INVESTIGATION OF THE RELATIONSHIP OF EARTHQUAKES AND UNDERGROUND WASTE DISPOSAL IN THE EL DORADO AREA, ARKANSAS

Randel Cox*
Department of Sciences
University of Arkansas at Monticello
Monticello, Arkansas 71655

and

Roy B. VanArsdale
Department of Geology
University of Arkansas
Fayetteville, Arkansas 72701

*Current address: 101 Geological Sciences Bldg.
University of Missouri
Columbia, Missouri 65211

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ABSTRACT

From December, 1983 to September, 1989 twelve small earthquakes were recorded for the El Dorado, Arkansas area. Magnitudes of these earthquakes were well below damaging levels. Prior to this time no seismicity was reported in the area, suggesting that the earthquakes were not naturally occurring and may have been the result of human activity. El Dorado is located at the margin of a region of underground waste brine disposal and along a major fault zone. Elevated pore pressures resulting from brine disposal may have reduced the normal (locking) stresses across fault surfaces and triggered fault movement.

Two injection wells (Great Lakes Chemical Corporation SWD# 7 and 13) in the El Dorado South field are in closest proximity to fault surfaces at the depth of injection. The two wells also lie at the center of the macroseismic area and show increases in injection rates prior to periods of seismicity. These relationships suggest that pressured fluid injection triggers earthquakes in the area.

Future research to corroborate these results should include detailed seismological studies of the El Dorado South field and detailed studies of formation pressures, *in situ* stresses and geologic structure for all sites of pressured fluid injection and secondary oil recovery operations in the region.

INTRODUCTION

El Dorado is located on the seismically quiet northern Gulf Coastal Plain, and prior to 1983 no earthquakes had been reported within a 75 km radius of the city. Between Dec. 10, 1983 and Feb. 5, 1989 five earthquakes between magnitude 2.0 and 3.0 in the El Dorado, AR area were instrumentally recorded by the Center for Earthquake Research and Information (CERI) in Memphis, TN. By Sept. 1, 1989 seven more events (magnitude 1.0 to 1.7) probably originating in the same area were recorded (James Dorman, 1990, personal communication). Earthquakes of these magnitudes pose no danger to human welfare or property. The absence of macroseismicity (felt events) in the El Dorado area prior to the sequence of tremors that began in 1983 suggests the possibility that the seismicity is not naturally occurring and was induced by human activity. Various activities have been recognized to trigger earthquakes, including reservoir impoundment, strip mining, subsurface mining, oil recovery, underground explosions, and underground fluid waste injection (Simpson, 1986).

Oil recovery is conducted in the El Dorado area, but the activity began in the early 1920's and peaked before mid-century without being accompanied by macroseismicity. However, underground disposal of waste brine generated by the bromine industry began in the early 1970's, and in 1983 large volumes began being injected under pressure into wells in the El Dorado South field near the epicentral area. Prior to this time, the only injection under pressure in the field involved a single low volume hazardous waste disposal well (PWD#2 in Appendix A).

Underground fluid disposal by pressured injection can induce seismicity at pressures lower than those necessary to fracture rock. The normal (locking) stress on pre-existing faults is reduced when increasing pore pressure forces fault surfaces apart, thereby increasing the potential for fault movement (Simpson, 1986). This region of the northern Gulf Coast is characterized by east-west oriented compressional stress (Zoback and Zoback, 1981; Dart, 1987) which may be capable of generating earthquakes along favorably oriented faults if fault strength is reduced.

This region of the northern Gulf Coast is underlain by approximately 3 km of Mesozoic and Cenozoic sediments above the transition from folded Paleozoic basement to Mesozoic oceanic basement. The South Arkansas Fault Zone, a major structure known as the Mexia-Talco Fault Zone in Texas and the Pickens-Gilbertown Fault Zone in Mississippi and Alabama, transects the region (Fig. 1). This structure was initiated as down-to-the-basin basement faulting during the opening of the Gulf of Mexico. The fault zone experienced recurrent activity through Mesozoic and early Cenozoic time, warping the overlying sediments and giving rise to a zone of horst and graben blocks (Murray, 1961).

Typical development of this horst-graben system can be seen in Figure 2. The fault zone is nearest to the field of waste brine disposal at the point of seismicity (Fig. 1), suggesting that this structure or a subsidiary structure could be the source of the earthquakes.

The relationship of fluid waste disposal and seismicity at the Rocky Mountain Arsenal (RMA) near Denver, CO in the early 1960's has been well documented (Major and Simon, 1968; Healy and others, 1968). The average disposal rate at the single RMA well during the initiation of seismicity was 21 million liters/month (Healy and others, 1968). From 1983 to 1990 the average disposal rate of four bromine waste wells injecting under pressure within a 1.8 km radius area in the El Dorado South field was 53 million liters/month/well, and seven additional wells began injecting under pressure during this time interval. This higher disposal rate in the El Dorado South field could be capable of inducing seismicity if structure and tectonic stresses are favorable (the RMA well is cited only as an example of induced seismicity, not as a criterion for evaluation of the El Dorado South field).

The objective of this report is to evaluate the temporal and spatial relationships of seismicity, fluid waste disposal rate and injection pressure, and fault zones, and to evaluate the possibility of genetic relationships from this analysis.

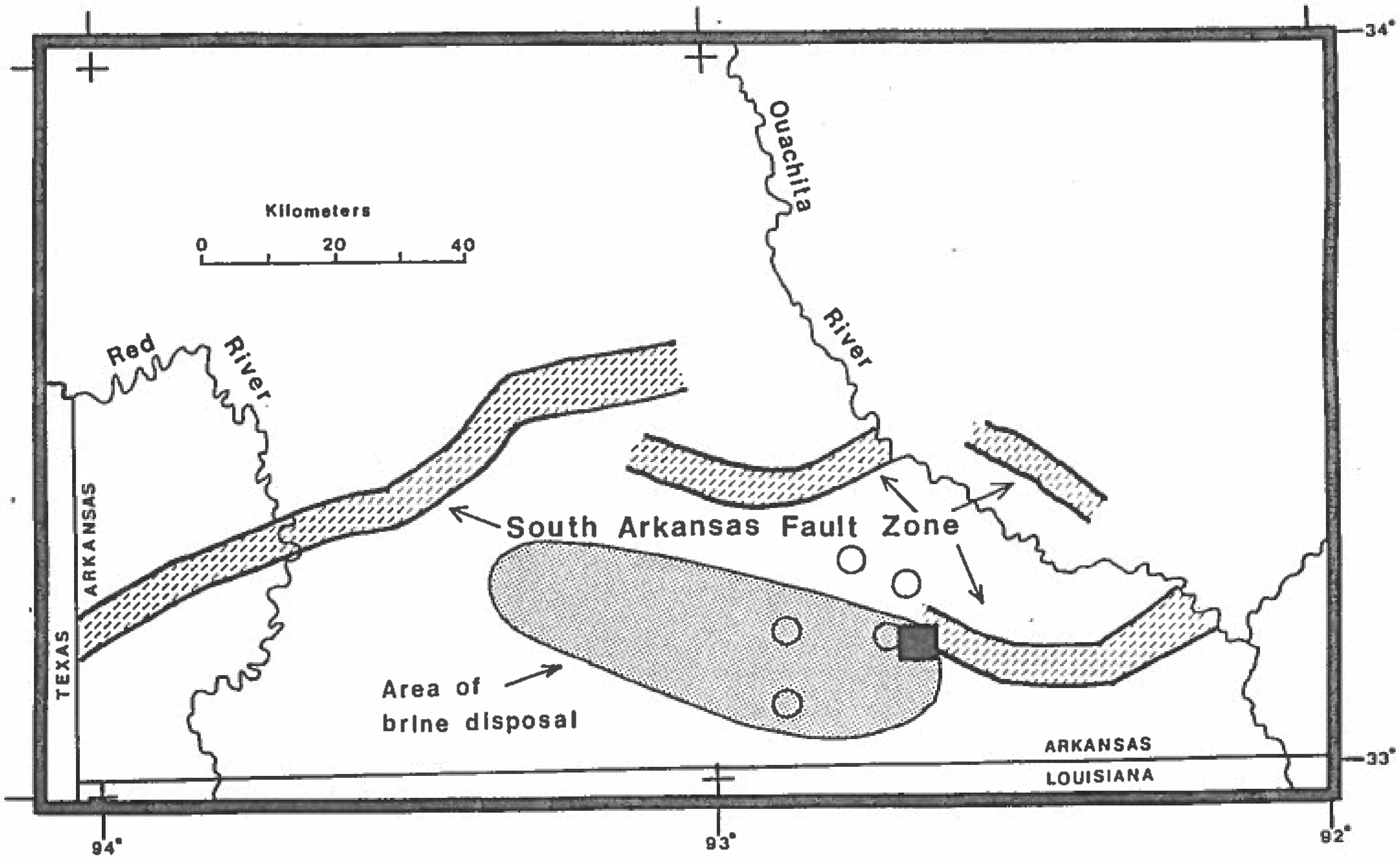

Figure 1. Regional map showing the spatial relationships of the area of underground disposal of waste brine generated by the bromine industry (shaded area), of the South Arkansas Fault zone (Hosman, 1982; Broom and others, 1984) and of the area of seismicity. Instrumentally located epicenters are designated by open circles; the macroseismic epicenter is designated by a square.

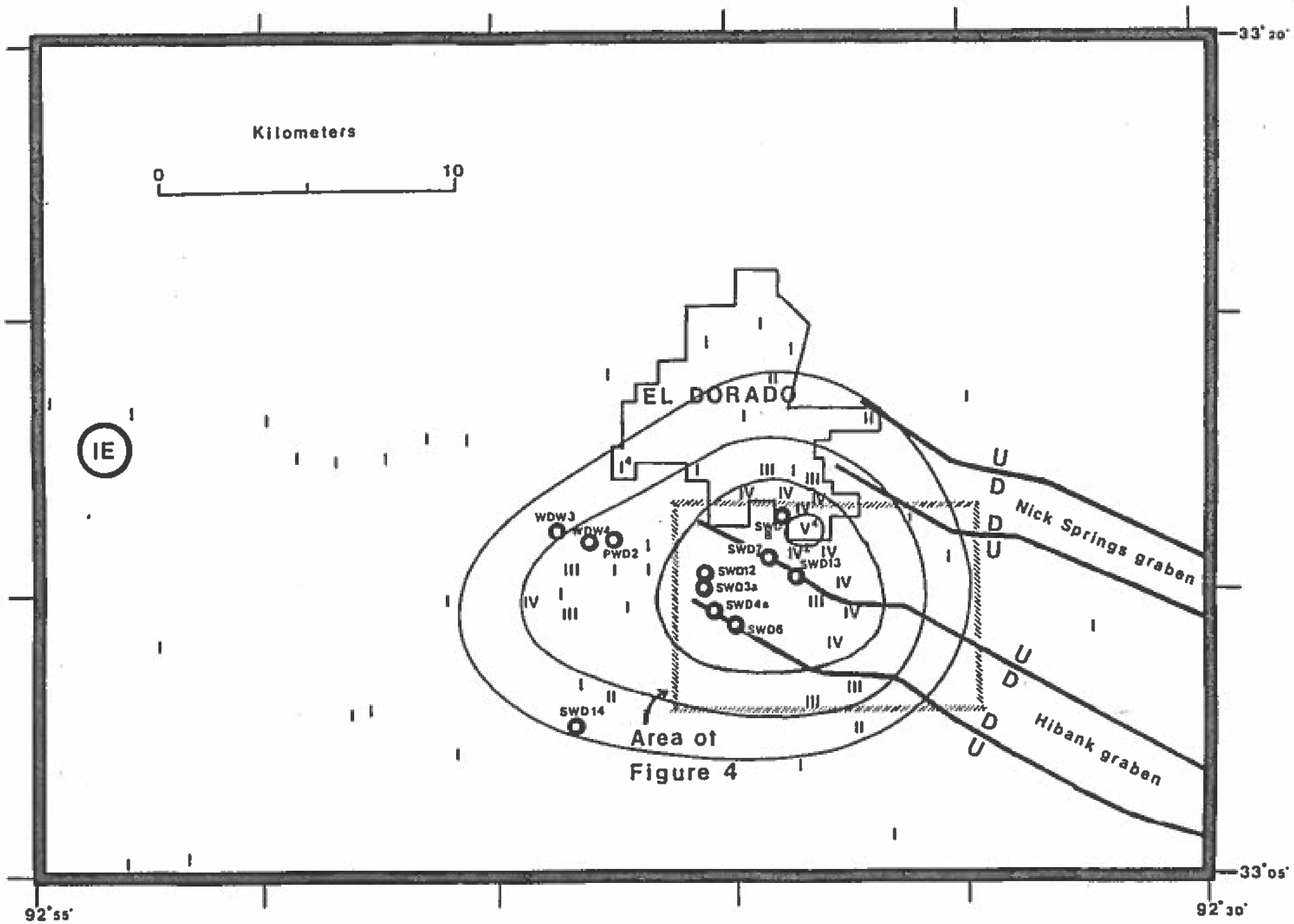

Figure 2. Isoseismal map of the macroseismic area of the Dec. 12, 1988 event (magnitude 2.5). Modified Mercalli intensities are designated by Roman numerals (superscripts indicate multiple reports). IE = instrumental epicenter. Locations of pressured injection wells are shown as open circles. Surface faults are projected from subsurface data (modified from Geo Map Regional Base Map #309, South Arkansas - North Louisiana, 1988, Dallas, TX). Intensity zone 4 approximates the position of the solid square in Figure 1.

