RECLAMATION

Managing Water in the West

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Overview of PVU-Induced Seismicity from 1996 to 2009 and Implications for Future Injection Operations

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
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Bureau of Reclamation
Technical Service Center
Seismotectonics and Geophysics Group

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Overview of PVU-Induced Seismicity from 1996 to 2009 and Implications for Future Injection Operations

1.0 Introduction

Induced seismicity during the current year (2009) has been characterized by a marked increase in the number of events with magnitude ≥ 2.5 (**M** 2.5+), compared to the previous eight years (2001-2008). This magnitude threshold is significant because it represents the approximate threshold for human detection in the nearby communities of Paradox and Bedrock. From January to November, 2009, six induced **M** 2.5+ events have occurred, compared to four such events from 2001 through 2008 (an average of only 0.5 events/year). While the total number of **M** 2.5+ events remains small, their current rate of occurrence has been exceeded in only one other year since PVU injection operations began - seven such events were recorded during 1999, prior to the decrease in injection flow rate by one-third in mid-2000. In contrast to the increased rate of **M** 2.5+ events, the current overall rate of induced seismicity remains relatively low compared to historic rates - only 79 induced events with magnitude ≥ 0.5 were recorded from January through November, 2009, compared to 658 such events recorded in 1999. The recent increase in the rate of production of larger-magnitude events, as well as the relatively low rate of production observed for smaller-magnitude events, has initiated a re-examination of the seismicity induced by PVU continuous injection operations. The immediate goal is to obtain a better understanding of how the induced seismicity has changed over time and how these changes may be related to injection operations.

2.0 Induced Seismicity During Continuous Injection Operations, 1996-2009

2.1 Characterizing the Induced Seismicity

We have used a simple approach to characterize the PVU-induced seismicity, by looking for broad trends in the historic seismicity data. The earthquake data were plotted in several ways to reveal any readily-apparent, large-scale trends. We begin with a space-time plot of induced seismicity recorded since the start of continuous injection operations in July, 1996. Figure 1 shows induced earthquakes with a duration magnitude of 0.5 or greater occurring within an epicentral distance of 9 km from the injection wellhead, plotted as a function of date and radial distance from the well. We use this plot to examine large-scale variations in seismicity over time and epicentral distance from the well. Each circle represents a single earthquake, with the width of the circle scaled by the earthquake's magnitude. Earthquakes locating within approximately 4 km of the injection well are in the primary zone of induced seismicity immediately surrounding the well ("near-well" events), while those locating farther than about 5 km are in the secondary zone of induced seismicity northwest of the injection well ("NW cluster" events). (See the map in Figure 3 for the earthquake locations.)

The data in Figure 1 indicate that the near-well seismicity changed markedly during mid to late 2000. In the early period, from late 1996 to 2000, the seismicity rate was much higher than in the later period (2001 to the present). Also, in the early period, induced earthquakes occurred in the near-well region at all distances from the injection well out to a radial distance of approximately 4 km. In contrast, the near-well earthquakes in the later period have tended to occur either within

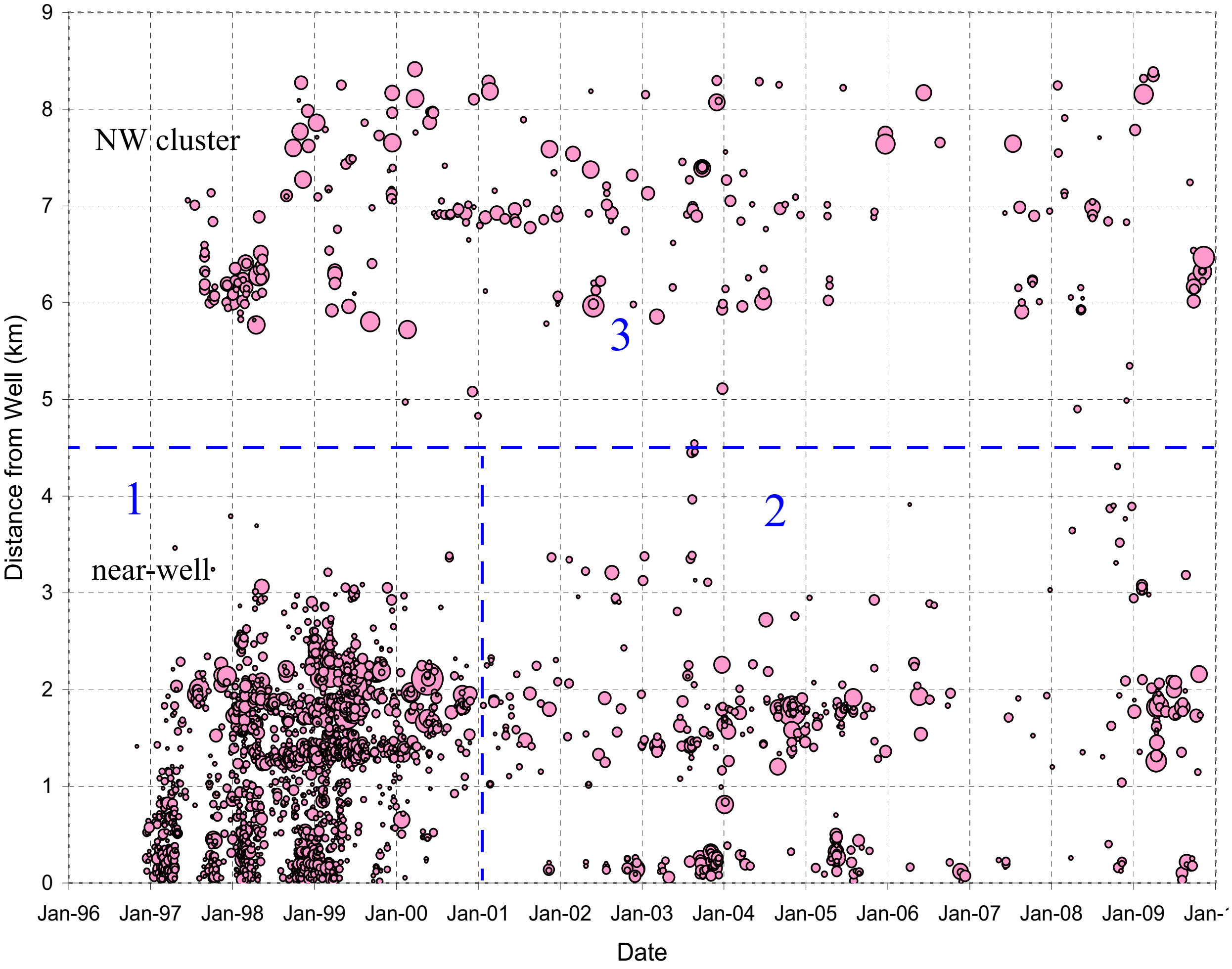

FIGURE 1: Scatter plot of induced earthquakes with $\text{magnitude} \geq 0.5$, plotted as a function of date and distance from the injection well. Each circle represents a single earthquake, with the width of the circle scaled by the event magnitude.The dashed blue lines and numbers (1 to 3) indicate the division of the seismic data into three sets, as discussed in the text.

