TECHNICAL SERVICE CENTER
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1998 Status Report-Paradox Valley Seismic Network
Paradox Valley Project
Southwestern Colorado

Prepared by

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Bureau of Reclamation

WATER RESOURCES MANAGEMENT.....FOR THE FUTURE

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

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Paradox Valley Unit
Southwestern Colorado

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1.0 Introduction

This report provides a brief summary of seismological observations from the Paradox Valley Seismic Network (PVSN) for the 1998 calendar year. The objective of the seismic monitoring program is to record and evaluate seismic events in the region surrounding Paradox Valley, with a specific focus on the immediate vicinity of the injection well; provide locations of the local seismic events; determine focal mechanisms of the events when feasible; and evaluate any relationships between seismicity, geology, 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 1998 the network consisted of 15 stations with locations as indicated on Figure 1 and with characteristics as 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 an diameter of approximately 80 km.

Each station of PVSN consists of a seismometer, amplifier, voltage control oscillator (VCO), low power telemetry radio, and broadcast tower with antenna. The systems are all powered by solar-recharged batteries. Thirteen of the stations operational during 1998 were equipped with single component, vertical motion seismometers. The Davis Mesa station (PV11) was operated as a three component site which includes vertical, east-west, north-south seismometers. The seismometers at all sites are Teledyne Geotech Model S-13's, a high-quality, 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 exclude some long-period noise. The characteristics of the field instrumentation are summarized in Table 1 and shown schematically in Figure 2.

