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The Application of Microseismicity for Monitoring Deep Disposal of Fluids

E.L. Majer and D. Gievers

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E. L. Majer and D. Gievers
Earth Sciences Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720

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The Application of Microseismicity for Monitoring Deep Disposal of Fluids

E. L. Majer and D. Gievers
Earth Sciences Division
Lawrence Berkeley Laboratory
Berkeley, California
Phone: 510-486-6709; Fax: 510-486-5686

Abstract

A three element array of three-component 4.5 hertz geophones in shallow boreholes (200 feet deep) were used to monitor a deep (8500 feet to 9500 feet) injection of waste water from a co-generation plant in the Central Valley of California. The purpose of this work was to determine if there was seismicity associated with deep injections that could be used to monitor the path of the fluids at depth, and if the seismicity could be used to guide injection practices. In this case there was a correlation between seismicity and injection, however, the events were small and accurate locations could not be determined. The experiment suggests that given proper monitoring techniques microearthquake monitoring would be useful in monitoring fracture generation and/or fluid movement in deep injection activities.

Introduction

Due to many industrial processes there is an increasing need to dispose of waste fluids in a safe and economical fashion. Surface treatment may be expensive and sometimes not feasible. In some cases it may be possible to dispose of the fluid by injecting it into the earth where it will be isolated. This implies that the waste fluids are injected into stable formations which are not connected to water resources that can be contaminated. This usually requires stable geologic formations of sufficient permeability such that reasonable quantities of fluid can be injected into the ground economically, i.e., the volume is large enough to make it cheaper than surface treatment, and that the formation is bounded by impermeable layers so that the waste fluids do not escape. If the permeability of the formation is too low the process of forcing the fluids into the formation by pumping may cause the rock to fail, and thus be fractured. This may not be of concern if the induced fractures are within the formation that is bounded by the impermeable rock, but if this fracturing "breaks out" of the formation in which the waste fluid was intended to be confined within, then the fractures may form a permeable pathway to uncontaminated water resources.

The objective of this work was to evaluate microseismicity as a tool for detecting unwanted fracturing in deep injection waste disposal operations. Specifically, could microseismicity be used to monitor the path of the fluids, and/or could it be used to at least determine if fractures were induced that may endanger confinement of waste fluids. The attractive aspect of utilizing microseismicity is that there is a broad base of technology that has been developed for earthquake monitoring that could be drawn upon. If seismicity was an indicator of fracturing then modern routine methods of processing the data in close to real time could be employed to provide an early warning to the operators to modify operations to mitigate any damage. In this case microseismic monitoring could be used as a tool to provide information for injection design. The fundamental question, however, is how reliable is microseismic monitoring as an indicator of fracturing? Many issues regarding the level of detection, frequency range and energy release mechanisms need to be addressed however, before microseismicity can be used for injection monitoring.

In order to address some of these issues the United States Environmental Protection Agency (USEPA) sponsored Lawrence Berkeley Laboratory to conduct a small pilot study in California's Central Valley. The project was envisioned to utilize surface instruments in shallow bore holes (about 200 feet deep) to monitor seismicity associated with a deep injection operation for waste water from a co-generation power plant. If sufficient seismicity was detected with a small surface array then further work to determine the location and character of the seismicity (source mechanisms, magnitudes, precise locations) as a function of injection and geologic parameters may be warranted.

Although significant seismicity was detected with the surface array, further studies were not undertaken.

There have been many cases of induced seismicity in the past: ranging from waste injections to gas production, i.e. the Denver Earthquakes, Colorado; the earthquakes in Larderello, Italy; the seismicity at the Geysers Geothermal Field, California, just to name a few. (Allis, 1982, 1989, Eberhard-Phillips and Oppenheimer 1984, Grasso and Feigner, 1990, Healy et. al., 1968, Majer and McEvilly, 1979, Simpson, 1986, Stark 1990). These cases of seismicity were either partially or totally induced by injection of water into a formation at depth (in the some cases there is also seismicity associated with withdrawal operations). Although there have been many observations of induced seismicity due to fluid injections there is a variety of mechanisms that may be causing the seismicity.