about 400 m of the well, or greater than 1 km from the well. With few exceptions, there has been a distinct, persistent aseismic gap between approximately 400 m and 1100 m from the injection well since about mid-2000. Also, a distinct concentration of near-well events during this later period occurs in a band from about 1.1 km to 2.3 km from the injection well.

A third characteristic that distinguishes the early and later periods of near-well seismicity is that the number of smaller-magnitude events as a fraction of the total number of induced events was greater in the early period in comparison to the later period. Equivalently, this can be expressed as the ratio of small-to-large magnitude events as a function of time. Although this characteristic can be seen somewhat in the space-time plot of Figure 1, it is displayed more clearly in the magnitude-time plot presented in Figure 2. The lower plot in this figure shows the near-well earthquake data (events occurring within 4 km of the injection well) plotted as a function of date and magnitude. The area of each circle in the plot is proportional to the total number of events for that quarter of the year that fall within the given magnitude range. Hence, the relative number of smaller- and larger-magnitude earthquakes can be evaluated for any time period based on the relative sizes

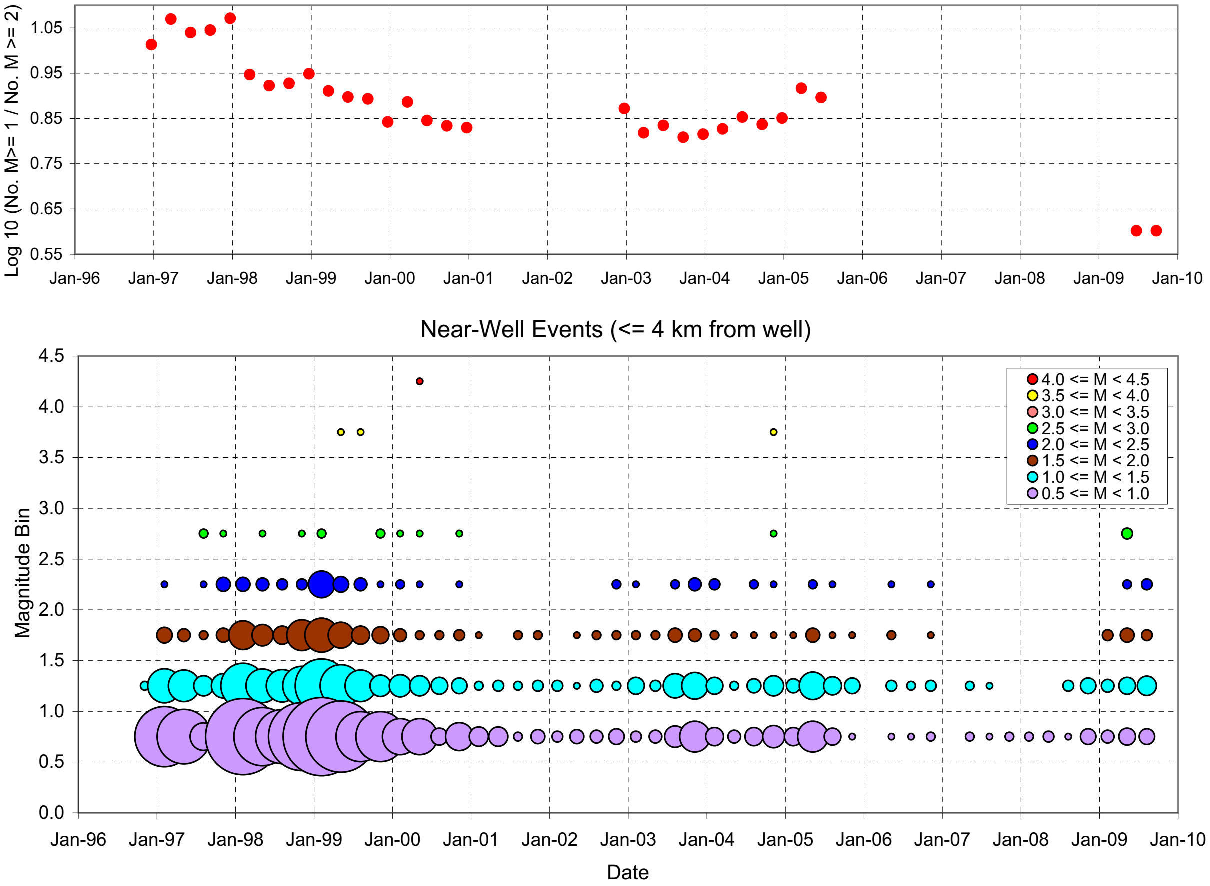

FIGURE 2: Occurrence of induced earthquakes in the near-well region (within 4 km of the injection well), plotted as a function of date and event magnitude (lower plot). The area of each circle is scaled by the number of earthquakes occurring in that quarter-year and magnitude range. The upper plot shows a measure of the ratio of smaller- to larger-magnitude events, computed for those time periods for which sufficient data are available. Each data point in the upper plot was computed as the log (base 10) of the ratio of the number of **M** 1.0+ events to the number of **M** 2.0+ events, for data within running time windows of up to 2 years.

of the circles near the bottom of the plot (representing the smaller earthquakes) to those closer to the top of the plot (representing the larger earthquakes). This plot suggests that the greatest ratio of smaller- to larger-magnitude events occurred in the early period prior to the end of 1999.