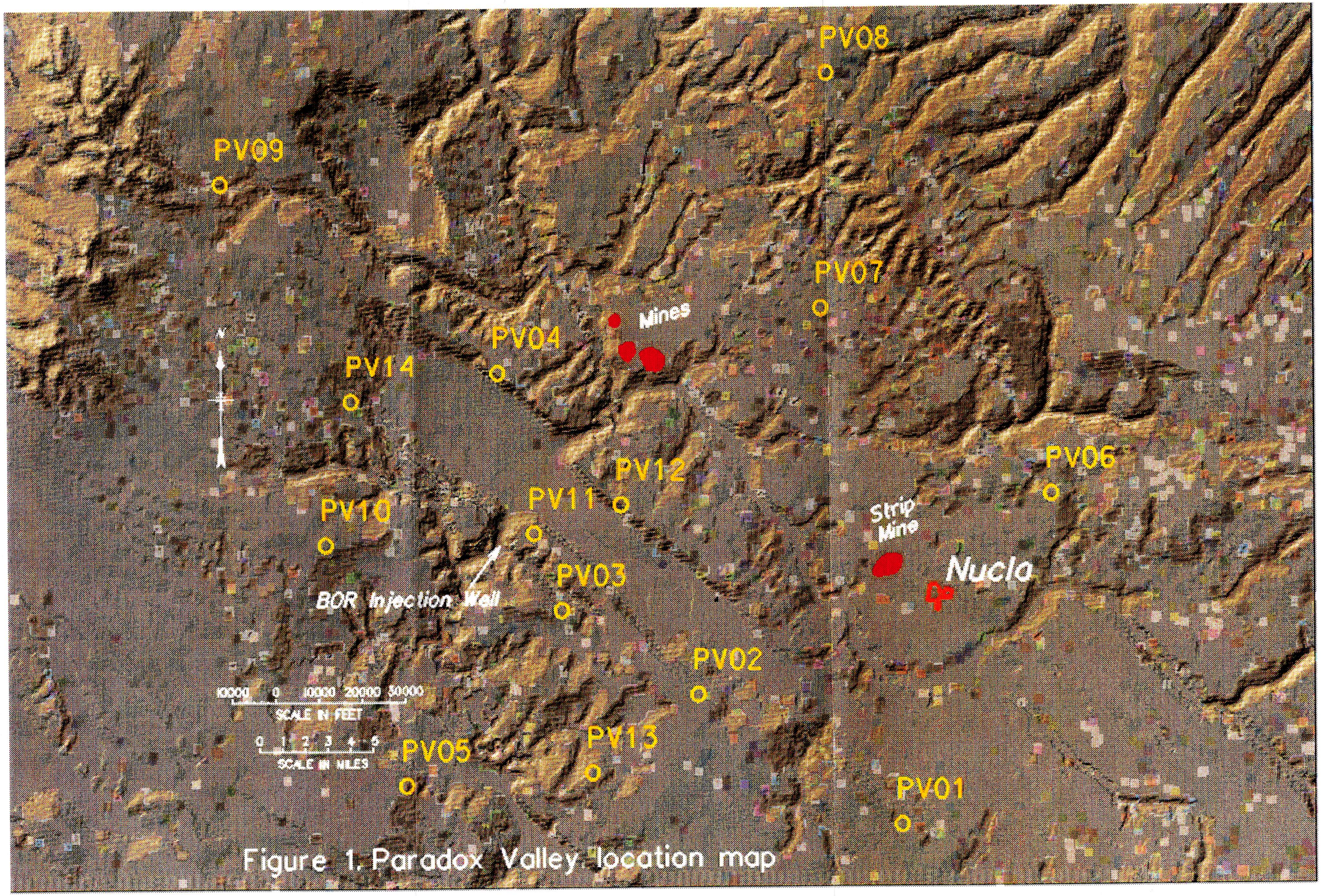


Figure 1. Paradox Valley location map

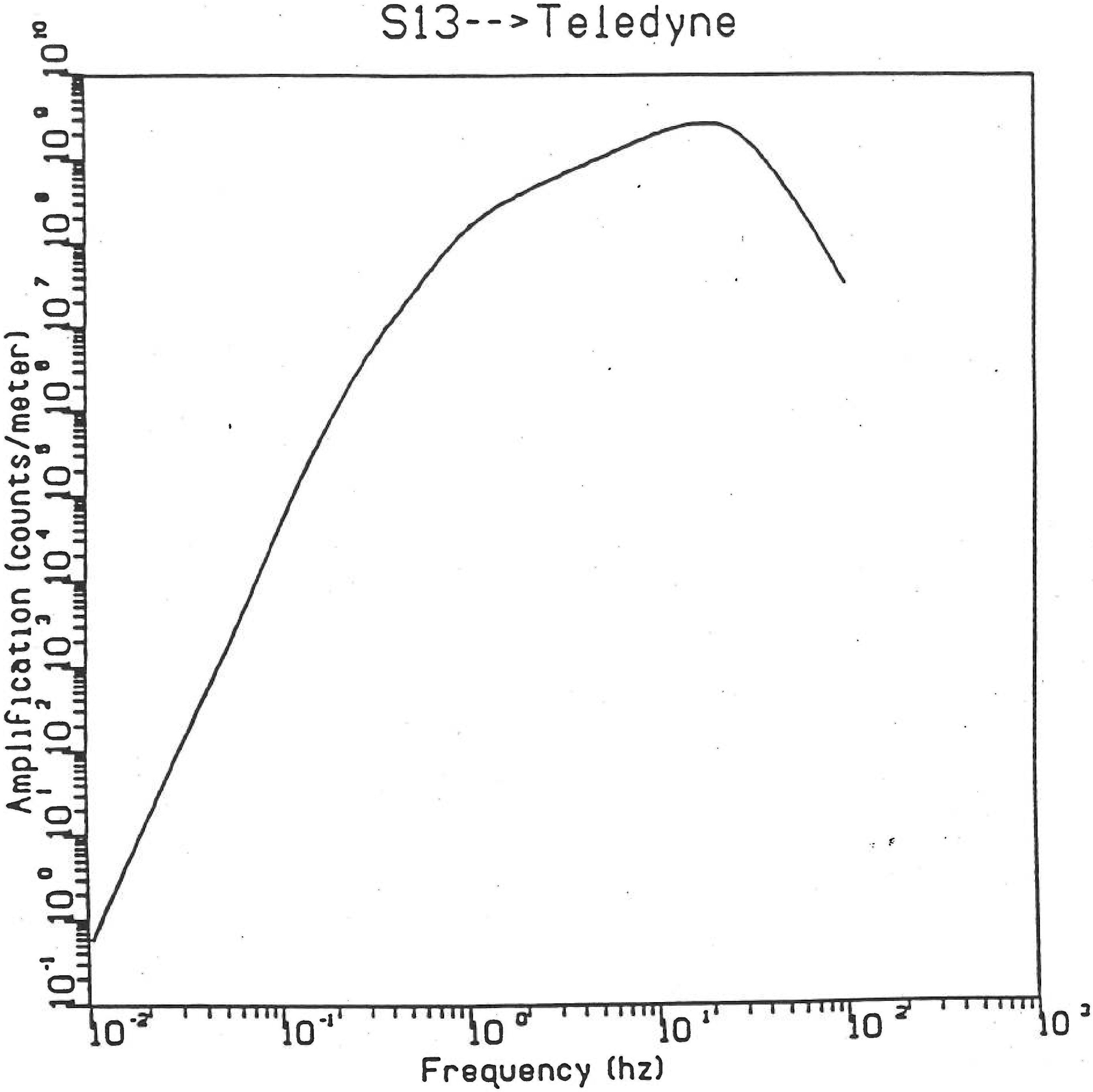


Figure 2. Typical response for PVSN station with a vertical-component Teledyne Geotech S13 seismometer and associated electronics and digital recording. Nominal gain of 48 db for curve displayed, Teledyne Geotech model 42.5 amplifier/VCO and model 4612 discriminator. Damping value of 0.71 of critical.

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	78 / 0.2-25
PV11E	Davis Mesa	38.30	108.87	1881	12/89	78 / 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

From each seismometer site, a continuous analog signal is radio telemetered to Montrose, 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 manually.

During 1998, the network operated satisfactorily. Minor, but not unexpected data outages occurred due to lightning strikes and telephone circuit problems. The network was online, capable of detecting and locating earthquakes in the Paradox Valley, for more than 90% of the year.

3.0 Analysis

In general, the size of an event can be computed using one of a variety of calculation methods. In most cases magnitude calculations for local events follow a general procedure that has been calibrated for local conditions. The magnitudes of the events recorded by the PVSN were 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 a broader area of events covering western Colorado. The relationship yields reasonable results for events with local magnitudes between 0 and 2.0, where the local magnitudes were 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 (**M**, a magnitude scale assumed equivalent to local magnitude in this range) 2.0, the duration-based magnitudes have not been adequately tested to assure accuracy. Additional studies regarding magnitude determination 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 are manually picked by experienced seismologists on a large format computer screen 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 station at Davis Mesa (PV11) and for the closest single-component station to the injection well at Wild Steer (PV3) (see Figure

1).

Initial 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 Paradox Valley area as sources for refraction surveys. The S-wave velocities in this model were computed from the P-wave velocities assuming Poisson's ratio of 0.25 (equivalent to a Vp/Vs of 1.732). Additional studies to increase event location accuracy are currently being conducted. The approache uses seismic tomography to develop a more accurate, three-dimensional velocity model.

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.

In addition to the earthquake signals of interest, 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 sources of noise requires experience and consistency in processing. Based upon 10 years of examining waveform data from the PVSN plus the well-defined 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.

4.0 Observations

During 1998, 1165 earthquakes were located within 7 km of the Paradox Valley injection well. Based upon previous observations (EnviroCorp, 1995; Ake and others, 1996), we inferred these events to be associated with the injection process. The largest events recorded in 1998 were two $\mathbf{M_D}$ 2.8 events that occurred on April 10 and May 8. The earthquakes located near the injection well during 1998 are shown in plan view on Figure 3. These events range in magnitude from -.5 to 2.8. The error in locating events decreases with increasing magnitude since identifying the P and S-phases in the smaller events is compromised by the weaker signal-to-noise ratio. As a result, most of our conclusions for this data set are based on the larger events, those with $\mathbf{M_D} > 0.8$.