METHODS

Instrumentally recorded seismicity data were obtained from CERI. The archives of the local newspaper (the El Dorado Times, 1933 to present) were searched for all records of historic seismicity. Macroseismic data (felt effects) were obtained from newspaper accounts and from a survey of 61 local residents, and intensities were assigned using the Modified Mercalli (MM) scale (Richter,1958). Most of the data pertain to the Dec. 12, 1988 event. The survey covered all topics included on U.S. Geological Survey Earthquake Report questionnaires. The area encompassing instrumentally located epicenters and newspaper accounts was targeted for the survey, and an isoseismal map was constructed using the macroseismic data for the 1988 event.

In addition to more accurately delineating the epicentral area, the isoseismal map was used to estimate hypocentral depth. The general formula for decreasing intensity with increasing distance from the epicenter is:

$$I-2 = 3\log[(r^2+h^2)/h^2]$$

where **I** is the maximum intensity; **r** is the radius of the macroseismic area (measured to the intensity 2 isoseismal); and **h** is the hypocentral depth (Bath, 1979). The shallower a hypocenter the more closely spaced the isoseismal lines (Bath, 1979; Bullen and Bolt, 1985). Manipulating the above relation, **h** was calculated as:

$$h^2 = r^2 / [\ 10^{((I-2)/3)}-1\ ]$$

Monthly records of volumes and average injection pressures for all disposal wells near the macroseismic area (all those in El Dorado South field) were obtained from the Arkansas Oil & Gas Commission and the Department of Pollution Control and Ecology. Because the influence of disposal fluid on formation pore pressure is a function of both volume and injection pressure (Healy and others, 1968), the product of these two values (expressed herein as bar-liters) was plotted against time for each well in the field. These well histories were then compared to the earthquake sequence for similarities.

Accurate data are not available for in situ stress orientations and magnitudes or for pore pressures before and during pressured injection in the El Dorado South field, thus quantitative analysis of fault failure could not be calculated. Average monthly pressure per unit volume was used to infer relative increases in pore pressure near individual wells through time.

Petroleum well log data obtained from the Arkansas Oil & Gas Commission were used to map the geologic structure of the macroseismic area. Logs from 176 wells in the El Dorado South field and adjacent areas were examined.

RESULTS

Seismicity. Table 1 lists all documented earthquakes of probable El Dorado origin. All were instrumentally recorded by the CERI seismograph network in NE Arkansas. Jackson (1979) lists an event immediately south of the town on June 19, 1939, but an unpublished CERI catalog (compiled by Ann Metzger) reports this same event to be one degree of latitude to the north near Arkadelphia, AR. Newspaper accounts of higher intensities near Arkadelphia (including structural damage to buildings) corroborate this northern epicenter.

The closest seismograph station is operated by CERI in Hoggard Bluff, AR 230 km to the north of El Dorado. This station began operating in June, 1985. Earlier, CERI operated a station at Star City, AR (115 km NE of El Dorado) from February, 1981 until September, 1985. Prior to installation of the CERI network, earthquakes below magnitude 3.0 in the El Dorado area would have been locatable by felt reports only (personal communication, Ann Metzger, CERI).

The events below magnitude 2.0 could not be located instrumentally but the epicentral distances (S-P= 27 sec.) were correct for El Dorado, and one of the events was reported felt there. Figure 1 shows the instrumentally located epicenters (circles) and the macroseismic epicenter (square) defined by felt reports. As the instrumentally located epicenters are subject to a high degree of error owing to the distance from CERI seismograph stations and to the small angle subtended by the array from the direction of El Dorado, the macroseismic area is a better estimate of the true epicenter (personal communication, James Dorman, CERI).

An isoseismal map for the Dec. 12, 1988 magnitude 2.5 event constructed from data collected from the survey of local residents is shown in Figure 2. Data from the survey are given in Appendix B. The highest values fell within the low range of intensity MM 5 (general alarm, people move outdoors, loud noises, small objects overturned). The intensity 5 zone was defined exclusively on reports of sounds of explosions or sonic booms and on the accompanying alarm. Reports of actual ground shaking did not indicate greater intensity for this zone.

DATE	Hr/Min.	LATITUDE	LONGITUDE	MAGNITUDE
12-09-83	2052	33.209N	92.739W	3.0*
12-10-83	0924	33.264N	92.686W	2.2
08-11-87	2031	33.105N	92.889W	2.0
12-12-88	1310	33.231N	92.884W	2.5*
02-05-89	0838	33.304N	92.742W	2.4*
02-11-89	2322			1.1
03-01-89	2055			1.7
03-03-89	2101			1.0*
04-27-89	1826			1.3
04-30-89	0126			1.3
08-24-89	0427			1.7
09-01-89	0252			1.3

Table 1. All documented earthquakes in the El Dorado, Arkansas area. Locations are instrumentally determined and are subject to errors of approximately 20 km owing to the distances to the nearest seismograph stations. All times listed are Greenwich, England time. Events felt in El Dorado are designated by *.

Disallowing these noises, the epicenter would be at the center of the intensity 4 zone, nearer the center of the macroseismic area.

Additional data were collected for earthquakes of Dec. 9, 1983 (magnitude 3.0) and Feb. 5, 1989 (magnitude 2.4) (see Appendix B). These two events occurred too remote in the past and too late at night, respectively, to be described sufficiently to construct isoseismal maps, but their greatest intensities appear to be coincident with the Dec. 12, 1988 macroseismic epicenter. Moreover, the instrumentally located epicenter of Dec. 9, 1983 is subject to the least error owing to the magnitude and to the operation of the Star City seismograph station. This instrumentally located epicenter is in close agreement with the macroseismic epicenter of the Dec. 12, 1988 event.

El Dorado is located on a maturely dissected upland surface of the coastal plain. The Cockfield sand and silt of the Claiborne Group (Eocene) is the only formation to crop out in the area, and is essentially horizontal. No relationship between the region of felt effects and topography, surface geology, or soil conditions is apparent.

Owing to the distance to the nearest seismograph station, instrumentally determined hypocenters are not valid for El Dorado events (personal communication, James Dorman, CERI). Using the intensity-distance formula given above, maximum and minimum radii of the macroseismic area from the center of intensity zone 5 yielded a hypocentral depth range of 1.6 km to 4.8 km for the Dec.12, 1988 event. A depth range assuming the epicenter at the center of intensity zone 4 is 3.4 km to 5.5 km.

Detailed inspection of the recordings of the earthquakes of magnitudes $\geq$2.0 by CERI personnel suggests there may be more than one source of the seismicity. The events of Dec. 9 and 10, 1983, although apparently related, are likely from different hypocenters (personal communication, James Dorman, CERI). There is no indication that these hypocenters are widely separated, and the differences may be due primarily to depth.

Fluid Disposal. More than 40 wells dispose of fluid waste in the El Dorado South field. The majority of these are oil field salt water disposal wells, and the remainder dispose of fluid waste generated by the bromine industry. With the exception of 12 of the waste bromine brine wells (operated by Great Lakes Chemical Corporation), all disposal in the field is by gravity flow. The 12 waste brine wells cited (listed in Appendix A) inject under pressure (or have at one time) and thus have the potential to induce earthquakes. Locations of the wells are shown on Figure 2. Bar-liter vs. time plots for each of the 12 wells and for all 12 combined are presented in Appendix A. Earthquakes are plotted relative to the time axis on each graph for comparison.

Figure 3 is a generalized stratigraphic column for the El Dorado area (see Murray, 1961 for a detailed description of the regional stratigraphy). Three of the wells (WDW# 3 and 4, and PWD# 2) inject into the Upper Cretaceous Ozan Formation, one well (SWD# 8c) injected into both the Ozan Formation and the Lower Cretaceous Pine Island Formation, and eight wells (SWD# 3a, 4a, 6, 7, 8t, 12, 13 and 14) inject into the Jurassic Smackover Formation.

Structure. 176 well logs were examined, and 71 penetrated the Lower Cretaceous section. Figure 4 is a structural contour map of the 'Hogg marker' of the Lower Cretaceous Pine Island Formation (the horizon nearest to hypocentral depths that could be mapped in appreciable detail). A graben (locally referred to as the 'Hibank graben') transecting the map from SE to NW diminishes in displacement to the NW. Cross-sections of this structure are shown in Figure 5. Shallow faulting above the Pine Island Formation is also shown on Figure 5. Because this fault zone occupies an Early Mesozoic rifted continental margin and was reactivated during Late Mesozoic and Cenozoic time, the boundary graben faults are interpreted to extend to basement. Calculated hypocentral depths support this interpretation.

In the SE quadrant of Fig. 4, the southern boundary fault of the graben dips 45° to 50°N, and the northern boundary fault dips 65° to 75°S. The southern fault shows greater displacement than the northern fault (350 m compared to 200 m). Although throw diminishes up-section on these faults, shallow Tertiary horizons are displaced as much as 40 m, and it is possible these faults reach the surface. Exposures are poor, and cursory field reconnaissance revealed no conclusive evidence