To clarify the trend in relative magnitudes over time, we computed a measure of the ratio of smaller- to larger-magnitude events as a function of time. We show this measure in the upper plot of Figure 2. Higher values in this upper plot indicate relatively higher ratios of smaller- to larger-magnitude events. No ratios are indicated for some of the time periods shown because of the lack of sufficient data (i.e., the seismicity rate is too low to compute a reliable ratio). This upper plot indicates that the ratio of smaller- to larger-magnitude events was greatest prior to 1998. The ratio gradually declines during the rest of the early period, from 1998 through 2000. The ratio maintains this lower level in the later period, at least from 2003 to mid-2005 (a time period for which we have sufficient data to compute reliable ratios). The limited data we have for the most recent years indicate that the ratio has decreased substantially in 2009 compared to 2003-2005.

Another characteristic that distinguishes the early and later periods of near-well induced seismicity is that during the early period the spatial extent of seismicity in the near-well region was expanding. From late 1996 to about mid-1998, the seismicity was expanding rapidly away from the injection well, to a maximum radial distance of a little less than 4 km. This rapid expansion of near-well seismicity can be seen in the time-distance plot in Figure 1 (set no. 1). It is also illustrated in the map presented in Figure 3, which shows the earthquake epicenters color-coded by time period. From mid-1998 through about 2000, the near-well seismicity was continuing to expand, more slowly, mainly along previously-active fault lines and into a few new areas within this 4-km radial distance. In the later period since 2000, relatively little expansion of the near-well seismicity is apparent.

In contrast to the near-well region, the seismicity in the secondary zone of induced seismicity northwest of the injection well (NW cluster) shows no clear change in characteristics over time (Figure 1 - set no. 3). In this region, at distances from approximately 5 to 9 km from the injection well, there are no distinct variations in seismicity rate over time. (The apparent minor decrease in seismicity rate in 2006 may be an artifact of seismic monitoring due to deteriorating network conditions that persisted until mid-2007.) The significant decrease that was seen in the near-well seismicity rate in mid- to late-2000 is not seen in the seismicity rate for the NW cluster. Neither does the NW cluster exhibit any major variations in the locations of earthquakes over time. By the end of 1998, the seismicity had expanded to a distance of about 8.5 km from the well. Since that time, earthquakes have continued to occur in the NW cluster, at distances mainly between 5.5 and 8.5 km from the well. Unlike the near-well region, the ratio of smaller- to larger-magnitude earthquakes in the NW cluster also appears to have remained relatively constant with time, as seen in Figure 4. Another characteristic that distinguishes the seismicity in the NW cluster from that in the near-well region is that no earthquakes larger than **M** 2.9 have occurred in the NW cluster. In contrast, four such events have occurred in the near-well region.

The above general characterization of the induced seismicity indicates that the earthquake data should be grouped into at least three separate sets (space-time areas): ***set no. 1*** - near-well events in the early period of continuous injection (events that locate within approximately 4 km of the injection well and occurred from 1996 to 2000); ***set no. 2*** - near-well events in the later period of continuous injection (events that locate within about 4 km of the injection well and occurred from 2001 to the present); and ***set no. 3*** - events in the NW cluster (events that locate between 5 and 9 km from the well in all time periods). These three sets are labeled in Figure 1.

The three data sets exhibit significantly different seismicity trends. For example, the overall near-well seismicity rate is much lower in the later period (2001-present) than in the early period (1996-2000), but that does not necessarily indicate that the risk of producing larger-magnitude events is lower now than it was prior to 2001. Also, the relationship between injection operations and the resulting induced seismicity may be different for each data set. For example, the relationship between injection operations and induced seismicity for the near-well region appears to have changed over time. Relations determined from the early period of continuous injection (1996-2000) therefore may not be applicable to the later period (2001-present). Events in the NW cluster appear to have a different relationship to injection operations than those in the near-well region. These differences in seismicity response to injection operations between the data sets should be considered when evaluating future changes to injection operations. This topic is discussed further in Section 5.