Note in Figure 3 that the spatial distribution of the seismicity recorded in 1998 is contained within an elongated envelope with the long axis of the envelope running approximately EW and extending about 3.5 km from the injection well. This elongated shape is similar to the spatial distribution of events observed previously. The shape suggests that the occurrence of induced earthquakes at this site (and hence fluid migration) is controlled by deterministic crustal attributes (e.g., stress, preexisting planes or zones of weakness, etc.) and is not entirely a random process.

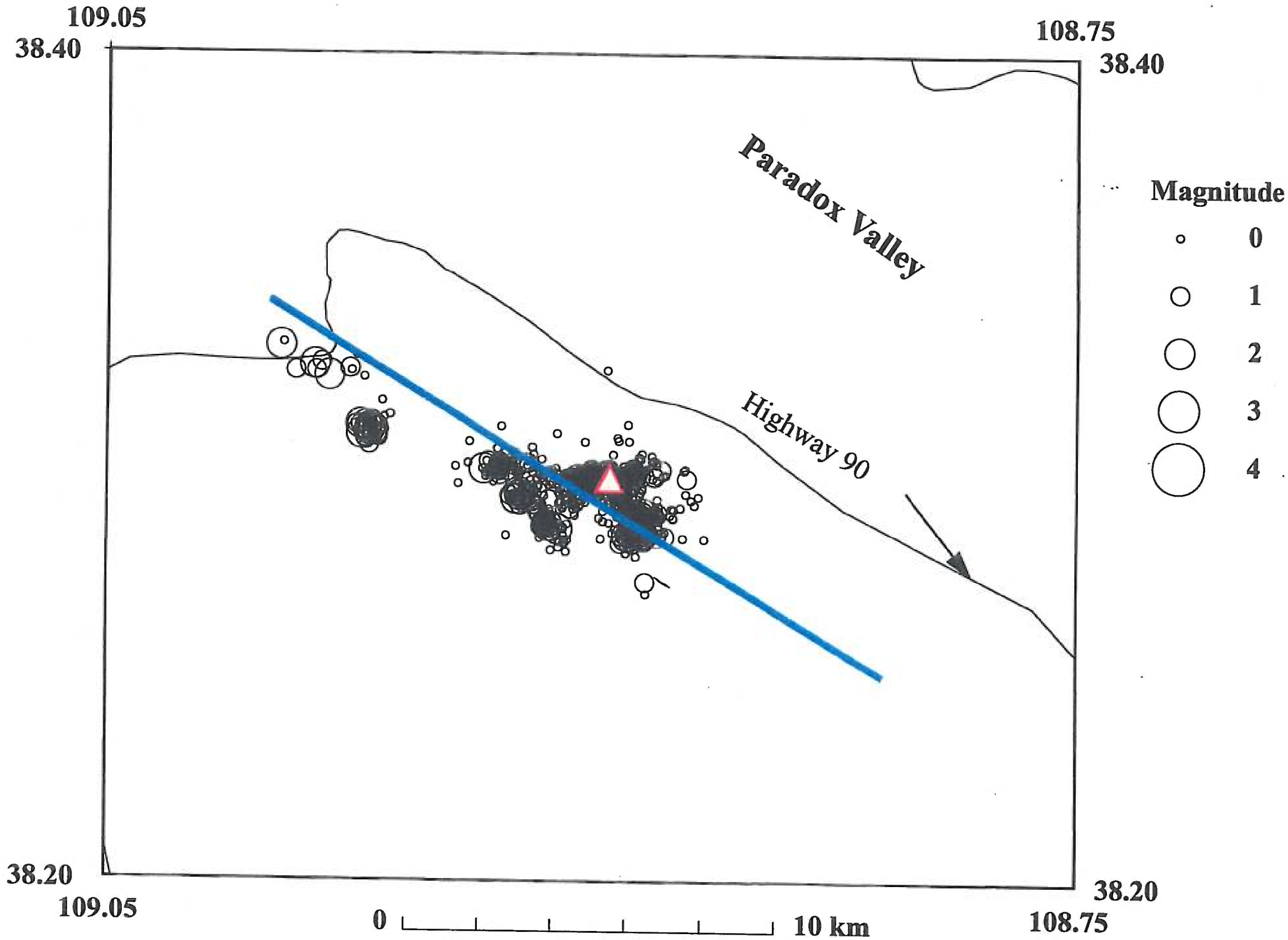


Figure 3. Seismicity located during 1998 by the PVSN, 1165 events plotted. Location of injection well shown by solid triangle. Trace of subsurface fault shown by solid blue line.

During 1998 a second group of events were located outside the primary envelope, approximately 6 km northwest of the injection well. These events are the most distant observed to date. Figure 4 summarizes the depth distribution of earthquakes with M_D >0.8 located during 1998. 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 1998 near the brine injection well. Figure 5 suggests that, as operated during 1998, 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 0.87. This value is consistent with other observations of earthquake recurrence within the seismically inactive Colorado Plateau (Wong and others, 1996; LaForge, 1996). This similarity in b-values suggests the occurrence of earthquakes at the Paradox site to be due to the release of existing tectonic stress rather than from widespread hydraulic fracture processes.

The number of earthquakes observed per day during 1998 is illustrated on Figure 6. The average number of events per day recorded by the network was 3.1 with a large variability (0 to 18 events per day with 72 days having no events and approximately 15 days having 10 events or more). Daily average injection pressure and injection rate for the brine injection well are plotted on Figure 7 and 8. Injection was halted entirely for 13 days for routine maintenance during 1998 (days 137-150, indicated by a solid bar at the bottom of Figure 6). When comparing Figures 6 and 7, the impact of cessation of injection on earthquake creation is striking. After injection was halted, nearly a hundred days passed before the earthquake frequency began to return to levels consistent with those observed prior to the shutdown period. This is similar to behavior observed during 1997.