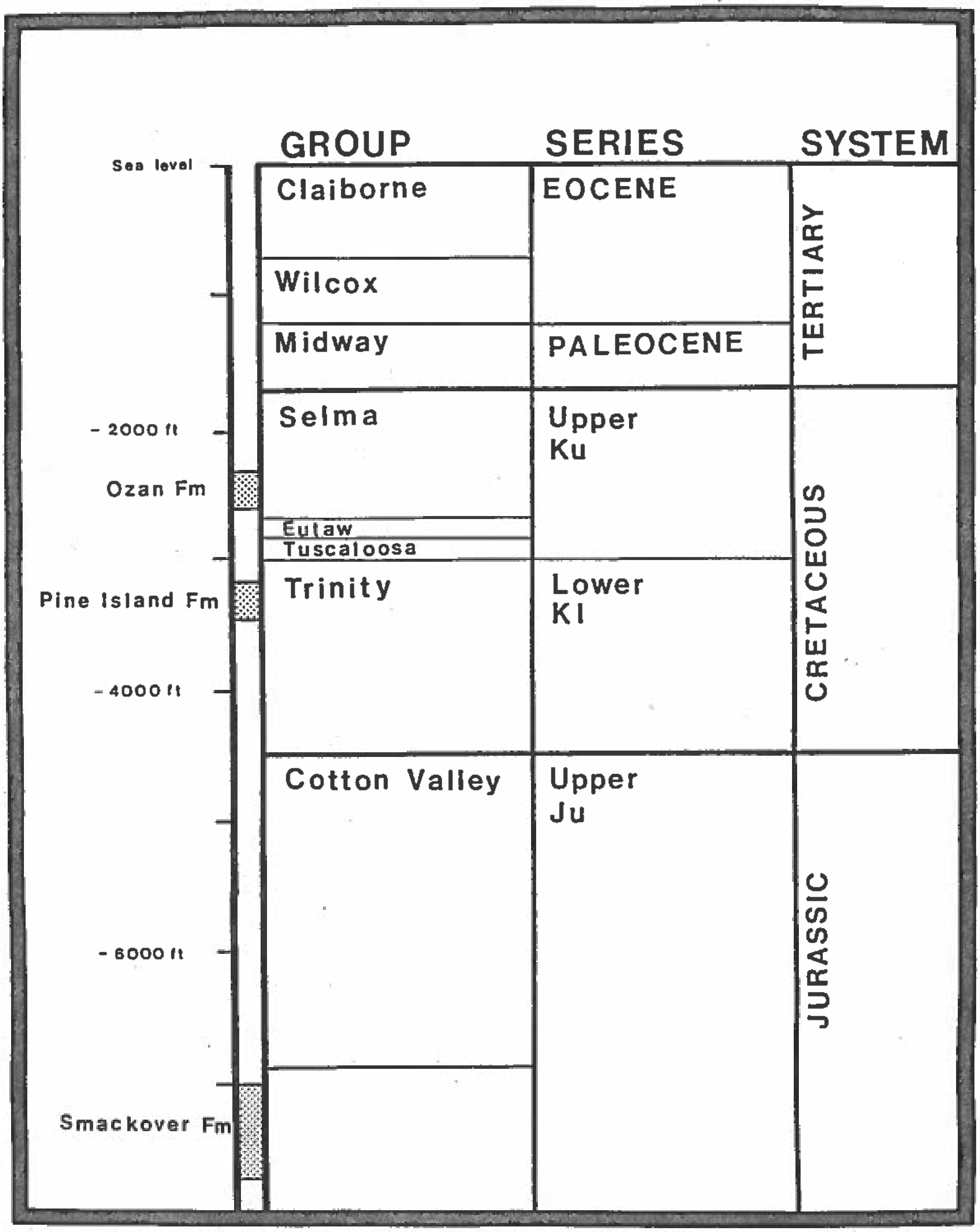

Figure 3. Generalized stratigraphic column for the El Dorado South field. Injection horizons shown as stippled patterns.

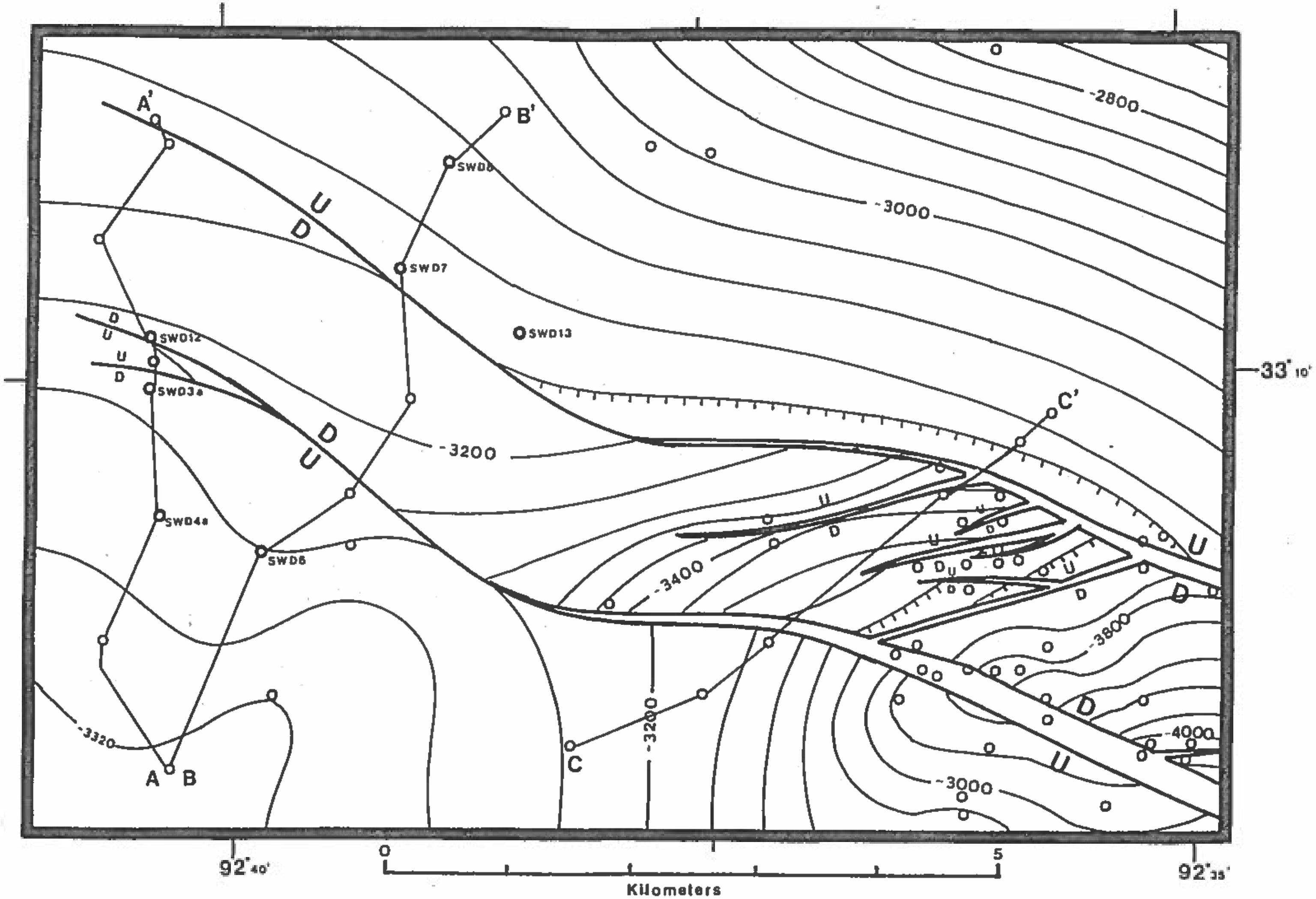

Figure 4. Structural contours on the 'Hogg marker' of the Lower Cretaceous Pine Island Formation (contour interval 40 ft). U = upthrown block; D = downthrown block. Pressured injection wells are labled. The location of Figure 4 is shown in Figure 2.

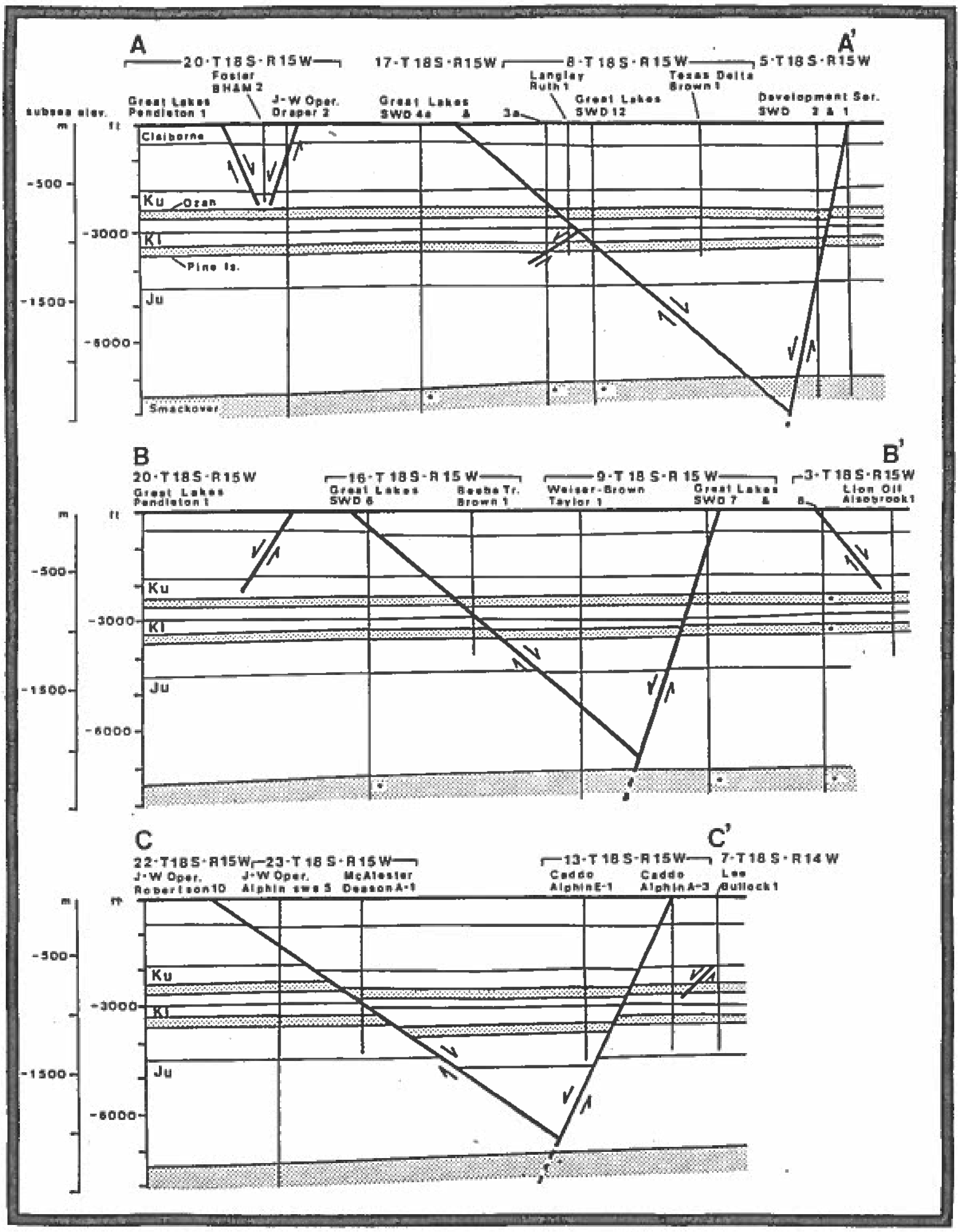

Figure 5. Cross-sections A-A', B-B' and C-C' from Figure 4. No vertical exaggeration. * designates pressured injection horizons.

of surface faulting. The geometries of these faults below 2.5 km (at calculated hypocentral depths) could not be determined.

In the NW quadrant of Figure 4, the southern fault dips 45°N and shows 5 to 7 m of throw. The northern fault in the NW is steeply dipping to vertical and shows a maximum throw of 20 m in the mid-Upper Cretaceous section (cross-section A-A', Fig. 5), diminishing both up-section and down-section.

A horst block separates the Hibank graben from a parallel graben immediately NE of Figure 4 (the 'Nick Springs graben', Fig. 2). The left-stepping offset in the trend of Hibank graben is also seen in the Nick Springs graben, which supports the structural interpretation in Figure 4.

DISCUSSION

The history of underground pressured fluid injection in the El Dorado South field is marked by two periods of rising bar-liter values (see Appendix A, graph A), the first begining in mid 1983 and the second begining in late 1987. Each of these periods of increase precedes one of the two principal periods of seismic energy release (late 1983 and late 1988 through mid 1989), thus showing a crude correlation to the seismicity. However, the injection histories of individual wells that constitute these two trends show greater or lesser degrees of correlation, and so permit more specific inferences as to the possible induced origin of the seismicity.

Both trends of rising bar-liter values reflect changes in injection rates in a number of wells. Initiation of pressured injection in wells SWD# 6, 7, 8t and 8c (see Appendix A, graphs D, E, F and J) constitute the earlier trend begining in mid 1983. SWD# 6 and 8t also show relatively large increases in 1984, and SWD# 8c shows a relatively large increase from 1985 to 1986. These increases were not accompanied by seismicity, and the injection histories of SWD# 6, 8t and 8c show no apparent correlation to seismicity following 1983.

Injection rates in wells SWD# 7 and 13, and WDW# 3 and 4 (see Appendix A, graphs E, H, K and L) constitute the later trend of rising bar-liter values for the field begining in late 1987. Pressured injection was initiated in wells SWD# 13, and WDW# 3 and 4 at this time. WDW# 3 and 4 increased to maximum bar-liter levels in late 1987, and so are not closely correlated to the seismicity of late 1988 through mid 1989.