Site Description and Experimental Configuration

The location of the microseismic monitoring was east of the city of Manteca, California in San Joaquin County. The subject of the monitoring was a waste water injection in a deep well (approximately 9500 feet deep) which was operated by San Joaquin Cogen Limited, a co-generation facility that is using warm waste water and easily available natural gas to generate electricity. The waste stream was water from a demineralizer and a cooling tower. The near-by Sharpe Army Depot supplied the source water for the facility. The facility was designed to operate for twenty years. The waste water was being injected over a depth range of approximately 8500 feet to 9500 feet in a packed off zone in a cased and perforated well. The design rate of injection was 77 gallons/minute with a maximum rate of 150 gallons/minute. The injection well is located approximately one half mile southeast of the intersection of Interstate 5 and Louise Ave in the northwest corner of Section 35, Township 1S, Range 6E (see Figure 1). The water was injected into a thick sedimentary sequence called the Lathrop formation (Figure 2). The Lathrop formation is a Cretaceous sandstone in excess of 1500 feet thick. The permeability of the sandstone, determined from injection tests was calculated to be 2 to 3 millidarcys. The porosity logs showed an average porosity of twenty percent. It was assumed that at the designed injection parameters, the injected water would have less than a quarter mile radius of penetration (see Figure 1). The injection parameters included a bottom hole (9500 feet) temperature of about 200 degrees F and a pressure at 9080 feet of 4,460 lbs. The calculated fracture pressure was 7,813 psi and the fracture gradient was calculated to be .911 psi/foot. (All of the above injection parameters and geologic information was derived from the initial application to operate by Cogen Inc. to the USEPA.)

Our monitoring effort did not start at the same time as the start of the co-generation operation (early 1990), but due to difficulty in maintaining injection rates, routine operation of the co-generation facility was just beginning when we started our microseismic monitoring in June of 1990. As it was, during our monitoring period the injection was sporadic and not continuous. It should be noted that the formation that was being injected into (the lower Lathrop) was not taking water as anticipated, and the company was applying for permission from the USEPA to inject into a shallower formation (Azevedo Zone, see Figure 2.) at the time of this study. All of our monitoring efforts, however, were when water was being injected into the deeper Lathrop formation.

Sensitive recorders and geophones must be used to detect any microearthquakes. In order to reduce the effect of surface noise (the San Joaquin Cogen Limited pumping site was in the country, but there was a freeway a mile away, and other industrial activity was also close to our array) we used borehole installations for the geophones. The geophones were borehole packages (Geospace Inc. 4.5 hertz, 0.6 critically damped with a generator constant of 0.4 V/in/sec) three components. The geophones were lowered to the bottom of three wells: PW-4, PW-3, PW-12, each about 190 to 200 feet deep (Figure 1). The boreholes used had been drilled for another purpose by SIMPLOT INC. and, fortunately, we were able use them for our geophones. Although the boreholes were not surrounding the well of interest, we felt that the advantage we would gain in signal to noise ratio outweighed the geometry disadvantage.

The geophones were attached to various recorders at different times. Recording started in June of 1990 and ended in June of 1991. The recorders used were very sensitive to ground motion. The first recorder used was a smoke paper recorder, Sprengnether MEQ-800. Before deploying a more expensive array we wanted to determine if there was any seismicity at all. If so, we would then deploy digital instruments. The MEQ-800 writes the data onto smoked paper, but it only detects one component of movement. We wired the vertical and one horizontal component in parallel so that both the P-wave and S-wave would be detected. The smoke paper recorder was used from June 13, 1990 to February 21, 1991 and were operated with filter setting between five and fifty Hz.

We then used the Sprengnether DR-100. This recorder is portable and similar in size to the smoke paper recorder, however it records digital data (12 bit) onto magnetic tape instead of paper. The DR-100 was used from February 21 to April 20, 1991 and was operated under the same filter settings as the smoke paper recorders. The rate of digitization was 200 samples/sec.

The last recording system used was a digital (16 -bit) telemetry system, Nanometrics Inc. The Nanometrics Remote Digitizer system (RD3) telemeters the data to a central site where a computer constantly monitors the incoming data. The system can be set such that only data signals with amplitudes above a predetermined level are recorded; thus when an earthquake comes the data are recorded. The RD3 was operated from April 20 to June 10, 1991 at a filter setting bandwidth of about eighty Hz.. Given the high background noise, each of these RD3's were sensitive enough to detect an earthquake of magnitude one or higher on the Richter scale. Three different recorders were used to ensure the purity of the data. If one recorder was not operating properly its data was balanced by the other two sets. Each of the recorders used was sensitive enough to detect microearthquakes that occurred in the Lathrop Sandstone Formation.

The Lathrop Sandstone Formation consists mostly of quartz sand ranging from fine to medium grained. Within the formation there are calcite lenses and beds of clay and silt. The entire formation is saturated with water which has a total dissolved solids of 21,639 milligrams per liter. The formation is also confined on all sides by two layers composed of virtually impermeable shale. The waste water pumped into the formation was at ambient air temperature and had total dissolved solids not exceeding 9,845 ppm. The waste water, which was slightly corrosive, was injected into the formation under a pressure of about 2000 pounds per square inch over hydrostatic.