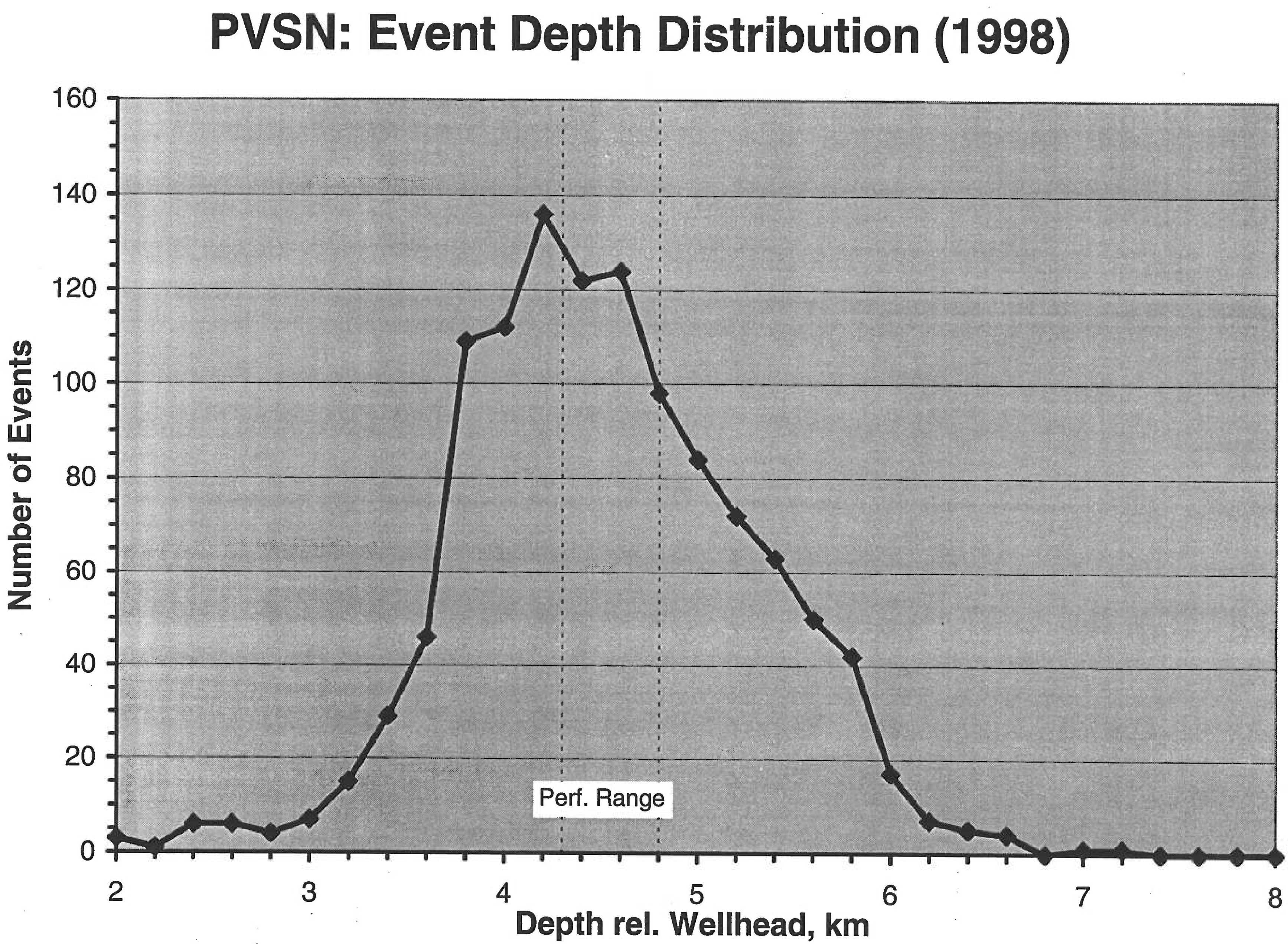

PVSN: Event Depth Distribution (1998)
Number of Events
160
140
120
100
80
60
40
20
0
Perf. Range
2
3
4
5
6
7
8
Depth rel. Wellhead, km