Injection histories for wells SWD# 7 and 13 correlate more closely with this later period of seismicity. Two relatively large earthquakes (magnitudes 2.5 and 2.4) and an abrupt increase in frequency of earthquakes of magnitudes ≤ 2.0 accompanied a doubling of the average monthly bar-liter values for SWD# 7 to approximately 2.8 billion during late 1988 to late 1989. This value exceeds the bar-liter values reached by other wells in the El Dorado South field with the exception of SWD# 6 in late 1984 and early 1985. As discussed above, this interval of elevated bar-liter values for SWD# 6 was not accompanied by seismicity. The decrease in bar-liter values for SWD# 7 in late 1989 corresponded to the cessation of low magnitude seismicity.

All of the wells discussed constituting the gross rising trends of bar-liter values for the El Dorado South field may have contributed to inducing seismicity, but the injection history of well SWD# 7 individually best correlates temporally to the seismicity. Although the initiation of disposal under pressure in well SWD# 13 corresponds to the later period of seismicity, its history is too short for a strong argument on the basis of temporal correlation alone.

In addition to the bar-liter histories, trends of increasing average monthly injection pressure per unit volume in wells SWD# 7, 8t and 8c from 1983 to 1990 (see Appendix C) suggest that formation pressure has risen in response to injection in the vicinity of these wells (the center of the macroseismic area). These three wells inject into the horst block between the Hibank and Nick Springs grabens, suggesting that these faults are prohibiting movement of fluids away from the wells. SWD# 7 and 8t inject into the Jurassic Smackover Formation, and SWD# 8c injects into the Cretaceous Ozan and Pine Island Formations. The only other brine disposal well under pressure for a comparable time span was SWD# 6 (injecting into the Smackover Formation south of the Hibank graben). SWD# 6 shows no increase in average monthly pressure/unit volume since 1983 (see Appendix C), suggesting that fluid movement is not prohibited outside the fault zone. In the case of the RMA well, a migrating pressure front triggered earthquakes away from the well during and after injection (Healy and others, 1968). This does not appear to have occurred in El Dorado to date.

Of all wells listed in Appendix A, SWD# 7 and 13 injected closest to the graben faults. These two wells inject into the Smackover Formation at 2.25 km depth at approximate horizontal distances of 650 m (SWD# 7) and 900 m (SWD# 13) from the northern fault plane (assuming a 70°S dip on the fault). SWD# 8c, which injected into the Ozan Formation at 0.83 km depth at an approximate horizontal distance of 1400 m from the northern fault plane, was the next nearest pressured well during the period of seismicity. Recently, SWD# 3a and 12 (which appear close to the southern fault in Fig. 4) have begun pressured injection into the

Smackover Formation. However, owing to the 45°N dip of this fault, the fault plane is >1100 m horizontally from the points of injection for these wells.

Wells SWD# 7 and 13 are located outside the intensity 5 isoseismal for the Dec. 12, 1988 event, but lie at the center of the intensity 4 isoseismal and the entire macroseismic area (Fig. 2). The injection depth of 2.25 km falls within the hypocentral range of 1.6 to 4.8 km calculated using intensity zone 5, but assuming that these wells are in the epicentral area at the center of intensity zone 4, hypocentral depths (3.4 to 5.5 km) fall below the injection horizon. Although this appears to argue against these wells having triggered the seismicity, a similar relation was observed at the RMA with hypocentral depths 0.8 to 1.8 km below injection depth (Healy and others, 1968).

As an alternate structural interpretation, the north-dipping fault may be the principal fault of the Hibank graben which extends to hypocentral depths. The 45° attitude of this fault would place it nearer to wells SWD# 7 and 13 at injection horizon and within the hypocentral region for intensity zone 5. This interpretation was not presented in Figure 5 because principal faults formed peripheral to actively subsiding basins typically dip toward the basin. However, the Hibank graben is but one element of a more complex fault zone, and the north-dipping fault may be antithetic to a deeper south-dipping basement fault. More information is needed to resolve this question.

Although the two principal episodes of seismicity follow the two principal increases in bar-liter values, the levels of seismic energy release do not correlate with bar-liter levels. For SWD# 7, the late 1983 and the late 1989-1990 seismicity episodes occurred when monthly bar-liter values were approximately 1.3 billion and 2.8 billion, respectively. Of the total seismic energy of the earthquakes listed in Table 1, 74% and 24% were released by these two episodes, respectively (log of seismic energy = 11.8 + (1.5 x magnitude); Bullen and Bolt, 1985). If SWD# 7 triggered the seismicity, this relationship suggests that the late 1983 earthquakes released much, if not most, of the accumulated strain in the vicinity. Otherwise, the bar-liter values in 1988 and 1989 should have induced greater energy release.

CONCLUSIONS

The absence of records of seismicity in the El Dorado area prior to 1983 suggests that the subsequent earthquakes were not naturally occurring. Well SWD# 7 and to a lesser degree SWD# 13 are implicated as having triggered the earthquakes in the El Dorado area by the following independent lines of evidence:

1) the injection histories and the seismicity are most similar temporally;

2) the wells are closest to the graben faults; and

3) the wells are closest to the center of the macroseismic area.

The recent increase in bar-liter values for SWD# 7 (see Appendix A, graph E) may lead to renewed seismicity. However, lower seismic energy releases accompanying increases in injection volume and pressure suggest that local strain has been reduced significantly. If injection induced these earthquakes, it appears unlikely that future seismicity along the same fault segment will exceed previous magnitudes (well below damaging levels).

RECOMMENDATIONS

1) To further test the hypothesis that injection has triggered earthquakes in this region, detailed structural studies utilizing well log data and available geophysical data should be conducted at all fields of pressured injection and secondary oil recovery operations involving pressured reservoirs in the region. Other sites of injection not marked by seismicity may not be in close proximity to fault zones.

2) Accurate virgin and current formation pressures and _in situ_ stress data should be collected in the El Dorado South field. These data should be used to calculate threshold formation pressures which could lead to movement on faults of the various geometries that might exist at hypocentral depths.

3) Temporary seismograph stations should be installed to monitor the vicinity of well SWD# 7. Raleigh and others (1976) demonstrated through controlled experiments that frequency and magnitude of earthquakes could be increased by increasing pore pressure near faults in the Rangley oil field (Colorado). Controlled variations of bar-liter values at SWD# 7 could verify the potential of this well to trigger earthquakes and quantify the injection levels that effect the seismicity.

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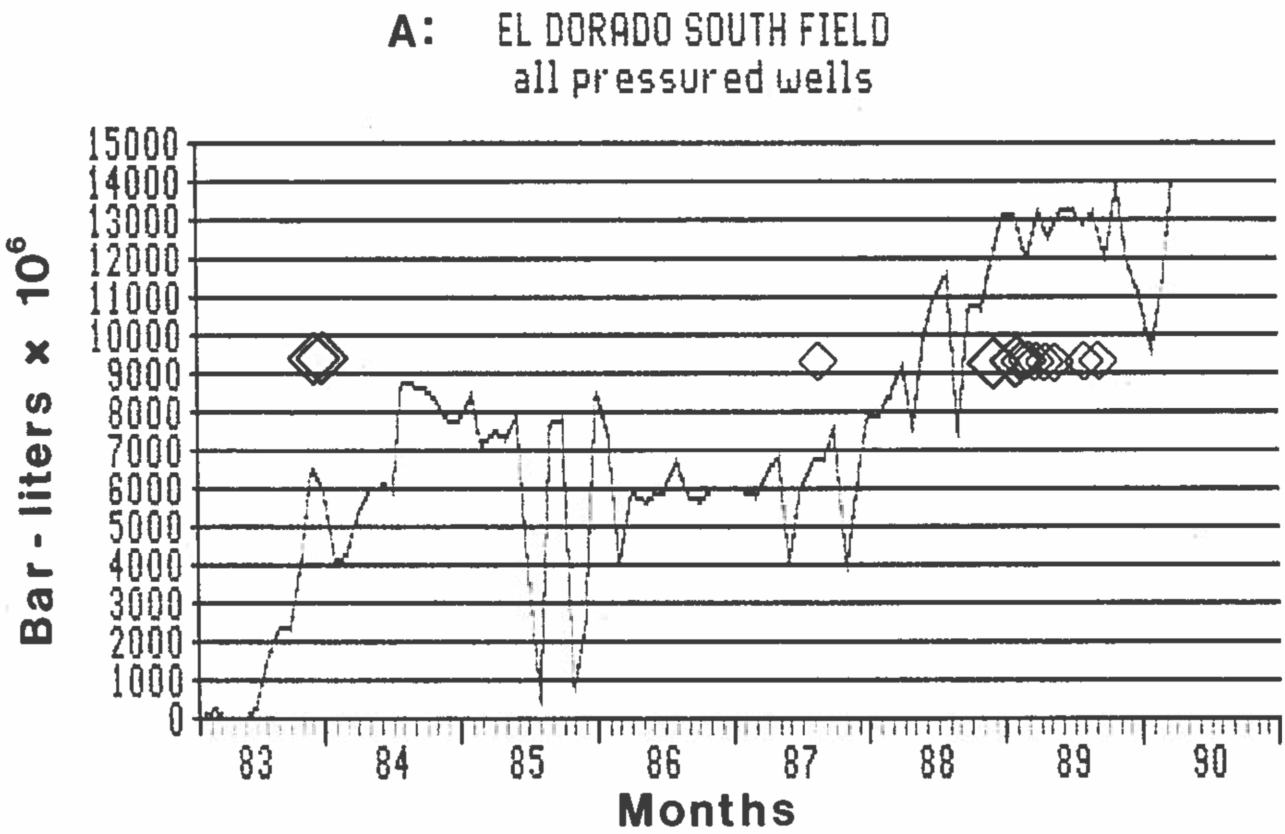
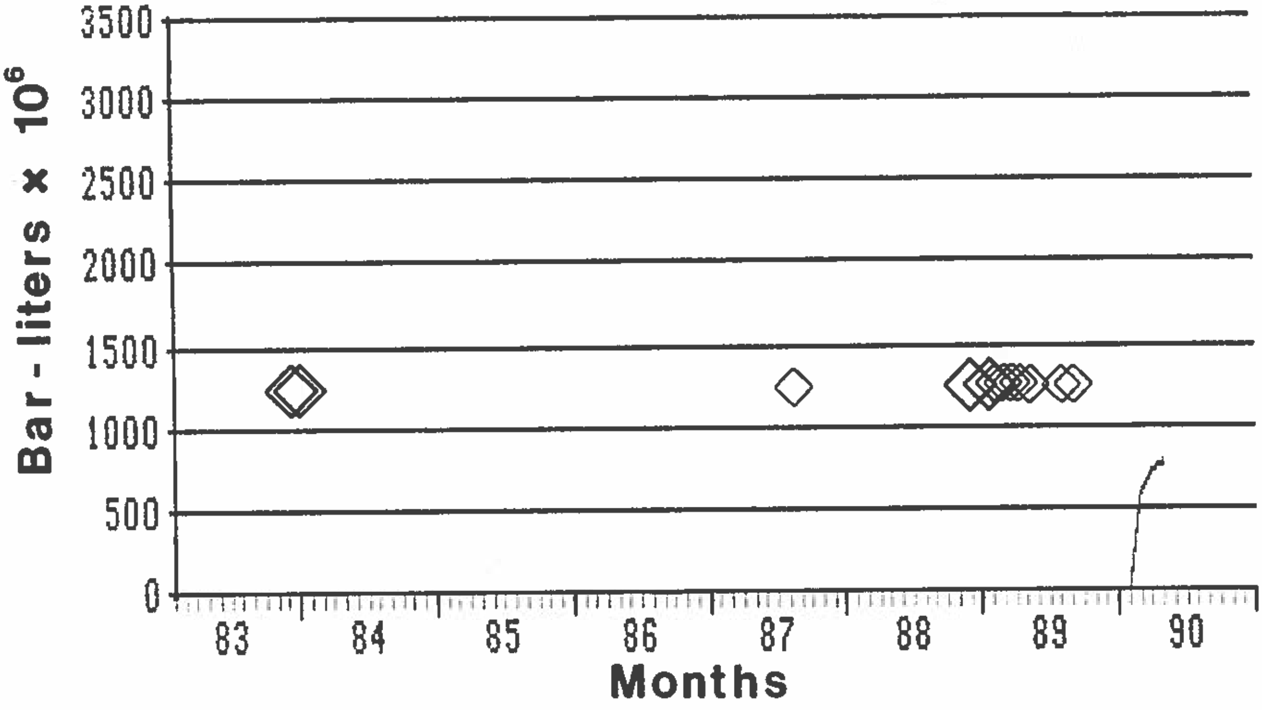
APPENDIX A

Bar-liter vs. time graphs for wells injecting under pressure in the El Dorado South field. See Figures 2 & 4 for well locations. Bar-liter values are given in millions. Earthquakes are represented by symbols: ◇ = > 2.0 magnitude; ◇ = ≤ 2.0 magnitude.