Results and Discussion

Table 1 and Figure 3 give the seismicity versus injection history of the experiment. Unfortunately, we did not have exact injection rates. The injection rates were inferred from the water outflow rates from Sharpe Army Depot, i.e., the water provided to the co-generation plant. It does provide a rough estimate of the water injected, but not, however, the exact time. There could be a lag lead time, depending on how the water is used from the holding facilities at the co-generation facility.

The first point to note is the rough correlation between injection and seismicity. There does seem to be some cause and effect relationship between injection and seismicity. The seismicity was very small in magnitude, just above our detection threshold, so that each seismic event was only recorded on one or two stations at a time. Thus we could not reliably locate the events. No increase in the magnitude of the events over time was observed. The injection rates were rather sporadic and never held constant for long periods of time, so we were never monitoring in the "production mode". This may account for the lag and lead on the events versus injection, although a more probable cause for an inexact correlation is not having the exact injection times. Figures 4 and 5 show some of the better examples of the data, as recorded on the digital telemetry system in early May of 1991. These events seem to be northeast of the array, several miles away, (these were not counted as events in table 1).

For injection to induce any earthquakes a few conditions must first be satisfied. The first and most important condition is tectonic strain. The formation that is being injected into must already be under considerable tectonic strain, near its breaking point, (Bishop 1960, Castle, 1976, Dietrich, 1968, Gale 1977, Molnar 1972). Another condition is depth. The formation must be very deep, at least a few thousand feet. The formation must also have a low permeability; this allows pore pressure to build up if external pumping is being applied and the formation can not take fluids fast enough. The injection of the fluids must also be at a high pressure so that the pressure in the formation is increased over a considerable area. The injection must also drive the natural stress regime closer to failure (Kisslinger, 1976). The San Joaquin Cogen Limited injection area meets all of these conditions. The San Joaquin Valley lies directly east of the Calaveras and the Hayward fault zones. These fault zones place considerable strain upon the surrounding rock; subjecting the Lathrop Sandstone Formation to considerable stress before the injection began. At nine thousand feet the formation is deeper than necessary to satisfy the depth condition stated above. The formation also has a very low permeability, even at the upper calculated limit of 2.36 millidarcys. And the injection pressure is very high at two thousand pounds per square inch. With all of the criteria satisfied it may be easy for the San Joaquin Cogen Limited injection to induce microearthquakes.

The most likely mechanism for the triggering of the microearthquakes is the build up of pore pressure. "The effect of increasing pore pressure is to reduce the frictional resistance to fracture by decreasing the effective normal stress... across the fracture plane" (Healy 1968). The increase in pore pressure will also affect the various materials in the formation differently. Since the calcite, clay, and shale each have a lower permeability than the sandstone, they will react diversely to the increase in pore pressure. Either they will be more resistant or less resistant to the pore pressure increase than the sandstone will be. This will place additional stress on the boundaries between the different materials. Therefore, the contacts between the different materials would be more susceptible to fracturing and stress failure. The increase in pore pressure has been cited as the cause for many other cases of induced earthquakes: the Denver Earthquakes, Colorado; the earthquakes in Larderello, Italy; and the seismicity at the Geysers Geothermal Field, California.

The waste water itself is another possible triggering mechanism for the induced earthquakes. The chemicals in the water could be reacting with their environment. These reactions would further weaken the formation causing it to give way and fracture. The chemicals could be reacting with the quartz in the sand or with the calcite in the lenses. Further studies should be conducted to determine if there are chemical reactions taking place under the pressures and temperatures at which the water is in contact with the sandstone.

Summary and Conclusions

With any, or a combination, of the above mechanisms the formation rock could be driven past its stress limit and an earthquake could be induced. The injection of waste water into the Lathrop Sandstone Formation may also be causing induced seismicity. There appears to be a correlation between the amount of seismicity and the amount of water injected into the formation. The conditions for induced seismicity, put forth by Kisslinger, (1976) are also satisfied in the Lathrop Sandstone Formation. From the correlation between the frequency of earthquakes and the amount of water injected there is a clear possibility that the San Joaquin Cogen Limited injection induced the seismicity. Further studies of the area and the seismicity would clarify exactly what is occurring at the San Joaquin Cogen Limited injection site. In general, it seems that microseismicity could be used to detect if pressures are exceeding a threshold level of pressure or injection rates. Due to budget constraints in this experiment, deeper installations were not emplaced, which would have answered many questions. At a minimum one deep borehole installation could be used for this purpose. In areas of potential induced seismicity arrays of sensors could be used to monitor the seismicity to locate the creation of any fractures that may endanger the confinement of the fluids. However, there is no guarantee that seismicity is associated with all fluid flow, the fluid may be flowing to areas where there is no associated seismicity.

Acknowledgments

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Figure Captions

Figure 1. Location of the injection well with respect to the three boreholes (PW-3, PW-4, and PW-12) used for geophones in this experiment.