Figure 4

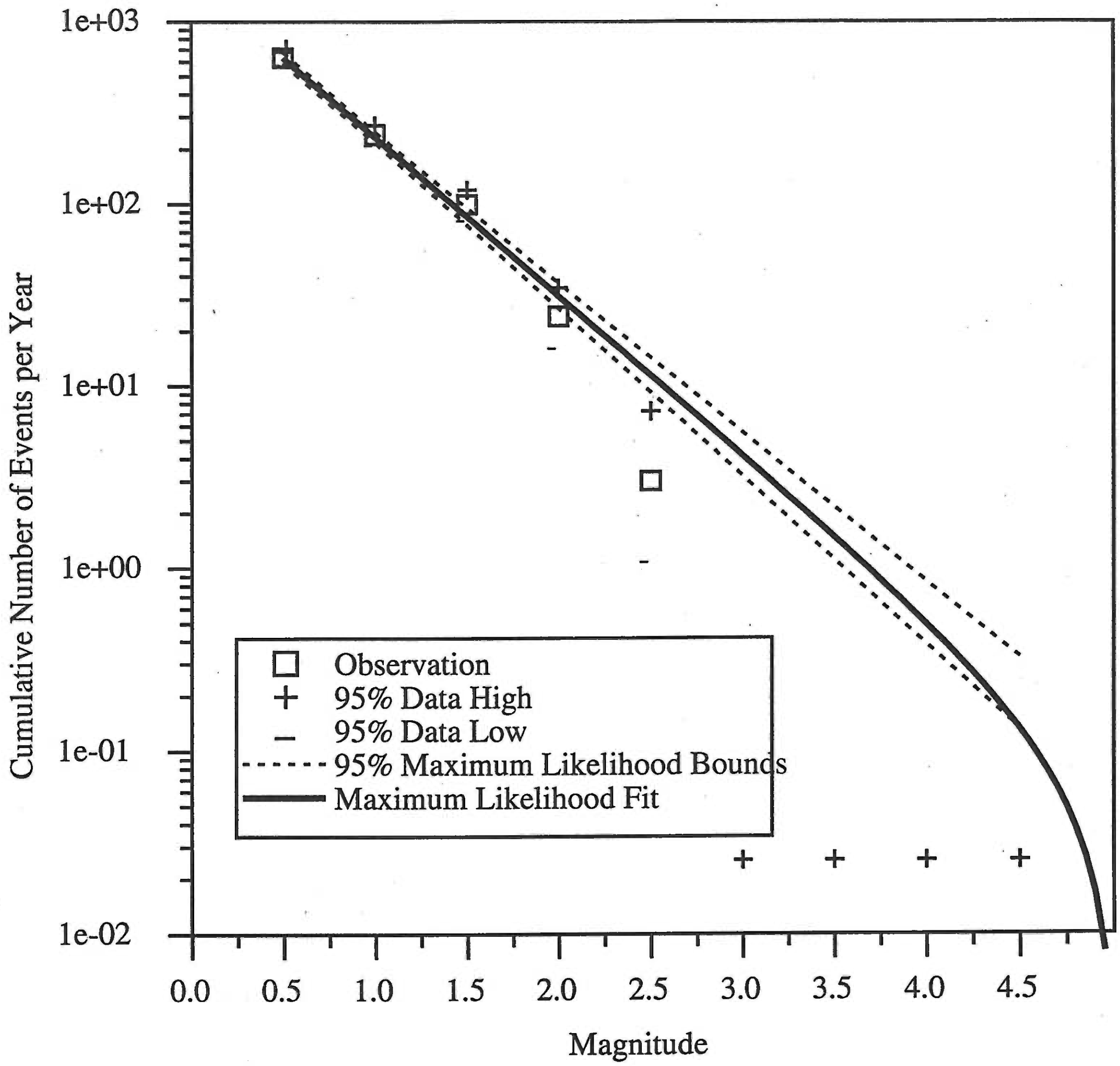
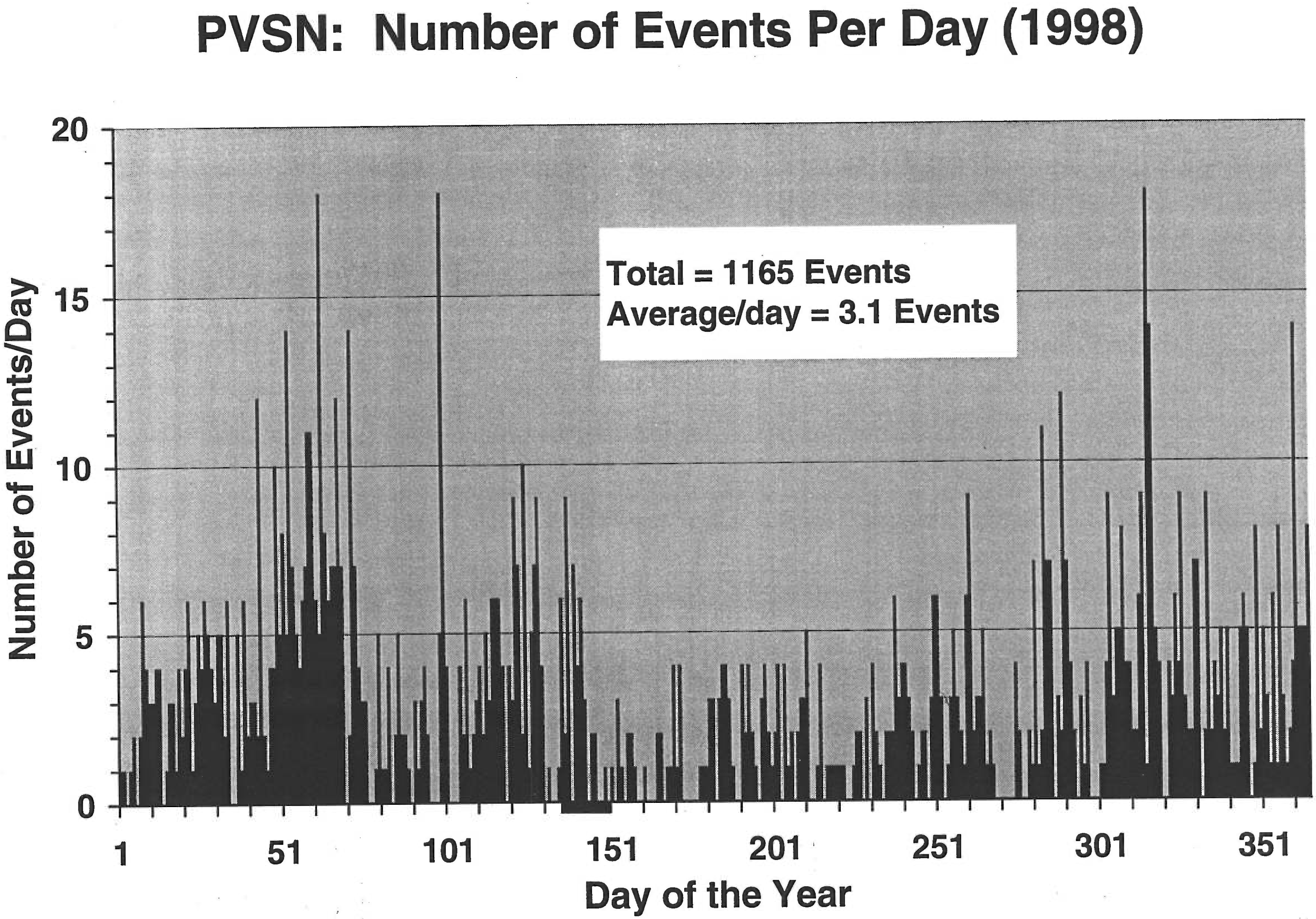


Figure 5. Cumulative recurrence curve for PVSN earthquakes located near the brine injection well during 1998. Maximum likelihood fit and 95% confidence bounds indicated.