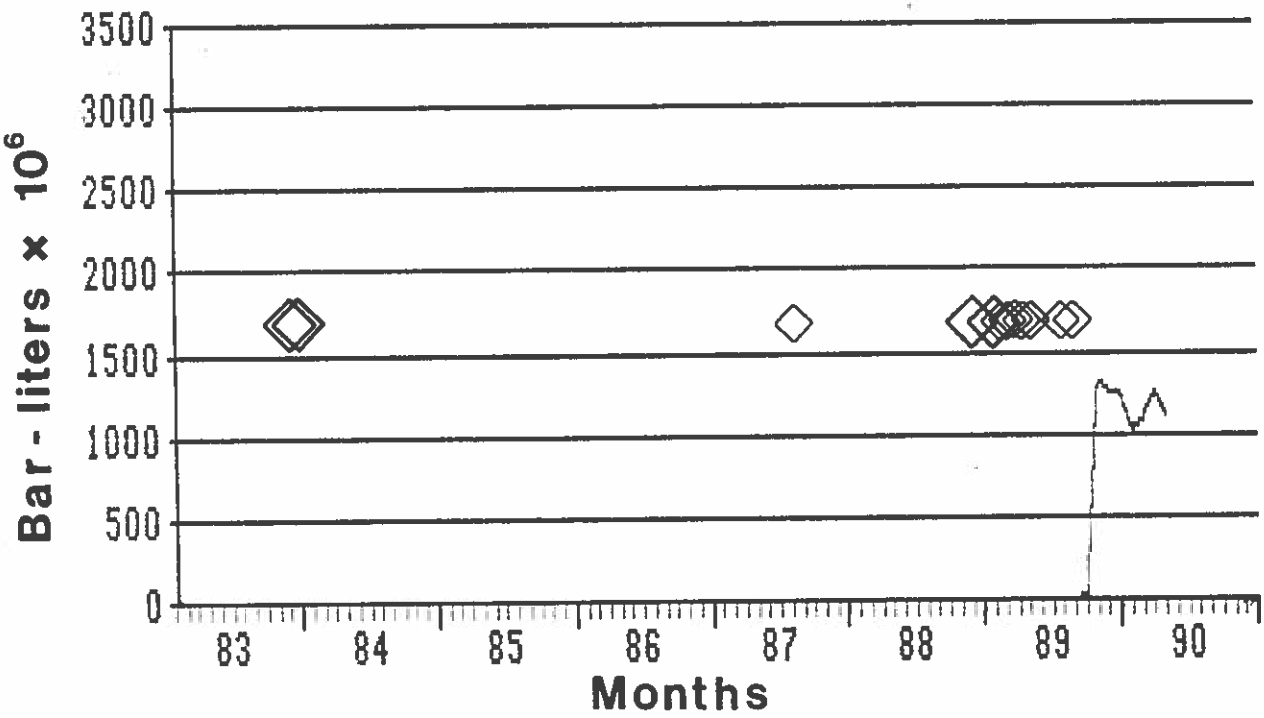
Graph A:	El Dorado South field, all pressured wells		
Graph B:	SWD# 3a,	Injection horizon	- Smackover Fm.
Graph C:	SWD# 4a,	"	"
Graph D:	SWD# 6 ,	"	"
Graph E:	SWD# 7 ,	"	"
Graph F:	SWD# 8t,	"	"
Graph G:	SWD# 12,	"	"
Graph H:	SWD# 13,	"	"
Graph I:	SWD# 14,	"	"
Graph J:	SWD# 8c,	"	- Pine Island/ Ozan Fm.
Graph K:	WDW# 3 ,	"	- Ozan Fm.
Graph L:	WDW# 4 ,	"	"
Graph M:	PWD# 2	"	

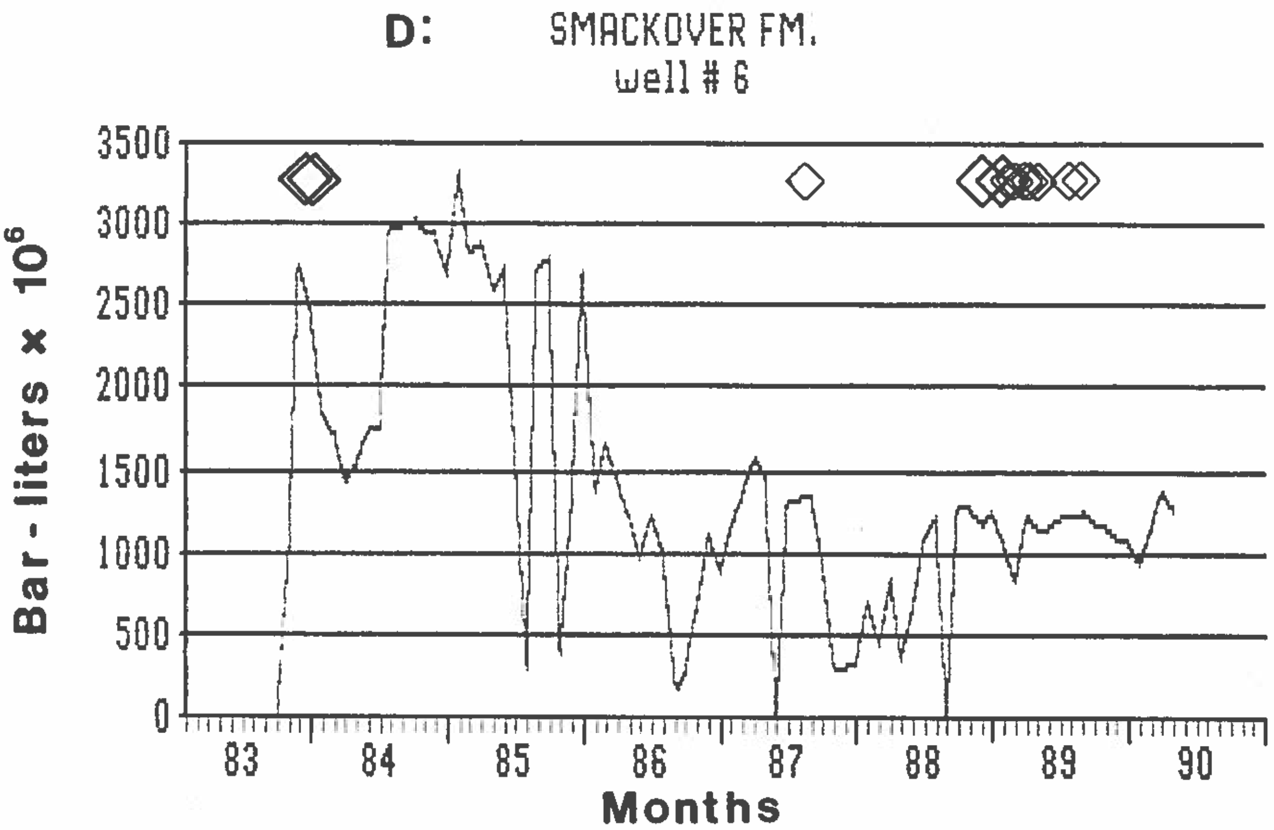

A: EL DORADO SOUTH FIELD
all pressured wells
Bar - liters x 10^6
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
83
84
85
86
87
88
89
90
Months