Figure 2. Geologic cross section of the Central Valley of California showing the location of the injection well and the formations into which the fluids were being injected.

Figure 3. Plot of the seismicity versus the injection rate for the entire experiment. The time bins are every ten days, as listed in Table 1.

Figure 4. An example of the seismic events recorded on the digital telemetry system on May 4, 1991. Channels 1, 2, and 3 are the vertical and two horizontal components, respectively, for station PW-3, channels 4, 5, and 6 are from PW-4, and the channels 7, 8, and 9 are from PW-12. Time is in seconds.

Figure 5. An example of the seismic events recorded on the digital telemetry system on May 5, 1991. Channels 1, 2, and 3 are the vertical and two horizontal components, respectively, for station PW-3, channels 4, 5, and 6 are from PW-4, and the channels 7, 8, and 9 are from PW-12. Time is in seconds

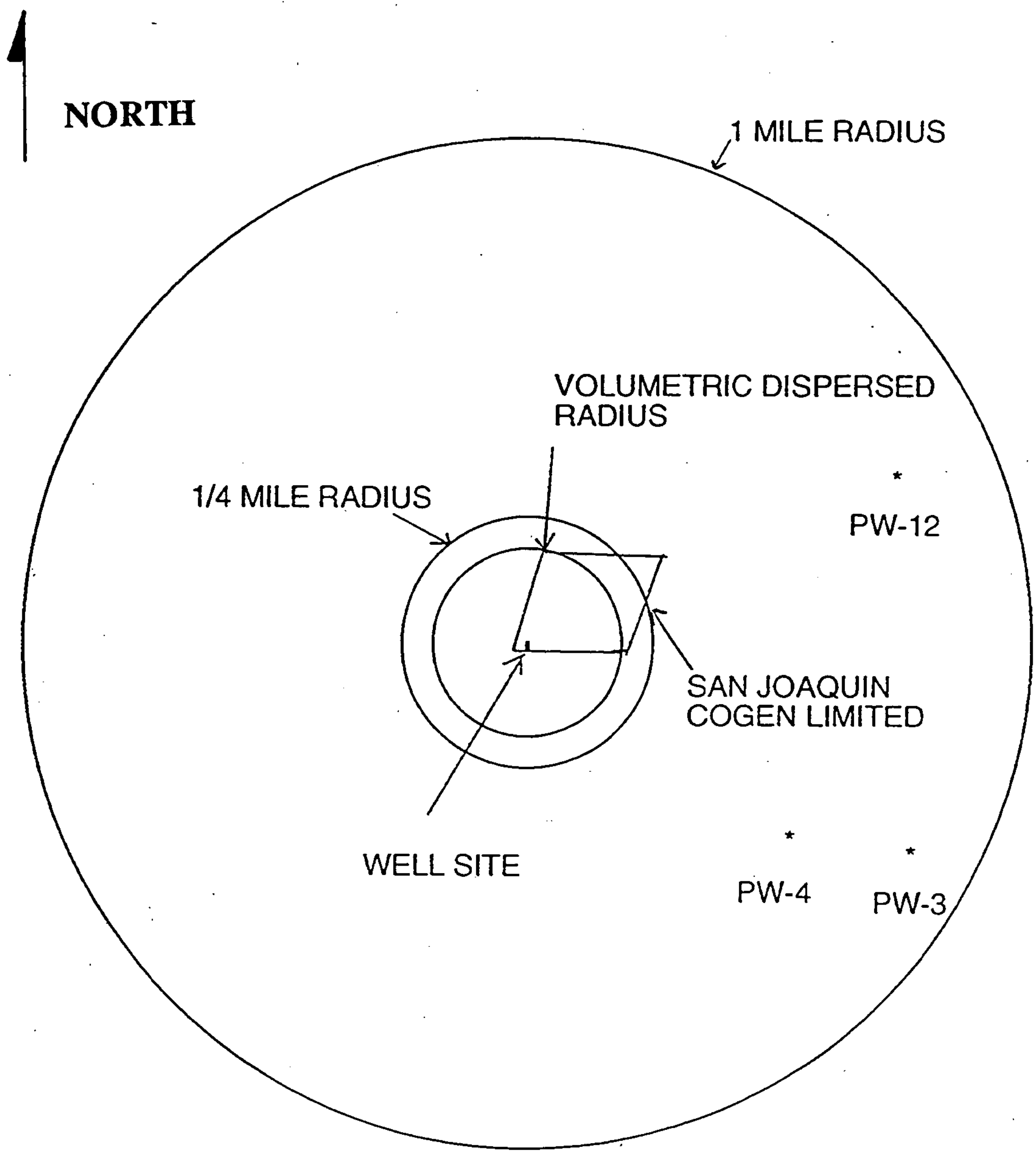
San Joaquin Cogen Limited

seismicity/injection data

Table 1

	seismicity	date	injection(gal)
1	26.000	06-11-90	2213.700
2	25.000	06-21-90	2364.900
3	4.000	07-01-90	2426.800
4	18.000	07-11-90	1954.400
5	16.000	07-21-90	2146.400
6	12.000	07-31-90	2068.200
7	14.000	08-10-90	1937.300
8	1.000	08-20-90	2085.000
9	1.000	08-30-90	2080.300
10	1.000	09-09-90	2071.000
11	1.000	09-19-90	2071.000
12	4.000	09-29-90	2851.100
13	46.000	10-09-90	3414.600
14	12.000	10-19-90	3898.600
15	6.000	10-29-90	3111.000
16	0.000	11-08-90	3250.000
17	0.000	11-18-90	3250.000
18	4.000	11-28-90	4192.300
19	47.000	12-08-90	2303.500
20	1.000	12-18-90	0.000
21	1.000	12-28-90	0.000
22	1.000	01-07-91	11.800
23	98.000	01-17-91	0.000
24	66.000	01-27-91	3528.600
25	7.000	01-06-91	4693.300
26	4.000	02-16-91	4575.400
27	2.000	02-26-91	4186.000
28	0.000	03-08-91	699.100
29	0.000	03-18-91	0.000
30	0.000	03-28-91	0.000
31	0.000	04-07-91	0.000
32	2.000	04-17-91	1270.500
33	0.000	04-27-91	1533.400
34	0.000	05-07-91	3379.800
35	0.000	05-17-91	1014.900
36	7.000	05-27-91	4659.500