PVSN: Number of Events Per Day (1998)
Total = 1165 Events
Average/day = 3.1 Events
Number of Events/Day
20
15
10
5
0
1
51
101
151
201
251
301
351
Day of the Year

Figure 6

PVSN: Average Daily Injection Rate (1998)

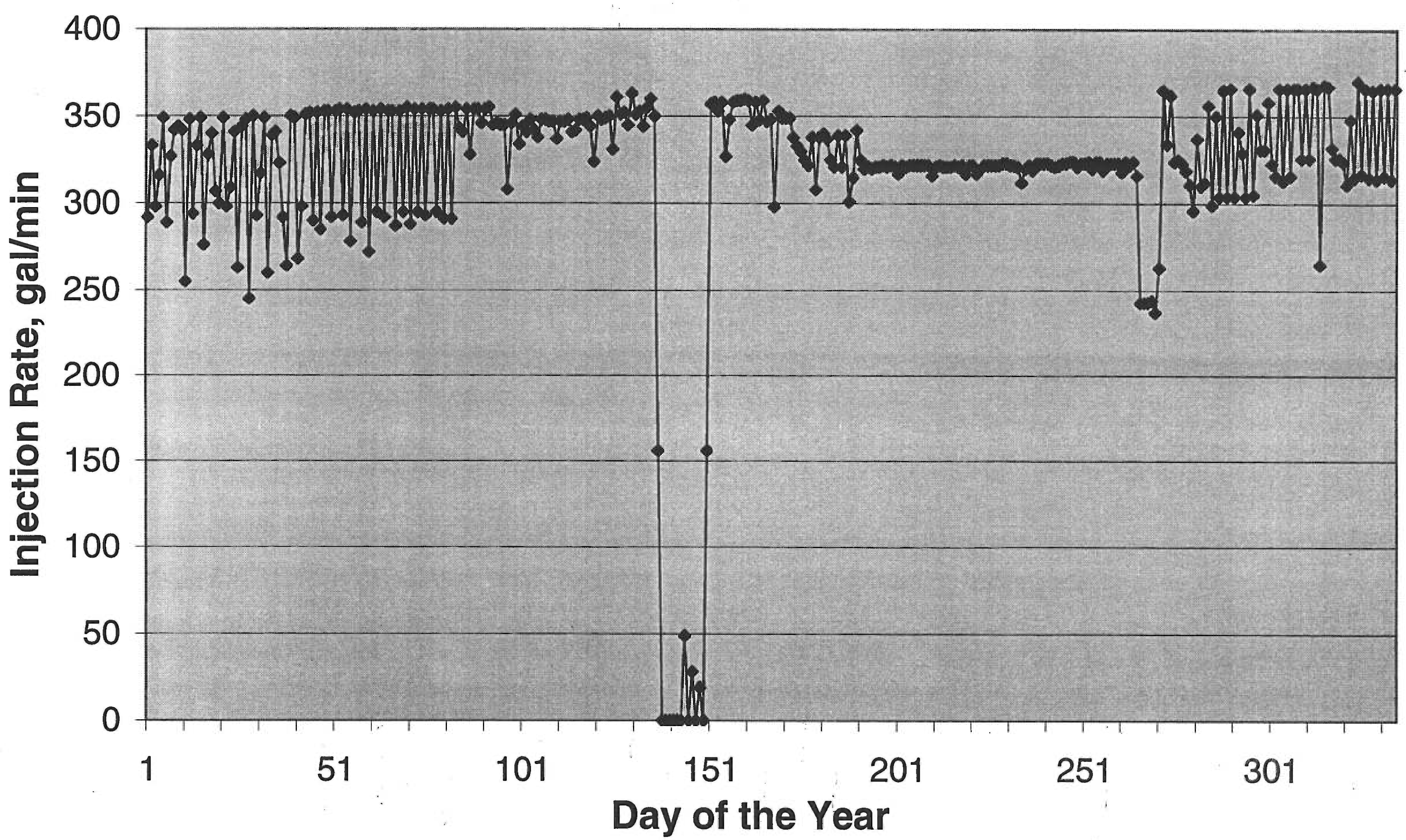
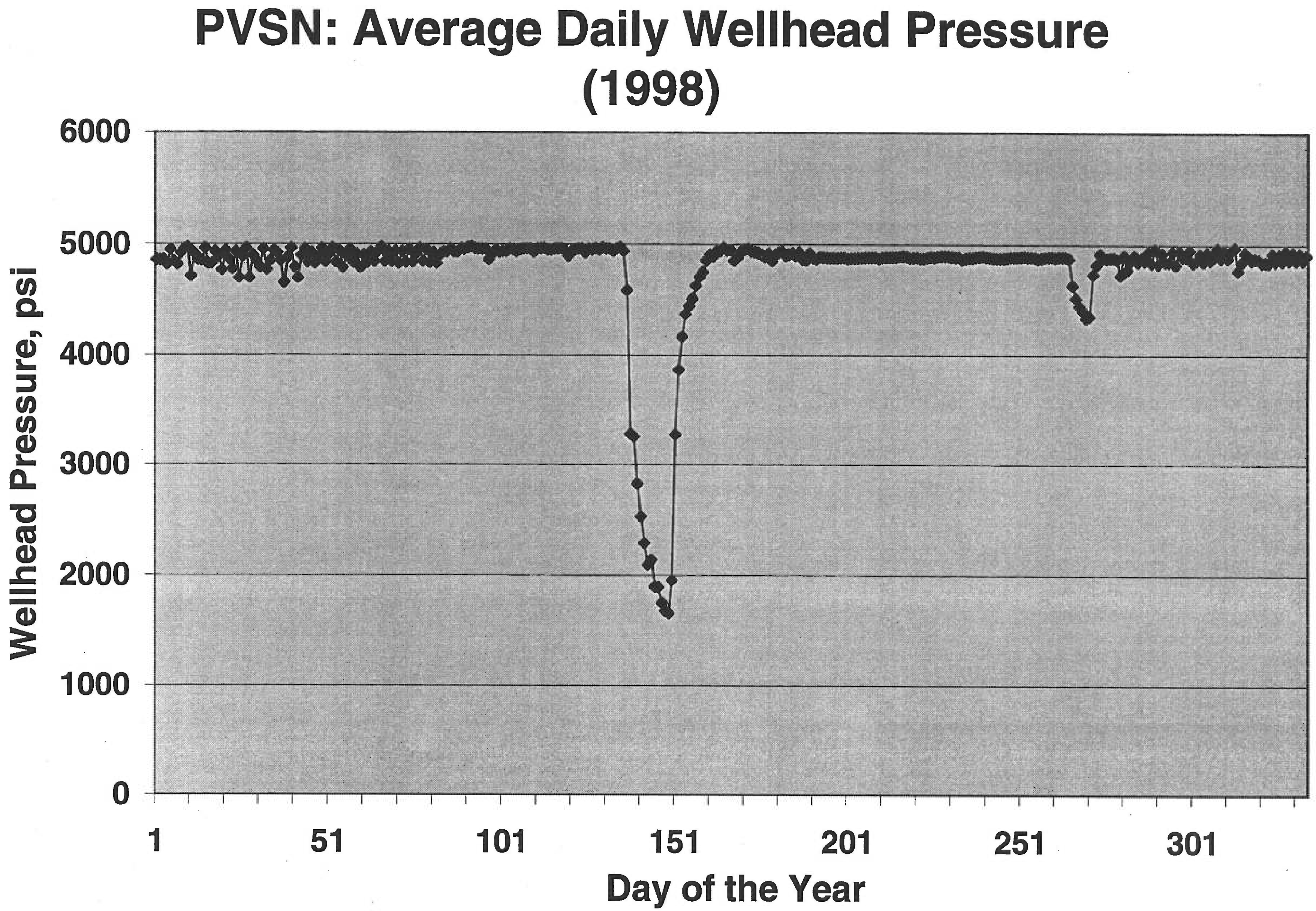