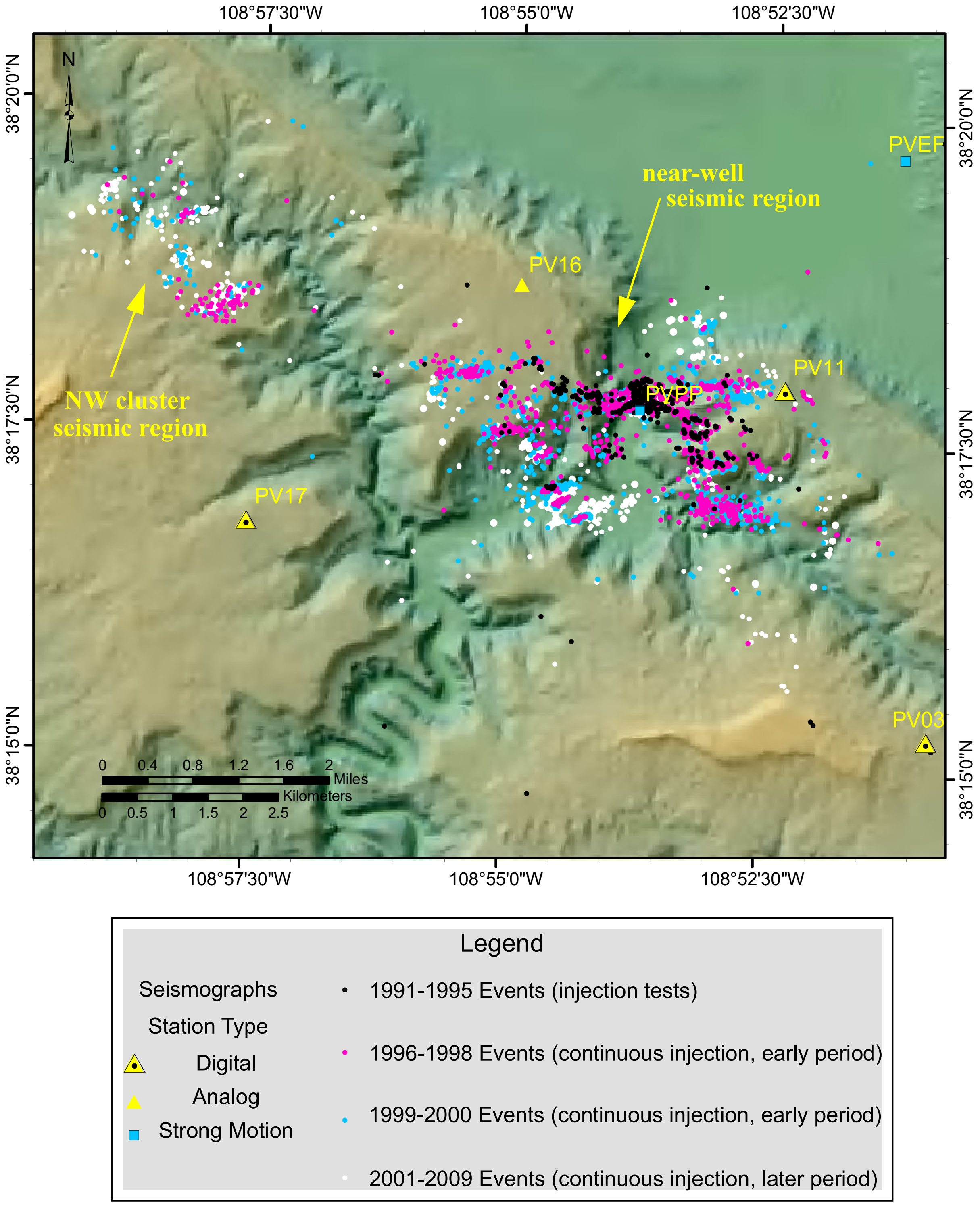

FIGURE 3: Map showing the spatial extent of induced seismicity during the injection tests (1991-1995, black dots), the early period of continuous injection (1996-1998, magenta dots, and 1999-2000, blue dots), and the later period of continuous injection (2001-2009, white dots).

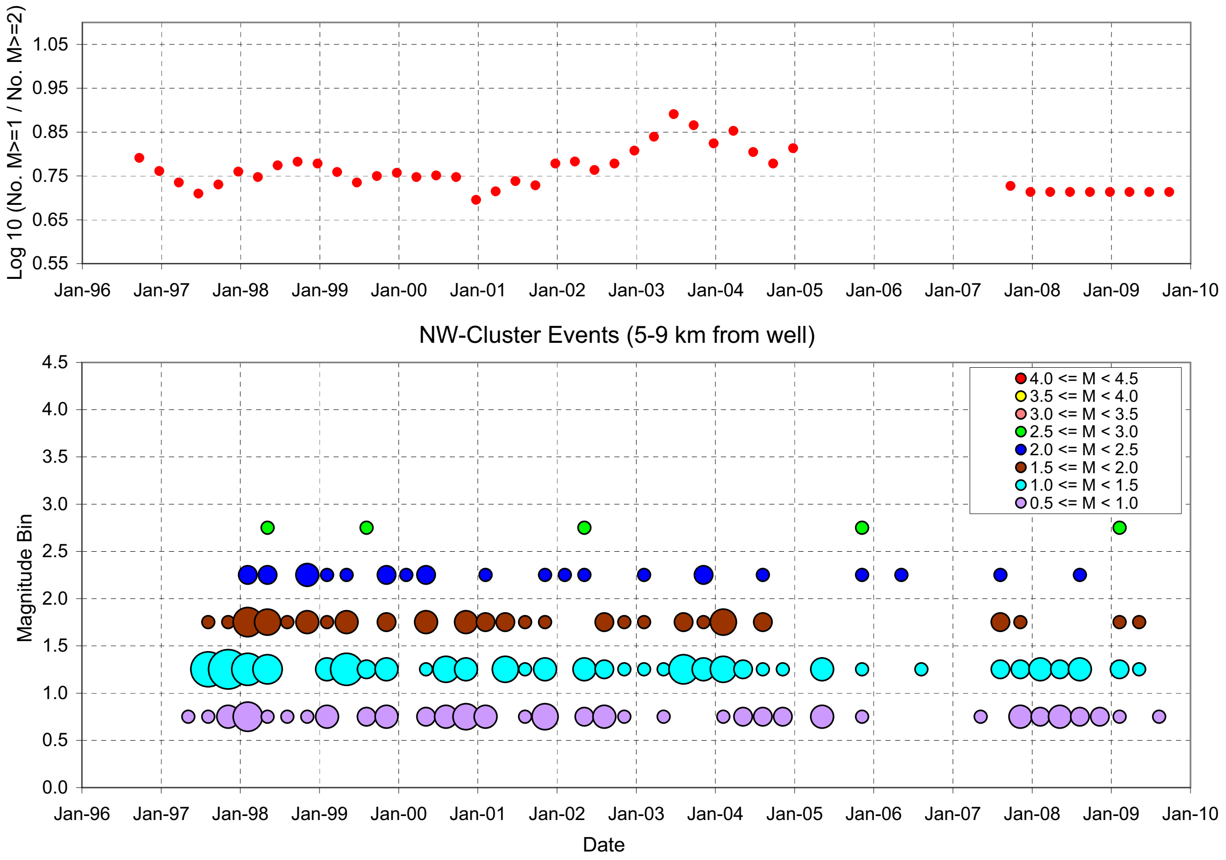

FIGURE 4: Occurrence of induced earthquakes in the NW cluster (5-9 km from the injection well), plotted as a function of date and event magnitude (lower plot). The area of each circle is scaled by the number of earthquakes occurring in that quarter-year and magnitude range. The upper plot shows a measure of the ratio of smaller- to larger-magnitude events, computed for those time periods for which sufficient data are available. Each data point in the upper plot was computed as the log (base 10) of the ratio of the number of **M** 1.0+ events to the number of **M** 2.0+ events, for data within running time windows of up to 6 years. (Longer time windows were required for the NW cluster data compared to the near-well data because of the relatively lower seismicity rate in the NW cluster.)

2.2 Patterns of Induced Seismicity Over Time

The near-well seismicity exhibits distinct increases and decreases in activity over time (Figure 2). Three periods of relative high activity are apparent: 1996-2000, 2003-2005, and mid-2008-present. These three relative high-activity periods are separated by two distinctly quieter periods that have lower seismicity rates (2001-2002 and 2006-mid-2008). Also, events with magnitudes of 2.0 or greater are largely absent during these two quieter periods. (The seismic network was experiencing poor performance during 2006 to mid-2007 due to aging equipment, and for this reason the recorded seismicity may be incomplete. However, we believe that a quiet period in the actual induced seismicity still occurred from 2006 to mid-2008 for the following two reasons. First, smaller-magnitude events (**M** 0.5 - **M** 1.5) continued to be detected at a fairly regular rate during this time period, while very few larger-magnitude events were recorded. If the decreased seismicity rate were due solely to deteriorating network performance, we would expect the opposite trend - i.e., detection of smaller-magnitude events would decline while larger-magnitude events continued to be recorded. Second, the seismic network was repaired and functioning well by mid-2007, but the seismicity rate continued to be low for another full year, until mid-2008.)