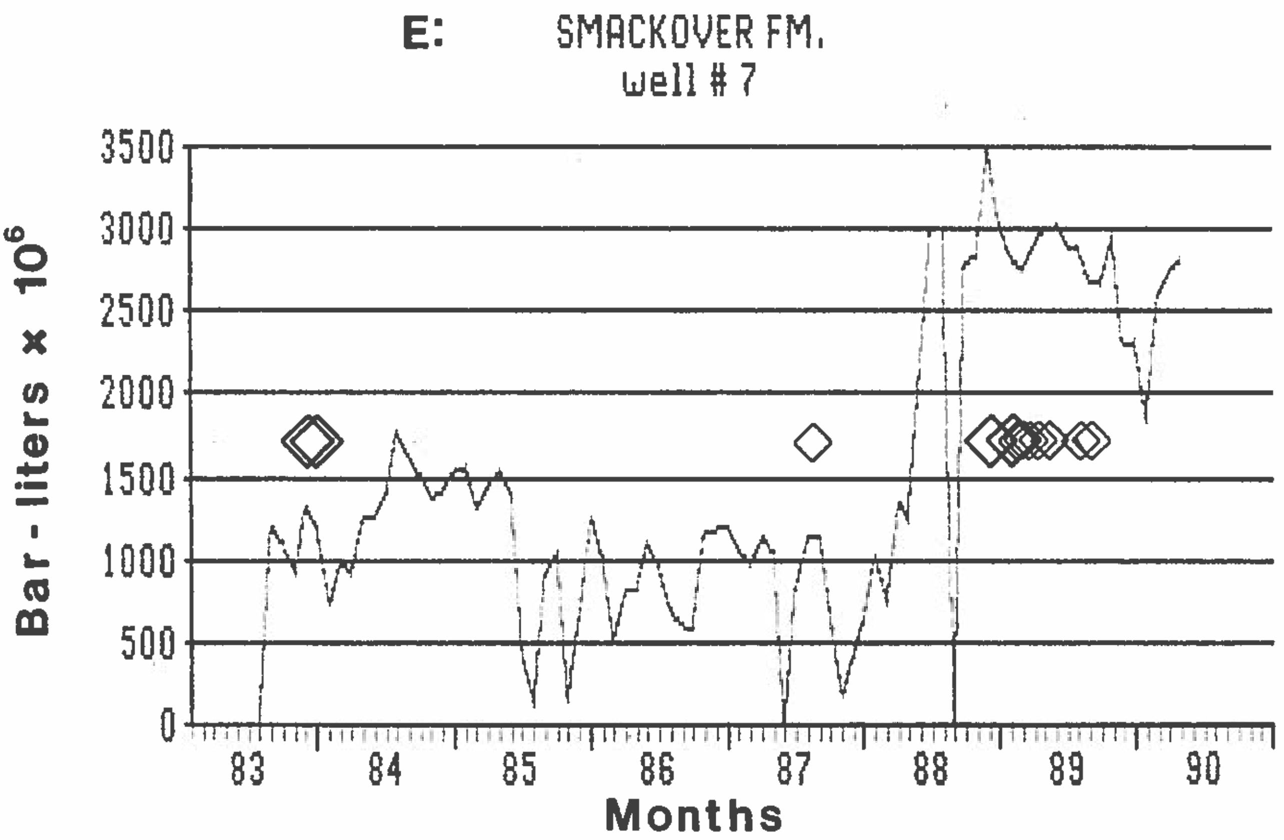
B: SMACKOVER FM.
well # 3a

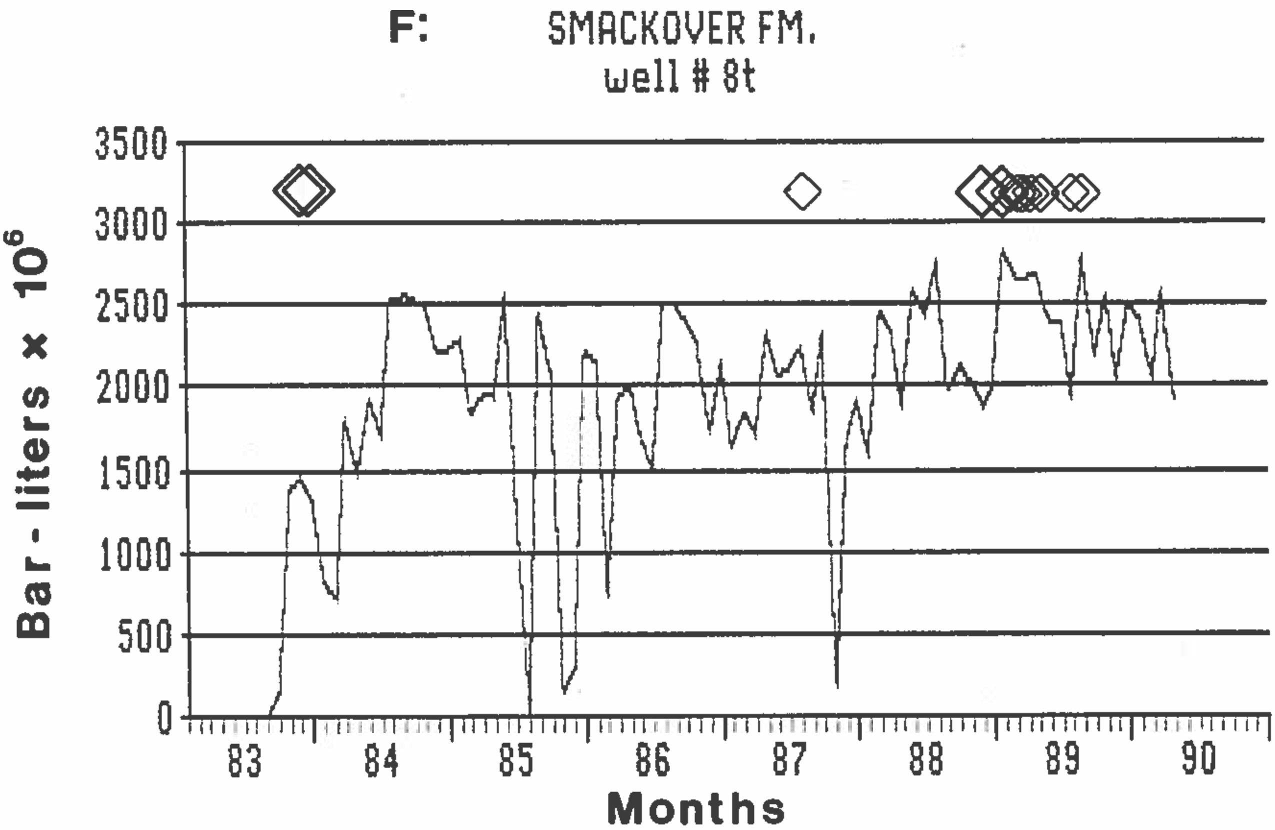


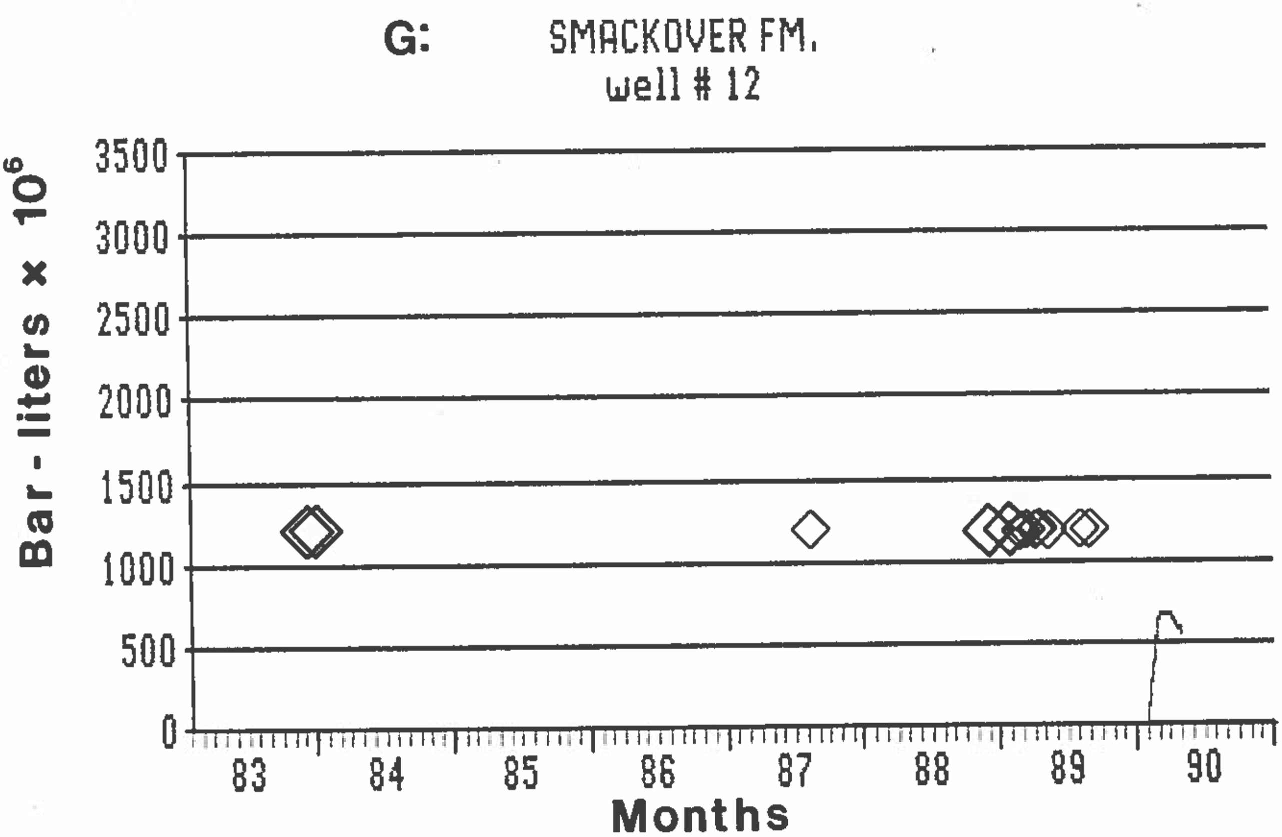
C: SMACKOVER FM.
well # 4a

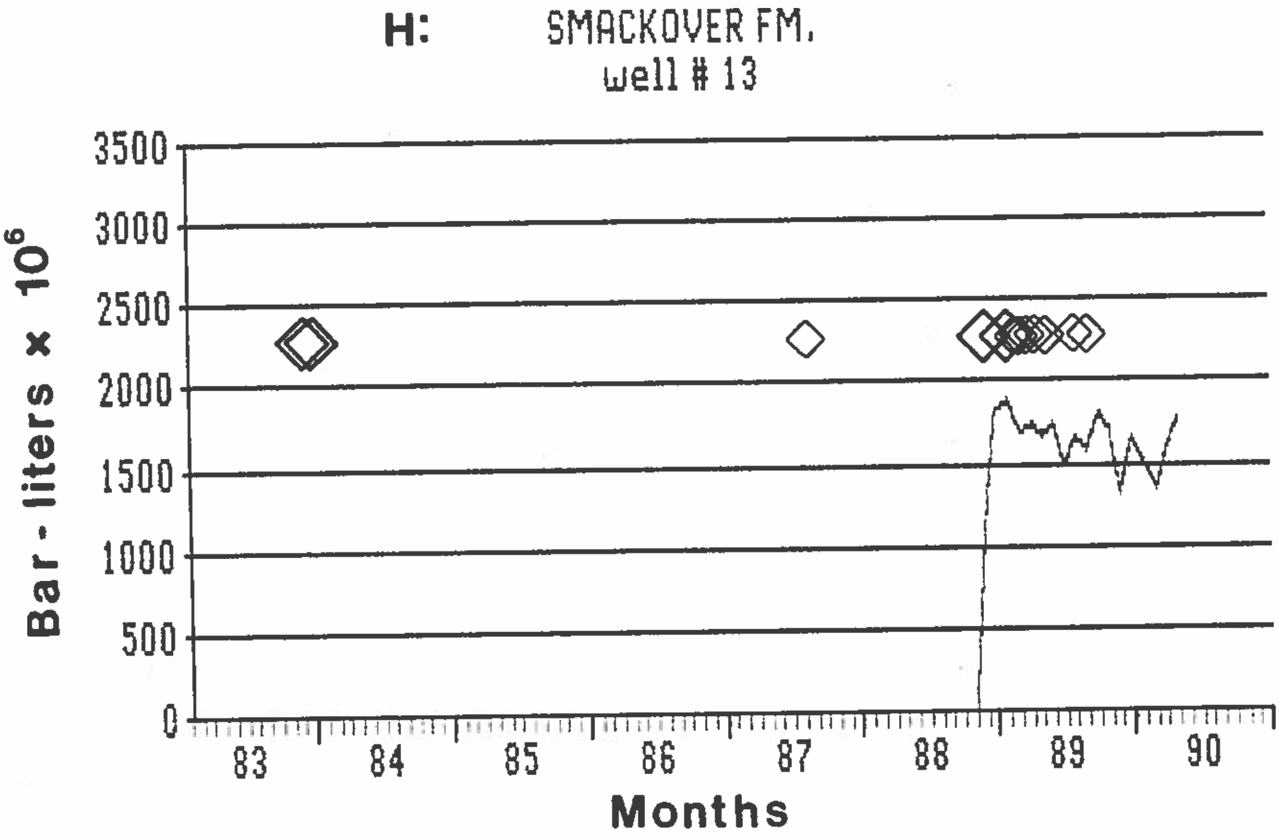


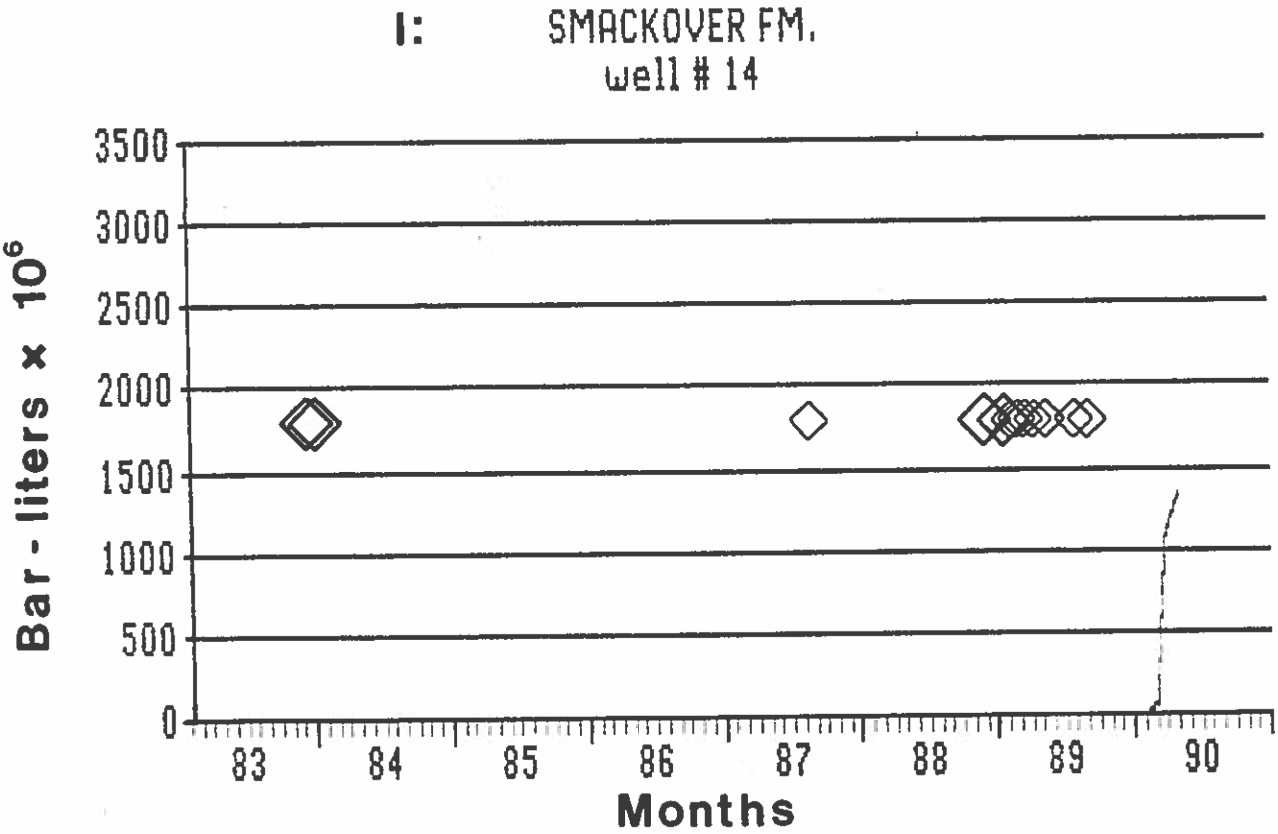

D:
SMACKOVER FM.
well # 6
3500
3000
2500
2000
1500
1000
500
0
Bar - liters x 10^6
83
84
85
86
87
88
89
90
Months