Figure 7



PVSN: Average Daily Wellhead Pressure
(1998)
Wellhead Pressure, psi
6000
5000
4000
3000
2000
1000
0
1
51
101
151
201
251
301
Day of the Year

Figure 8

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 1998 earthquakes with strong first motions and occurring over a range of locations, 79 focal mechanisms were constructed. As with earlier observation periods, the results are dominated by strike-slip faulting on west-northwest trending, steeply dipping fault planes. An example of a focal mechanism plot is shown in Figure 9. A Rose diagram of the fault plane angles of the 79 focal mechanisms is shown on Figure 10. The Tension (or T) axes for these events is a consistent east-northeast direction. No difference in spatial distribution of focal mechanism types was evident within the 1998 data set.

5.0 Conclusions

The general objective of recording and analyzing seismicity in the Paradox Valley region was successfully carried out during 1998. 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, significant and sustained reduction in frequency of occurrence of observed earthquakes following 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 1998 are consistent with previous reporting periods.

6.0 References

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A 9811211712 41.43 38N1720 108W5298   5.93   1.8 13/014  64   1  .04    .2AA P4
Gradient Velocity Model:   V0 = 5.80 km/s, DV = 0.05 km/s/km
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Lower hemisphere  equal area
Strike=191  dip=75
Strike=100  dip=85
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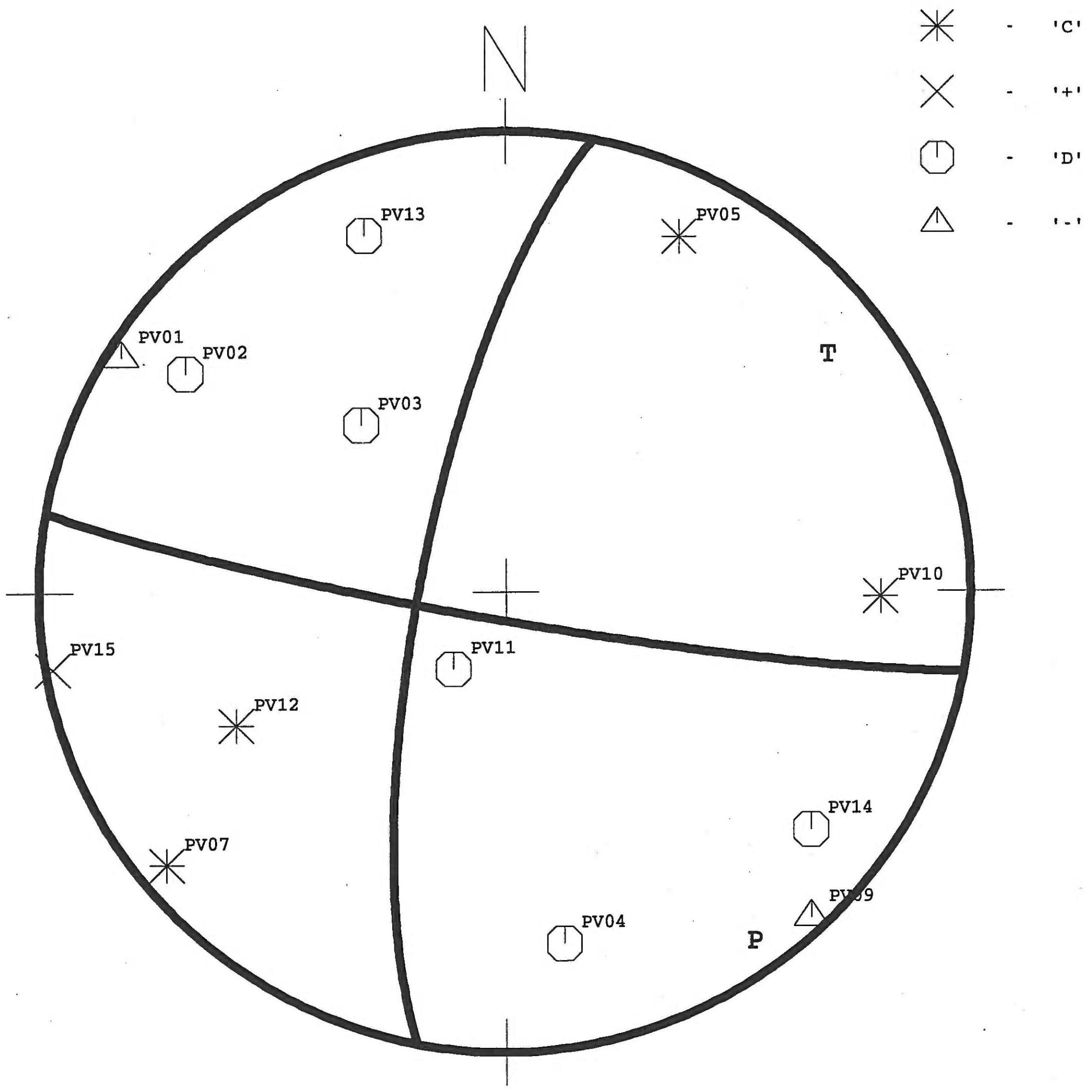