Careful examination of Figure 2 indicates that, during each of the three periods of increased near-well seismic activity, the rate of the lower-magnitude events increased first, followed by increases in the rates of larger-magnitude events. For example, the trends seen during the current period of increased near-well seismic activity are: in mid to late 2008, the rate of occurrence of events with magnitudes between 0.5 and 1.5 increased; in the first quarter of 2009, the rate of occurrence of events with magnitudes between 1.5 and 2.0 increased; and, in the second quarter of 2009, the rate of occurrence of events with magnitudes between 2.0 and 3.0 increased. Although specific details vary somewhat, detailed examination of the data reveals similar patterns for the earlier two periods of increased seismic activity. The elapsed time between the increase in the smaller-magnitude events (those with **M** 0.5 - **M** 1.5) and the subsequent increase in felt events (here defined as those with **M** 2.5+) is roughly 9 to 21 months.

Because only four induced events greater than **M** 3.0 have occurred during PVU operations, trends for earthquakes of this size are not well-defined by the current data. Some general observations can still be made from examination of Figure 2, however. The three induced events in the magnitude range **M** 3.5 - **M** 4.0 recorded to date have occurred either simultaneously with the onset of events in the **M** 2.5-**M** 3.0 range (i.e., the **M** 3.9 event in Nov., 2004), or about two years later (the two **M** 3.5 events in mid-1999). The single induced earthquake with **M** > 4.0 (in May, 2000) occurred nearly one year after the two **M** 3.5 events. In summary, events with **M** > 3.0 occurred approximately 1.5 to 2.5 years after the onset of increased seismic activity during the first two cycles of relatively high near-well seismic activity (1996-2000 and 2003-2005). (We are currently about 15 months into the third cycle of relatively high near-well seismic activity, and no event with **M** > 3.0 has occurred to date during this cycle.)

Figure 2 also shows that, during the second cycle of high near-well activity (2003-2005), a second increase in small-magnitude events (**M** 0.5 - **M** 1.5) occurred in the second quarter of 2005 and was not followed by any **M** 2.5+ event. However, beginning in November, 2005, the injection well was shut down for a period of more than 2 months due to needed equipment repairs. This extended shutdown may have disrupted the seismicity pattern seen in the 2003-2005 cycle.

No readily apparent changes in the rates of seismicity in the NW cluster have occurred (Figure 4). Events in this region generally tend to occur at approximately the same rate over time for all magnitude ranges.

3.0 Relating Seismicity Trends to Injection Operations

Given the distinct periods of relatively higher and lower near-well seismic activity discussed above, we examined several injection parameters to see whether any of those parameters exhibit similar trends. Because the migration of injectate into the surrounding sedimentary rocks is expected to follow a diffusion-type process (to first order), the pore-pressure changes introduced near the injection well are expected to take a significant amount of time to propagate out to the seismically-active areas, especially for the later period (2001-2009) when most of the seismicity occurs at distances greater than 1 km from the injection well. We therefore decided to look for long-term trends in injection parameters. We did this by either summing or averaging each injection parameter of interest over varying lengths of time, ranging from 6 months to 30 months.

The injection parameters investigated include injectate volume, injection flow rate, downhole pressure, and percent of days injecting. For each parameter, we present the daily values and values computed for longer periods of time (Figures 5 to 8). For instance, Figure 5 shows the volume of fluid injected into the well over time. The upper plot in Figure 5 shows the number of gallons injected during each day from July, 1996 through October, 2009. The lower plot shows the total volume (in millions of gallons) injected during time periods of 6, 12, 18, 24, and 30 months. The curves are plotted as one-sided running sums. For example, the data point on the 6-month curve at a given date represents the total volume injected for the 6-month time period starting 6 months prior to that date. The curves for longer time periods were constructed in a similar way. Similar plots were constructed for the flow rate and downhole pressure data (Figures 6 and 7). Because of the nature of these parameters, average values were computed for each time period rather than summed values. Like the volume data, the curves are one-sided, with the value at a given date representing the average of the values for the specified time period preceding that date. Figure 8 shows data representing the injection status as a function of time. The upper plot gives the daily injection status as either “injecting” (defined as a daily volume injected of 1000 gallons or more) or “not injecting”. The lower plot indicates the percent of days for which the status was classified as “injecting” for each specified time period (again computed as one-sided running values ending on the date plotted).

Of the four injection parameters investigated, the downhole pressure exhibits the best correlation with the occurrence of near-well seismicity over time. Short-term and long-term averaged downhole pressure data are compared to the temporal pattern of near-well seismicity in Figure 9. The current period of increased near-well seismic activity (mid-2008 to the present) and the last period of increased near-well seismic activity (2003 to 2005) correlate with highs in the 30-month average downhole pressure data (red curve in Figure 9). The intervening period of low near-well seismic activity (2006 to mid-2008) correlates with relatively low 30-month average downhole pressures. The low long-term average downhole pressures from 2006 to mid-2008 appear to have been caused by an unusually large number of injection well shut-down days from early 2004 to mid-2006, including a shut-down of more than 2 months beginning in November, 2005. Although the daily average downhole pressures and 6-month average pressures (dashed gray and solid blue curves in Figure 9) had both recovered by late 2006, the 30-month average pressure curve (and near-well seismic activity) did not recover until mid-2008.

In contrast to the later period of continuous injection just described, the majority of the near-well seismicity in the early period of continuous injection, from 1996 through 2000, correlates with relatively short-term pressure changes, such as the 6-month curve shown in Figure 9. However, the largest-magnitude events during this early period, the two **M** 3.5 events in mid-1999 and the **M** 4.3 event in mid-2000, occurred after the 6-month average pressure curve and smaller-magnitude seismicity rate had both started to decline. The occurrence of these largest earthquakes correlates better with the longer (30-month) average pressures than the shorter-term average pressures.