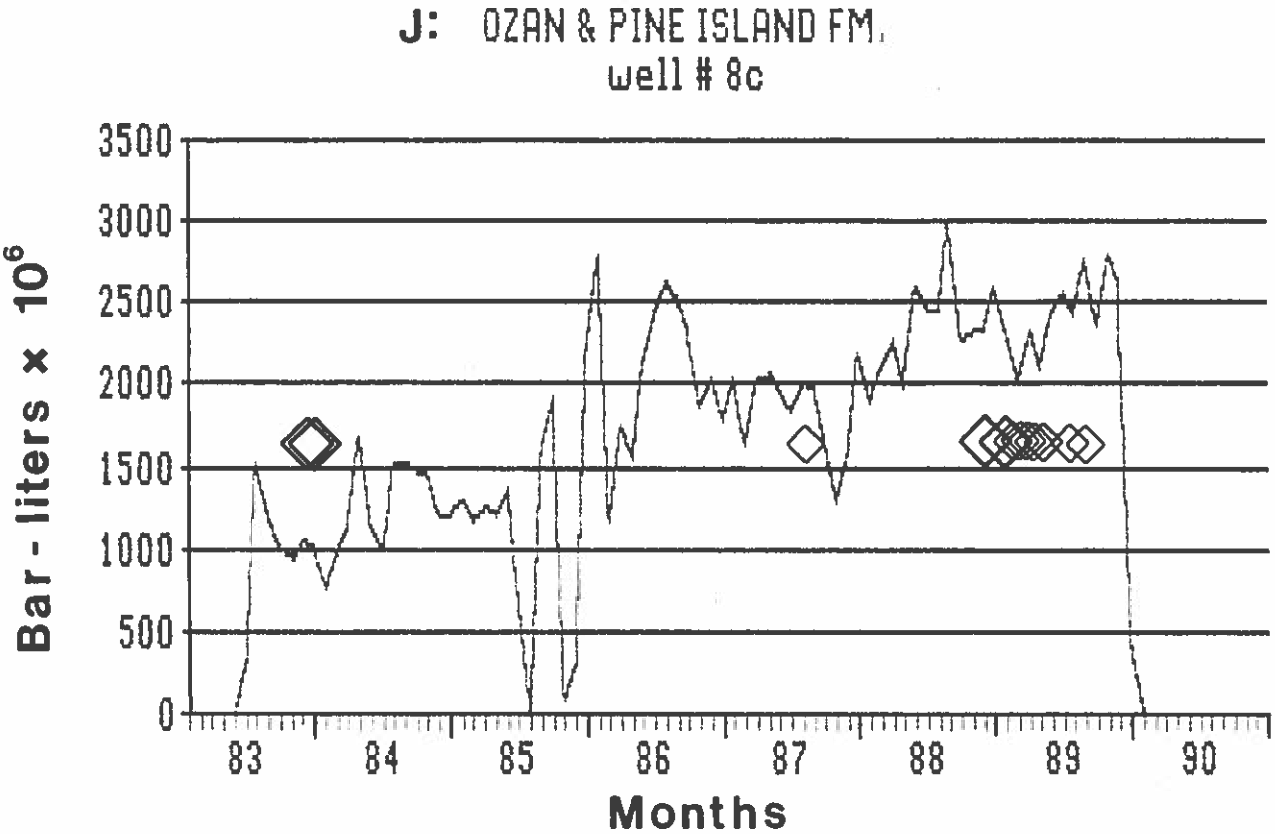

E:
SMACKOVER FM.
well # 7
3500
3000
2500
2000
1500
1000
500
0
Bar - liters x 10^6
83
84
85
86
87
88
89
90
Months

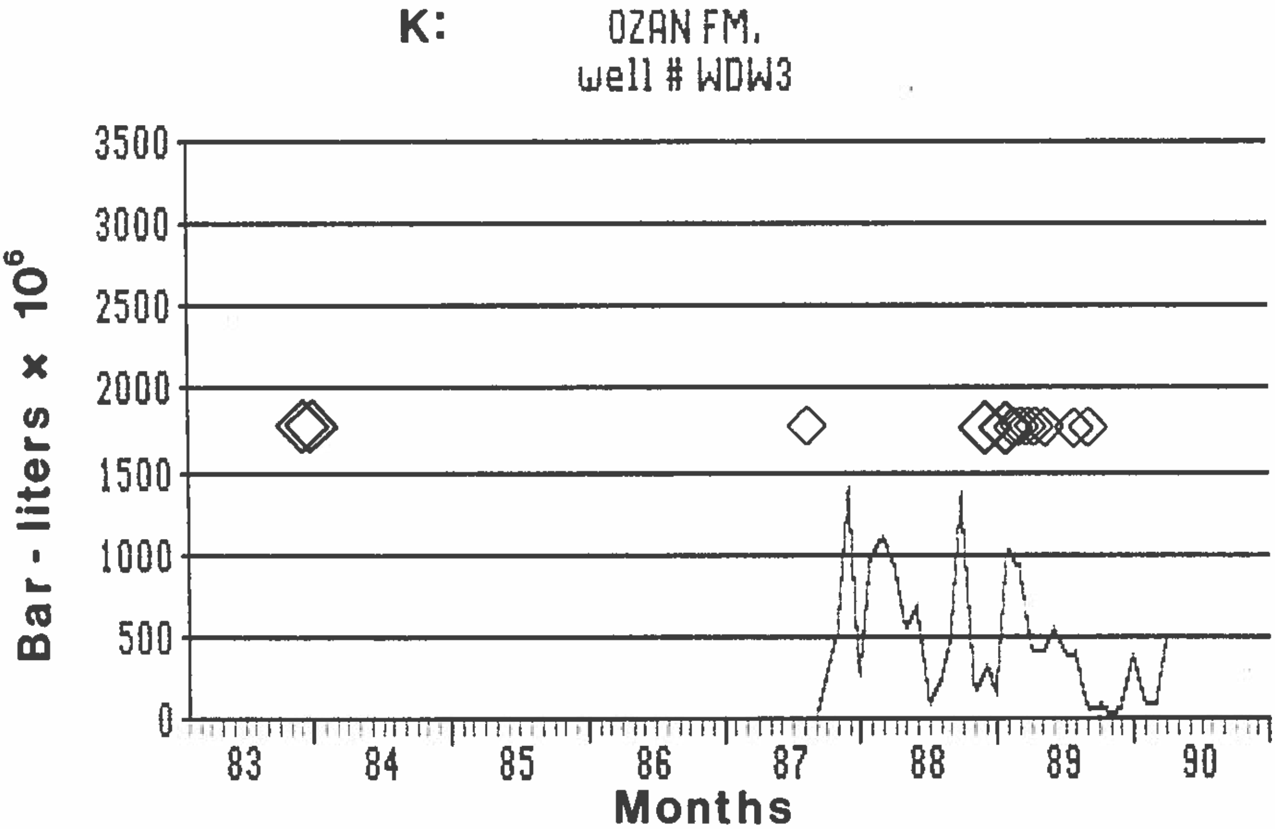

F:
SMACKOVER FM.
well # 8t
Bar - liters x 10⁶
3500
3000
2500
2000
1500
1000
500
0
83
84
85
86
87
88
89
90
Months


G:
SMACKOVER FM.
well # 12
Bar - liters x 10⁶
3500
3000
2500
2000
1500
1000
500
0
83
84
85
86
87
88
89
90
Months

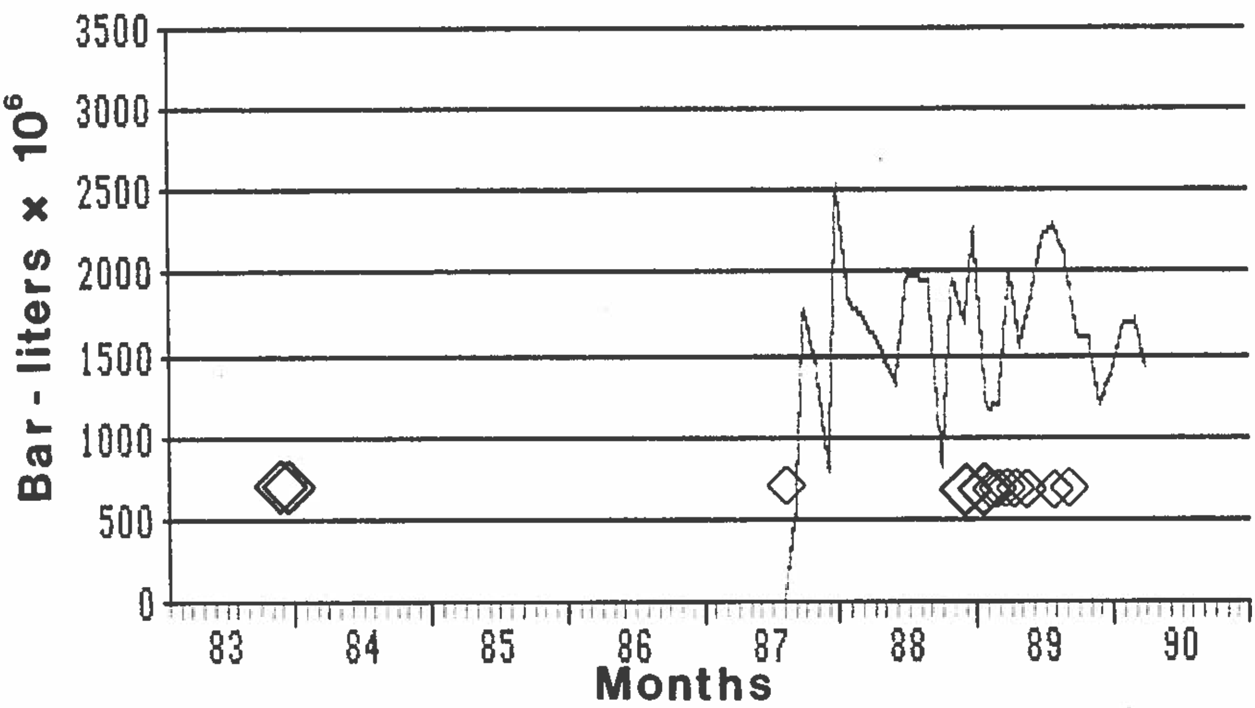

H: SMACKOVER FM.
well # 13
3500
3000
2500
2000
1500
1000
500
0
Bar - liters x 10⁶
83
84
85
86
87
88
89
90
Months


I: SMACKOVER FM.
well # 14
3500
3000
2500
2000
1500
1000
500
0
Bar - liters x 10⁶
83
84
85
86
87
88
89
90
Months