Figure 9. Example focal mechanism from 1998 data set. Earthquake located near injection well, depth of ~6 km, M_D 1.8. Strike-slip sense of motion on steeply dipping planes. Approximately +/- 10 degrees of uncertainty in strike permissible.

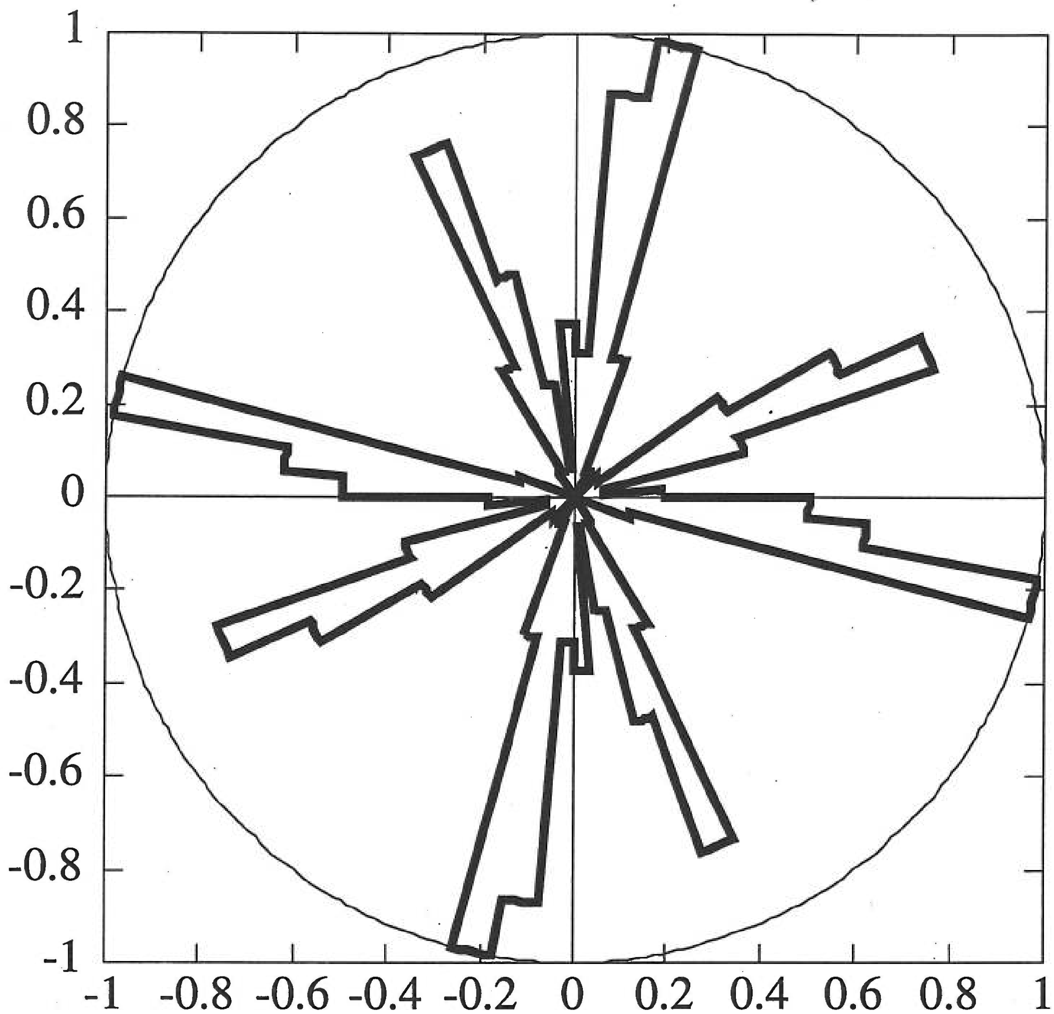

Figure 10. Rose diagram of fault plane directions from 79 focal mechanisms obtained during 1998 from the PVSN, southwestern Colorado. The strike of the Paradox Valley is approximately N 55 W.