Because of the greater distance to the NW cluster compared to the near-well region, we would expect that the time lag between changes in injection operations and changes in induced seismicity in the NW cluster to be considerably longer than that for the near-well region. However, it is beyond the scope of the present analysis to determine a numerical estimate of the time lag. Quali-

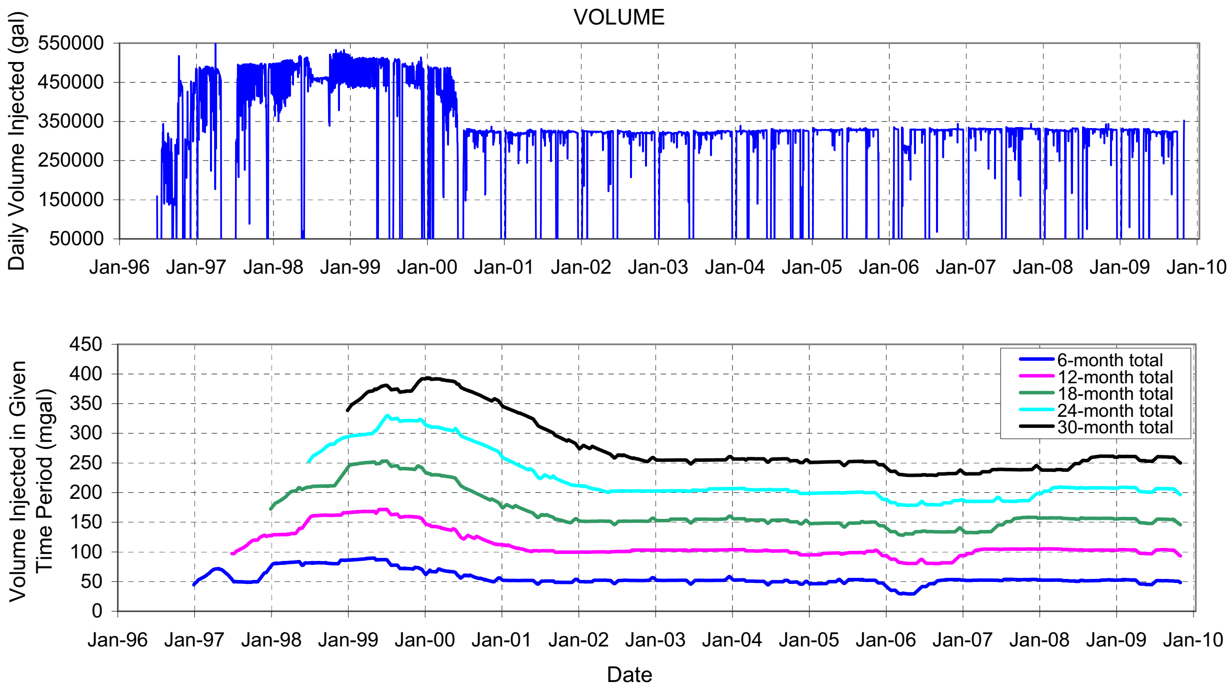

FIGURE 5: Daily injectate fluid volume (top) and total volumes injected for 6-month to 30-month time intervals (bottom).

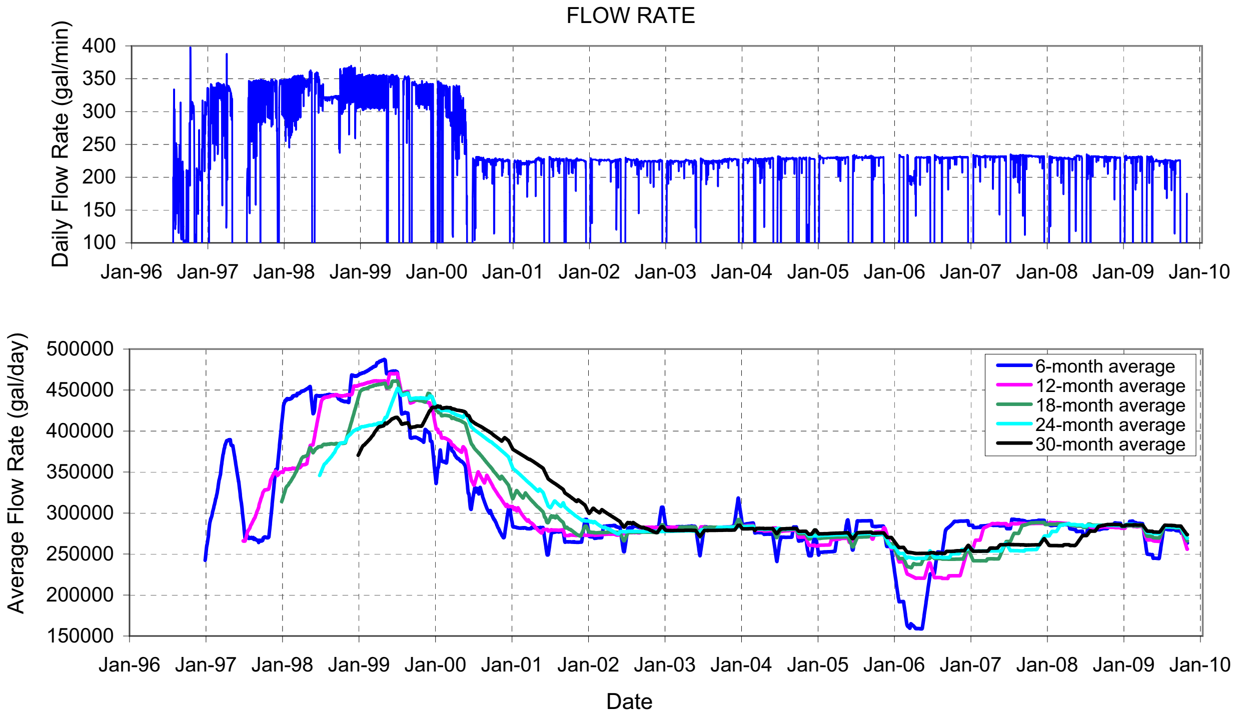

FIGURE 6: Average daily flow rate (top) and average flow rates for 6-month to 30-month time intervals (bottom).