San Joaquin Cogen Limited Well Location Map



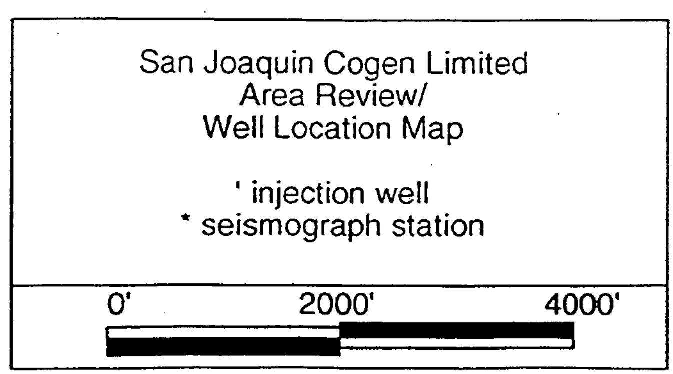


Figure 1

SAN JOAQUIN COGEN LIMITED

REGIONAL CROSS SECTION

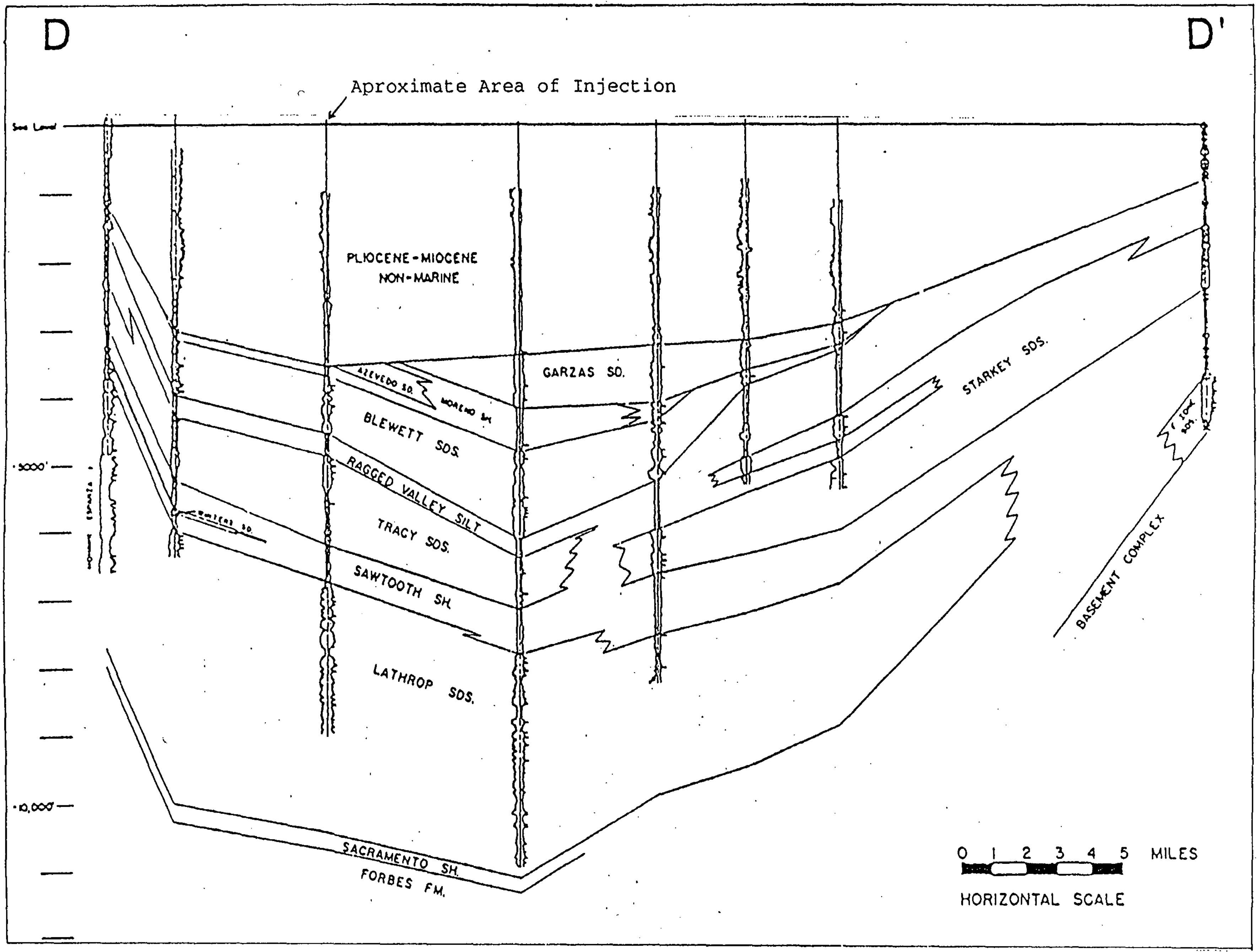
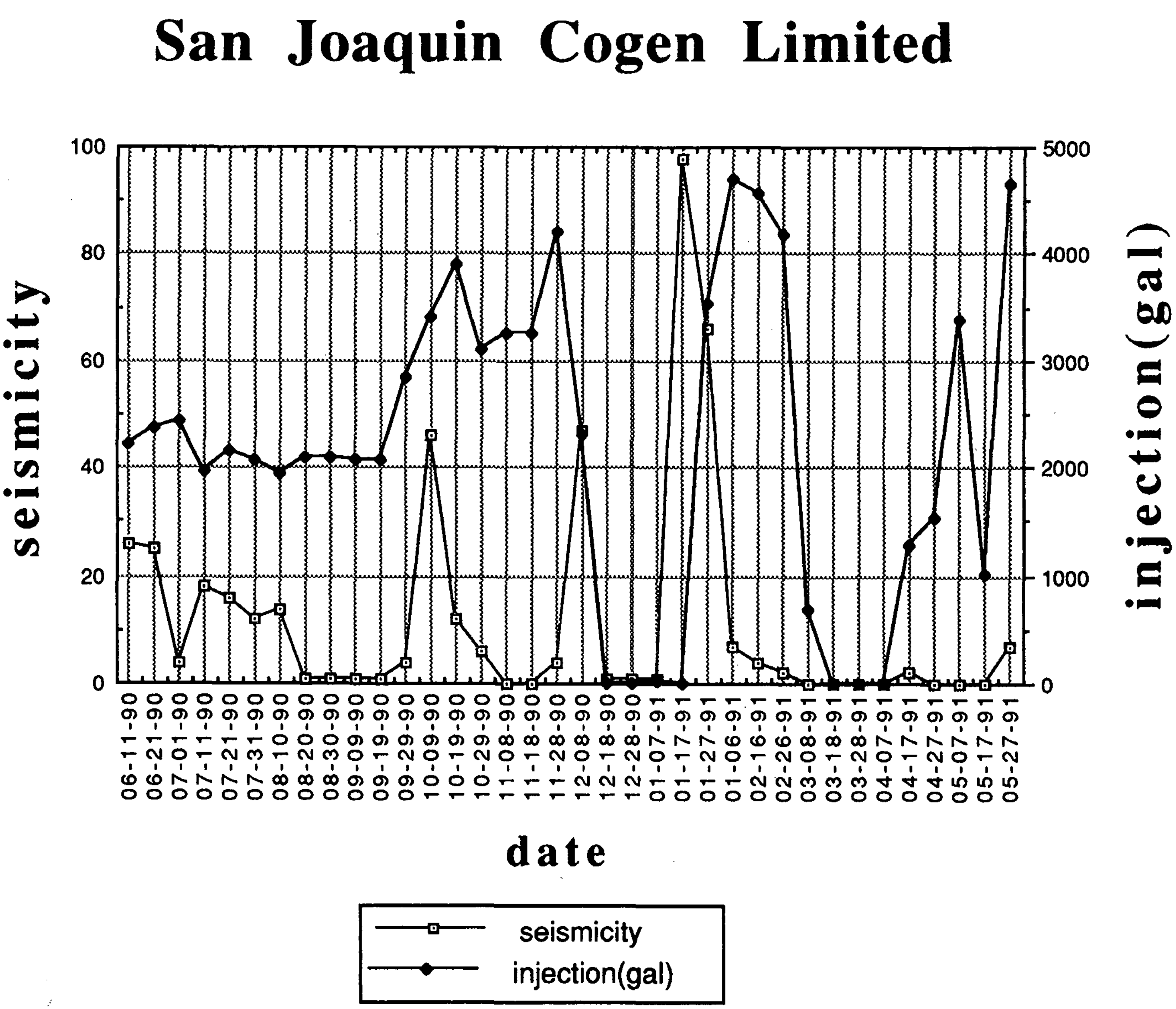


