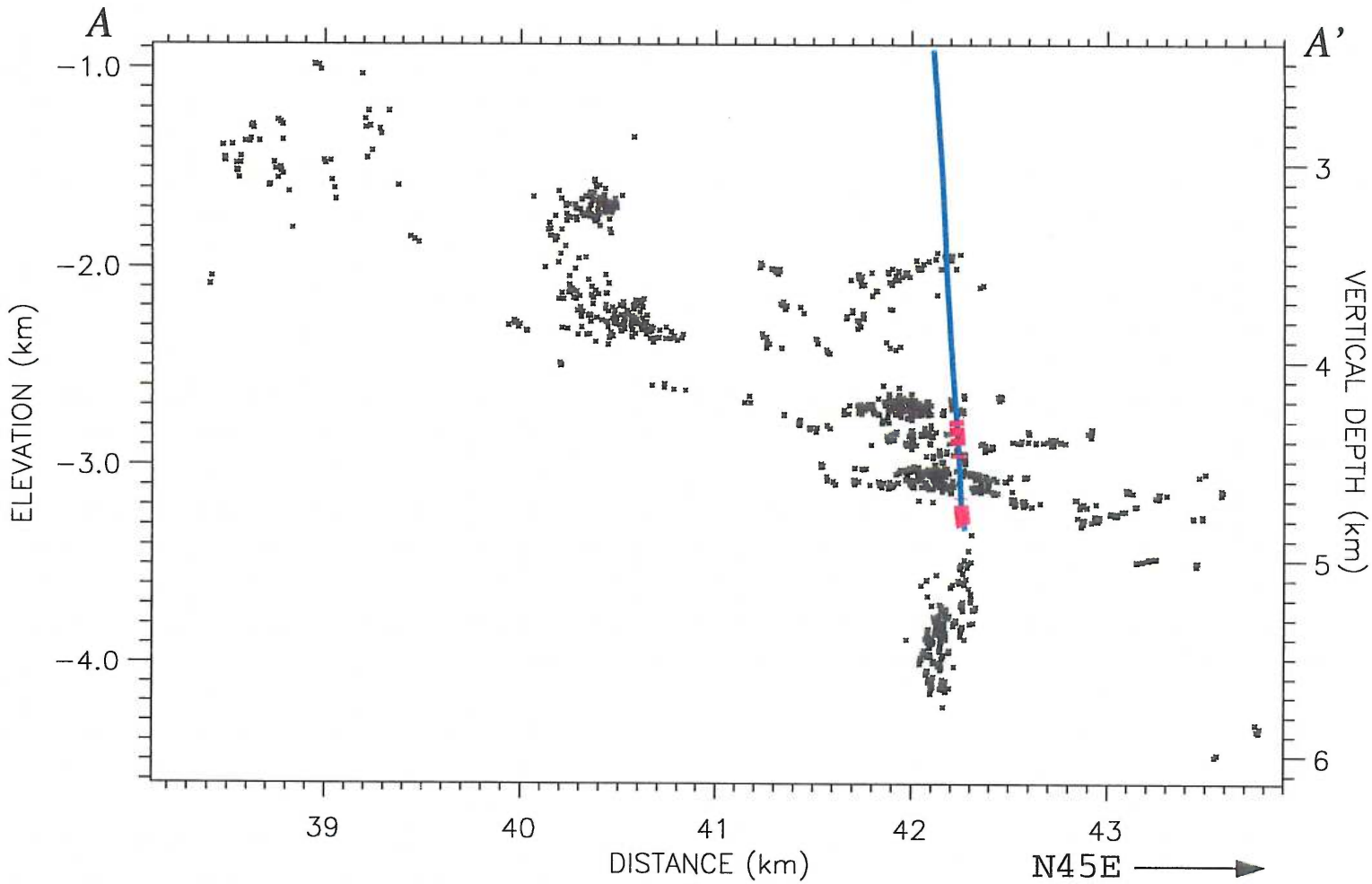

Figure 13. Cross-sectional view of earthquakes (1991-1999) relocated using 3-D velocity model and relative relocation technique. View is looking northwestward. Injection well shown in blue, perforated intervals indicated in red.

5.0 Conclusions

The general objective of recording and analyzing seismicity in the Paradox Valley region was successfully carried out during 1999. Relevant observations from this reporting period include: (1) the location of more than 1100 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; (3) the 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.

The general observations from 1999 are consistent with previous reporting periods.

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