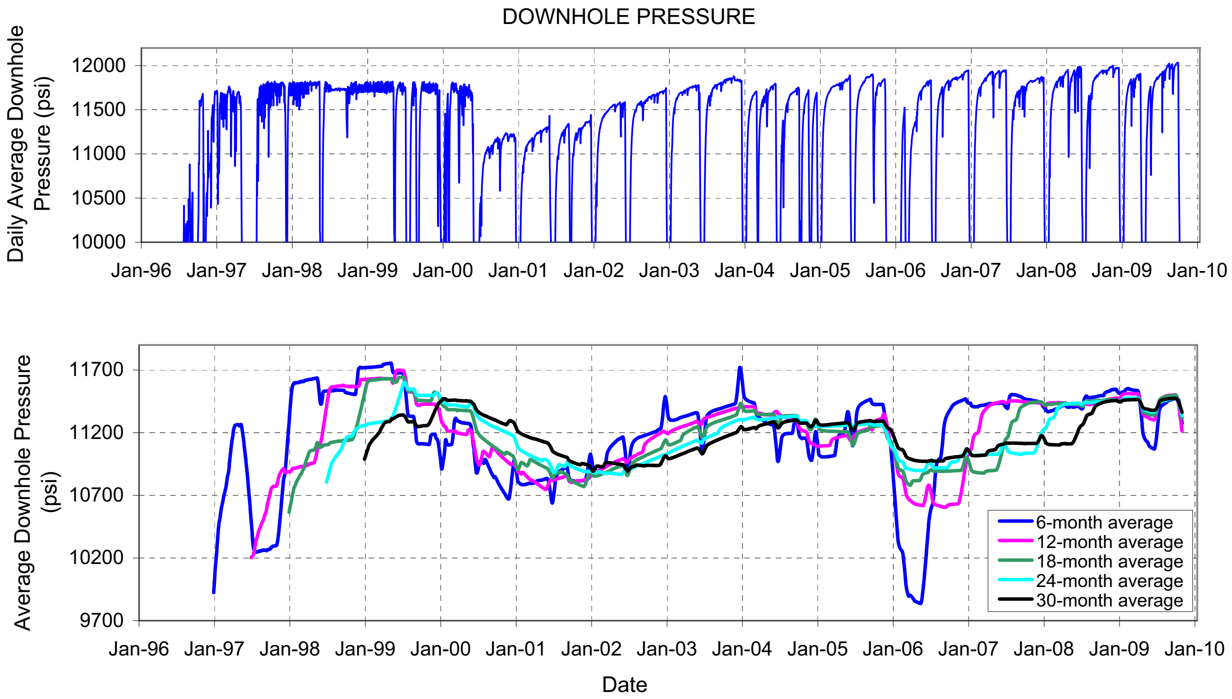

FIGURE 7: Average daily downhole pressure (top) and average downhole pressures for 6-month to 30-month time intervals (bottom).

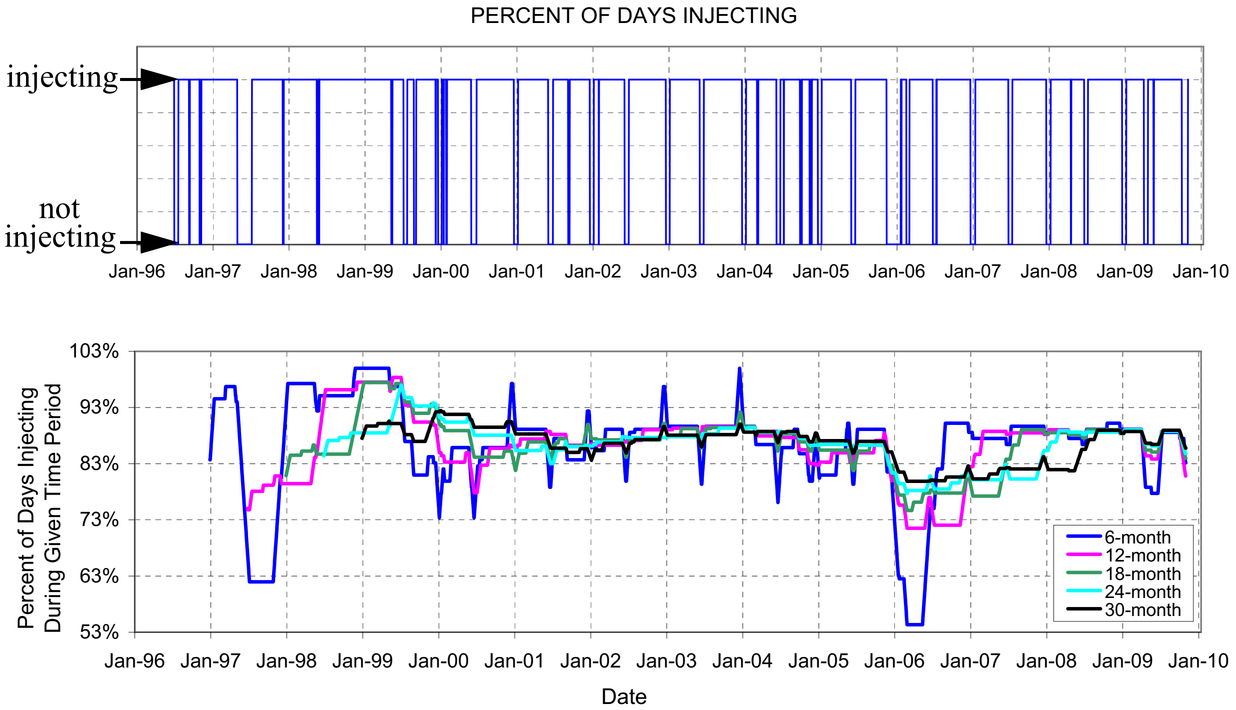

FIGURE 8: Daily injection status (top) and percent of days injecting for 6-month to 30-month time intervals (bottom). The daily injection status is defined as “injecting” if the daily flow volume is 1000 gallons or greater.