Figure 2


San Joaquin Cogen Limited
seismicity
injection(gal)
date
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40
60
80
100
0
1000
2000
3000
4000
5000
06-11-90
06-21-90
07-01-90
07-11-90
07-21-90
07-31-90
08-10-90
08-20-90
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03-18-91
03-28-91
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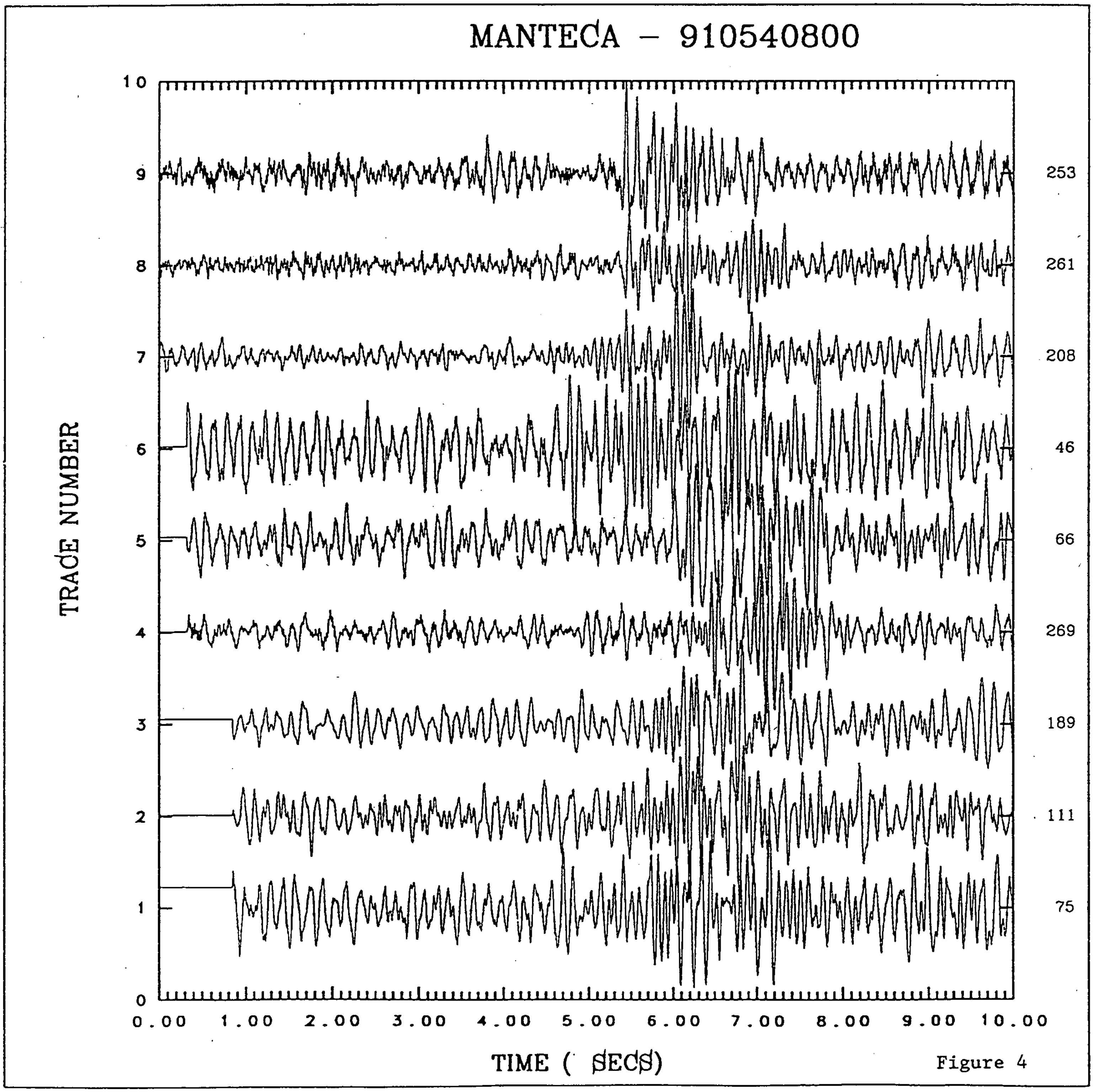
05-27-91
seismicity
injection(gal)

Figure 3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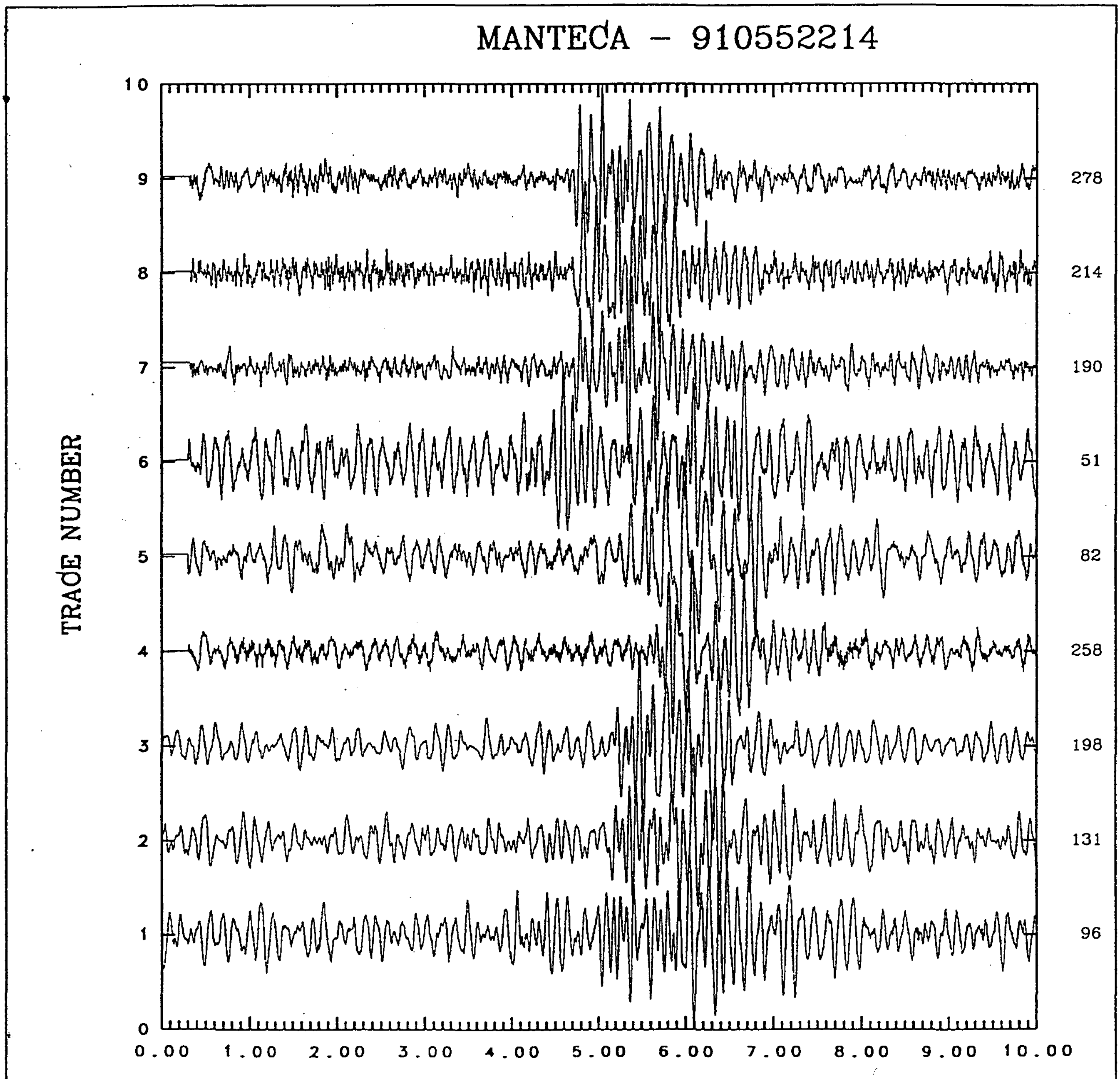
269
189
111
75

Figure 4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5.00
6.00
7.00
8.00
9.00
10.00
278
214
190
51
82
258
198
131
96

Figure 5

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