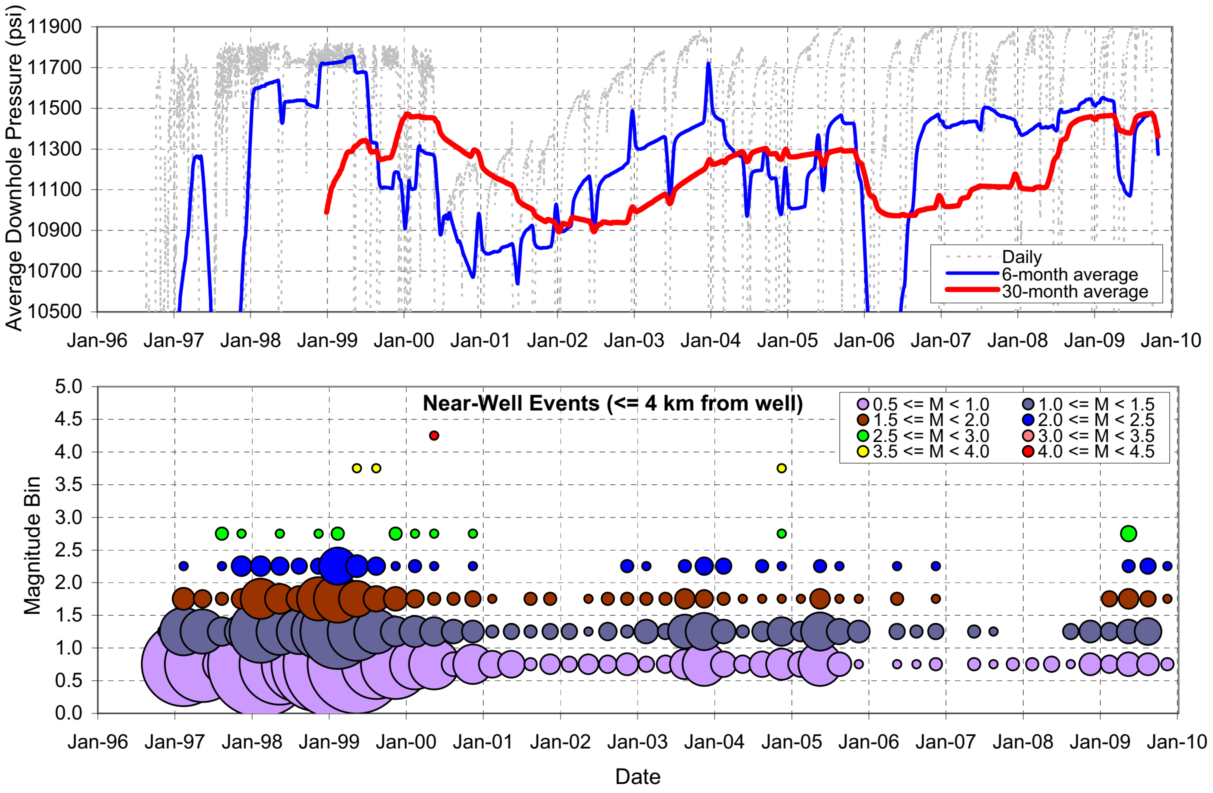

FIGURE 9: Average downhole pressure data for daily, 6-month, and 30-month time periods (top) and occurrence of near-well seismicity (bottom).

tatively, we also expect that the increased distance to the NW cluster likely buffers that region from direct response to injection operations by reducing the changes in pore-pressure compared to the near-well region. That is, not only does it take the NW zone longer to be affected by changes in downhole pressure at the injection well, the magnitudes of the pore-pressure changes the NW region experiences are likely less than those experienced in areas closer to the well. An increased time lag and buffering of pressure response for the NW cluster is consistent with the observed lack of distinct variations with time of the seismicity in the NW cluster.

4.0 Limits of this Analysis

The analysis presented here was performed quickly, in response to concerns about increasing felt seismic activity. It is based on simple empirical exploration of the data rather than a rigorous mathematical analysis, and therefore is largely qualitative rather than quantitative. For example, the seismicity data have not been corrected for variations in network performance with time. No substantial mathematical analysis of the apparent changes in the ratio of smaller- to larger-magnitude events over time has been performed. Only a few different time periods were tested when computing the time-averaged injection data curves. The computed curves were compared to the near-well seismicity data visually, but no mathematical fit was performed. Additionally, all the near-well earthquake data (events occurring within 4 km of the well) were grouped together, although those occurring within a few hundred meters of the well almost certainly have a different time response to injection operations than those occurring at larger distances. In short, because of the simple qualitative nature of this analysis, only broad trends and general conclusions should be drawn from this work. Also, because of the inherently dynamic nature of the physical system producing the seismicity, the relationship between injection operations and induced seismicity currently observed may change in the future.

5.0 Implications for Future Injection Operations and Induced Seismicity

The most reliable basis for determining appropriate operational changes necessary for avoiding future **M** 3+ earthquakes will likely be derived from the trend of seismicity in the near-well area (distance < 4 km). This conclusion follows from the observation that there is a better correlation of the induced seismicity in the near-well region to injection operations, as compared to the response of the NW cluster, and because the four PVU-induced M 3+ events to date have occurred in the near-well region.

The analysis presented here indicates that effecting meaningful changes in induced seismicity by changing injection operations may take longer than previously had been expected. This conclusion follows from the observation that the response of induced seismicity (in the near-well region) to injection appears to have changed over time. This analysis suggests that immediate changes in injection operations may *not* have a significant short-term impact on induced near-well seismicity. Instead, operational changes could take several months to a year or longer to produce a meaningful effect on induced seismicity, and the full impact of those changes may not be achieved for approximately 2 to 3 years.

5.1 Short-Term Implications

During 2009 we have seen what appears to be a significant increase in the number of **M** 2.5+ earthquakes compared to the previous three years, as well as a reduction in the ratio of small earthquakes to large earthquakes. While the absolute number of **M** 2.5+ events (six) is still small, they are occurring at a much higher rate than has been observed for the previous eight years (total of four **M** 2.5+ events for 2001-2008). Because of the limited scope of this analysis, no formal statistical tests have been made to quantify the significance of this result, but we can make a qualitative assessment of the likely short-term implications.

Because the observed near-well seismicity rate appears to correlate best with the long-term time-averaged injection pressures, and these pressures will remain high regardless of near-term changes in injection operations, it is reasonable to assume that the currently increased rate of felt events will continue for the next 6 to 12 months. Even larger events, in the range of **M** 3 - **M** 4, are possible over this period based on comparison to historic seismicity trends.

Induced near-well seismicity, especially the risk of generating felt events, may decrease somewhat in mid to late 2010 due to the additional injection down-days that occurred in 2009 (approximately 75 shut-down days from mid-Dec. 2008 to mid-Dec. 2009, compared to the nominal 40 days/year). However, if the current 20-day bi-annual shut-down schedule is maintained in 2010 and 2011, the seismicity risk may increase again sometime in 2011 or 2012.

5.2 Long-Term Implications

If the current 20-day bi-annual shutdown schedule and current flow rate are maintained for the next several years, and if the pressures required to inject under these conditions continue to increase, then the current relatively-high rate of induced earthquakes with $\text{magnitude} \geq 2.5$ is likely to continue, and may even increase. In addition, there may be an increased likelihood of producing larger-magnitude events (with **M** 3.5+), if the current pattern of induced seismicity follows previous patterns. In order to decrease the occurrence of felt events over the long-term, including larger-magnitude events, it likely will be necessary to take actions which will moderate the long-term average injection pressures. This can be done through either an increased number of shut-down days, or a decrease in average flow rates.