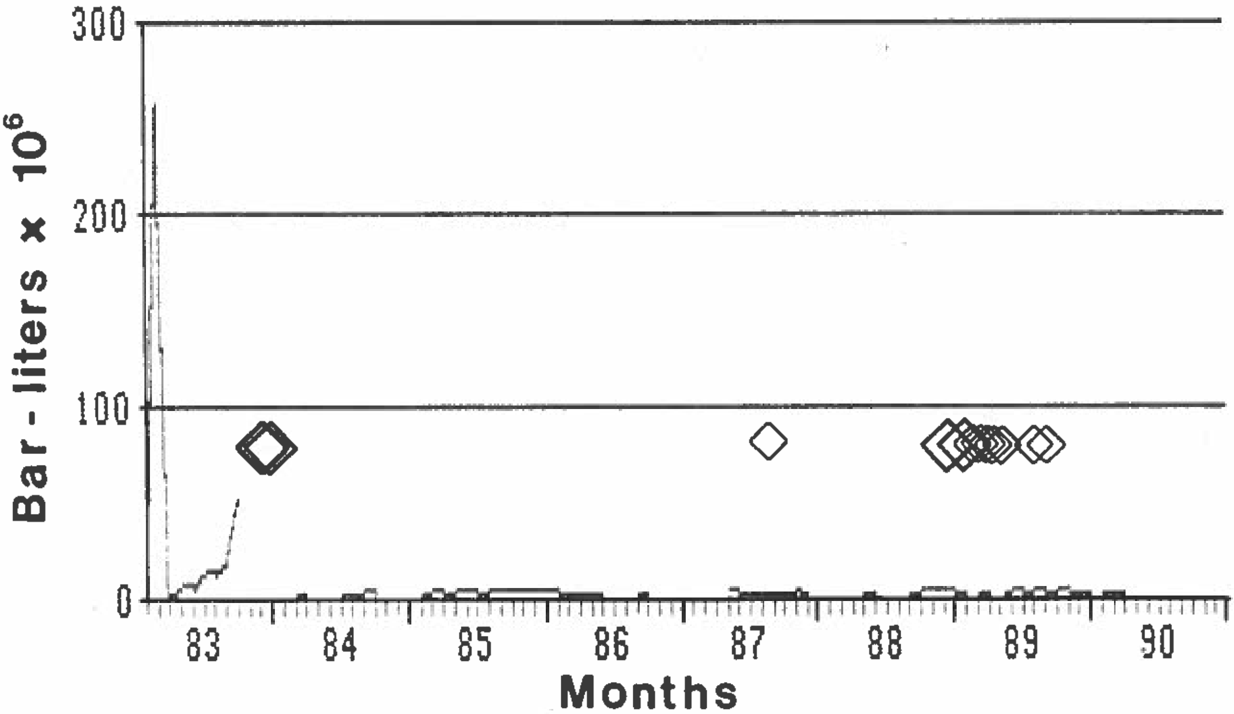

J: OZAN & PINE ISLAND FM.
well # 8c
3500
3000
2500
2000
1500
1000
500
0
Bar - liters x 10^6
83
84
85
86
87
88
89
90
Months


K: OZAN FM.
well # WDW3
3500
3000
2500
2000
1500
1000
500
0
Bar - liters x 10^6
83
84
85
86
87
88
89
90
Months

L: OZAN FM.
well WDW#4



M: OZAN FM.
well PWD#2



APPENDIX B

Responses to telephone survey of 61 area residents regarding felt effects of the magnitude 2.5 earthquake of Dec. 12, 1988 (7:10 am, CST) in the El Dorado, AR vicinity, and assigned Modified Mercalli intensities. Three newspaper accounts are also included. Additional responses and newspaper accounts regarding the earthquakes of Dec. 9, 1983 (magnitude 3.0) and Feb. 5, 1989 (magnitude 2.4) are given following the 1988 data.

Location: Modified Mercalli intensity (MM)

a) estimated vibration strength (light, moderate, strong) and duration (seconds).
b) description of physical effects of vibrations.
c) activity during vibrations.
d) description of associated noises and their direction of origin.
e) reaction to earthquake.

DECEMBER 12, 1988

1. Sec. 23- 18S- 15W: IV
   a) moderate, 30s; b) windows rattled; c) standing; d) boom, north; e) alarmed.

2. Sec. 25- 18S- 17W: I
   a) very light, 5s; d) noise of distant thunder, east.

3. Sec. 14- 18S- 16W: III
   a) light, 10s; c) standing; d) boom, east.

4. Sec. 11- 18S- 16W: III
   a) light-moderate; c) sleeping; d) boom; e) awakened.

5. Sec. 33- 18S- 15W: I
   a) not felt.

6. Sec. 10- 18S- 15W: IV
   a) moderate-strong, 3s; b) windows rattled; c) seated; e) alarmed.

7. Sec. 19- 18S- 17W: I
   a) not felt

8. Sec. 13- 19S- 15W: I
   a) not felt

9. 606 Nolia St.: I
   a) not felt

10. 2404 Ripley St.: V
    a) strong, 60s; b) windows rattled, small items fell; c) seated; d) violent sonic boom, south; e) ran outside, neighbors also.

11. Sec. 15- 18S- 15W: III
    a) light, 5s; b) trembling; d) sonic boom.

12. Sec. 26- 17S- 17W: I
    a) not felt

13. Sec. 12- 18S- 16W: I
    a) not felt

14. Sec. 29- 17S- 16W: I
    a) not felt

15. Sec. 36- 17S- 17W: I
    a) not felt

16. Sec. 31- 17S- 16W: I
    a) not felt

17. Sec. 36- 18S- 17W: I
    a) not felt

18. Sec. 26- 18S- 15W: III
    a) light, 5s; c) standing; d) noise like something heavy dropped.

19. Sec. 27- 18S- 15W: III
    a) light, 10s; b) slight jolt; d) noise.

20. Sec. 25- 17S- 18W: I
    a) not felt

21. Sec. 23- 18S- 16W: I
    a) not felt

22. Sec. 16- 18S- 16W: I
    a) not felt

23. Sec. 14- 18S- 15W: IV
    a) moderate, 20s; b) like something hit the house; c) standing; d) sonic boom; e) alarmed, ran out side, neighbors also.

24. Sec. 6- 18S- 15W: I
    a) not felt

25. 117 Sunset Rd.: IV
    a) moderate-strong, 3s; b) dishes and windows rattled; c) seated.

26. Sec. 19- 19S- 17W: I
    a) not felt

27. Sec. 14- 18S- 16W: I
    a) not felt

28. 615 Nolia St.: I
    a) not felt

29. Sec. 34- 17S- 16W: I
    a) not felt

30. Sec. 18- 18S- 15W: I
    a) not felt

31. 117 Lilac Dr.: IV
    a) moderate, 5s; c) seated; d) loud boom, south.

32. 613 Garland St.: I
    a) not felt

33. Sec. 27- 17S- 18W: I
    a) not felt

34. Sec. 15- 18S- 16W: IV
a) moderate-strong, 10s; b) knocked bowl off shelf; c) seated.

35. Sec. 28- 17S- 16W: I
a) not felt

36. Sec. 7- 18S- 15W: I
a) not felt

37. 1326 E. Burns St.: IV
a) moderate, 5s; b) windows rattled; c) reclined; e) frightened.

38. 810 S. Murphy St.: I
a) not felt

39. 1119 Marable Hill Rd.: I
a) not felt

40. 1338 N. Madison Ave.: II
a) light, 5s; b) rattling; c) standing; d) like squirrels in attic.

41. 630 Garland St.: I
a) not felt

42. Shadow Lane: IV
a) moderate-strong, 10-20s; b) rattling of sheet metal building; c) standing.

43. 1230 Marable Hill Rd.: III
a) light, 5s; b) slight tremor; d) boom.

44. 5th St. & Northwest Ave.: I
a) not felt

45. Sec. 10- 19S- 17W: I
a) not felt

46. Sec. 24- 18S- 16W: II
a) light, 10s; b) little wiggle; c) standing.

47. 412 Sunset Rd.: IV
a) moderate-strong, 5s; b) rattled windows & dishes; c) seated; e) alarmed.

48. 202 Burns St. (just east of city airport): IV
a) moderate; b) bed shaking; c) sleeping; d) roaring, south; e) awakened.

49. 1208 E. Burns St. (by Mattox Park): IV
a) moderate, 3s; c) standing; d) loud crack like car struck house.

50. 1207 E. Beech St.: III
a) light, 10s; b) bump; c) seated; d) slight noise.

51. Sec. 1- 18S- 15W: I
a) not felt

52. Sec. 7- 18S- 14W: I
a) not felt

53. Sec. 15- 18S- 14W: I
a) not felt

54. Sec. 2- 19S- 15W: II
a) light, 10s; b) very slight shake like motor running; c) seated.

55. Sec. 4- 19S- 16W: I
a) not felt

56. Sec. 13- 17S- 16W: I
a) not felt

57. E. 19th St. & N. Quaker St.: I
a) not felt

58. Sec. 19- 17S- 14W: I
a) not felt

59. 3215 Edgewood St.: II
a) light, 10s; b) little shake; c) standing.

60. 3325 Calion Rd.: I
a) not felt

61. 2609 Ford St.: I
a) not felt

NEWSPAPER ACCOUNTS ('a' is estimated from physical effects)

2300 Marilynn St.: V
a) moderate-strong; d) explosion or sonic boom; e) ran outside, neighbors also.

2416 Lakeland St.: V
a) moderate-strong; b) windows rattled, pictures moved; d) boom; e) startled.

2107 Marilynn St.: V
a) moderate; c) sleeping; d) loud noise like car hit house; e) awakened.

DECEMBER 9, 1983

1. Sec. 10 -18S -15W: V
   a) strong; b) windows rattled; e) alarmed.

2. 117 Sunset Rd.: V
   a) strong; b) floor shook.

NEWSPAPER ACCOUNTS

U.S. Hwy. 167 / Hillsboro Rd. Jct.: III
a) moderate, 5-7s; b) hanging objects swaying.

2023 Marilynn St.: V
a) strong; b) sever vibrations.

2014 Marilynn St.: V
a) strong; b) mistaken for plane crash; e) visibly shaken.

2017 Marilynn St.: IV
a) moderate-strong; b) house shaking.

2011 Helena St.: V
a) strong; b) bottles moved; d) sonic boom; e) ran outside.

2217 Lakeland: V
a) strong; b) chandelier swinging; d) sound of explosion.

FEBRUARY 5, 1989

1. 1326 E. Burns: III
   a) light-moderate; e) awakened.

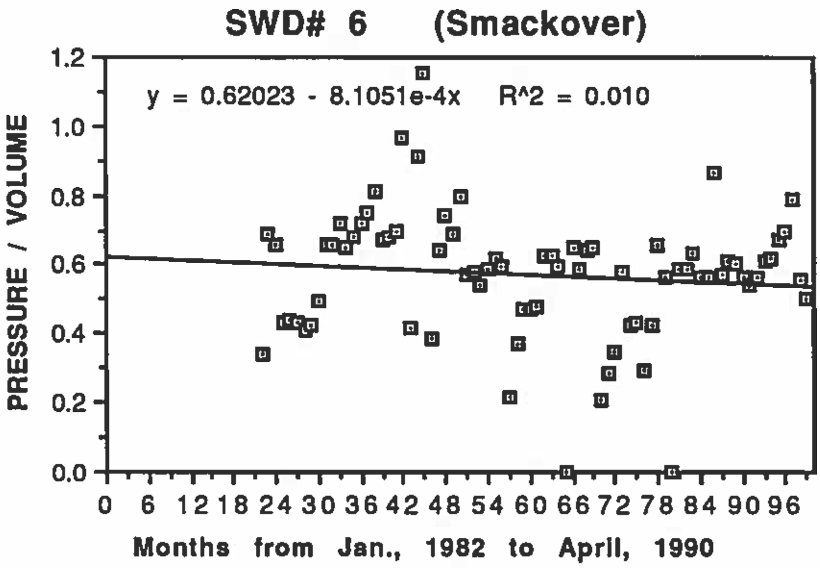
NEWSPAPER ACCOUNTS

Helena St.: no description.

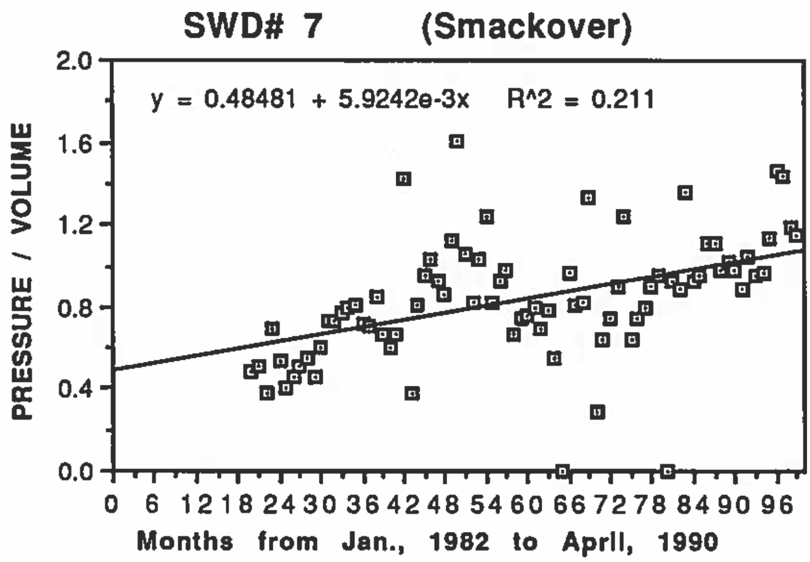
U.S. Hwy 167 south: no decription.

APPENDIX C

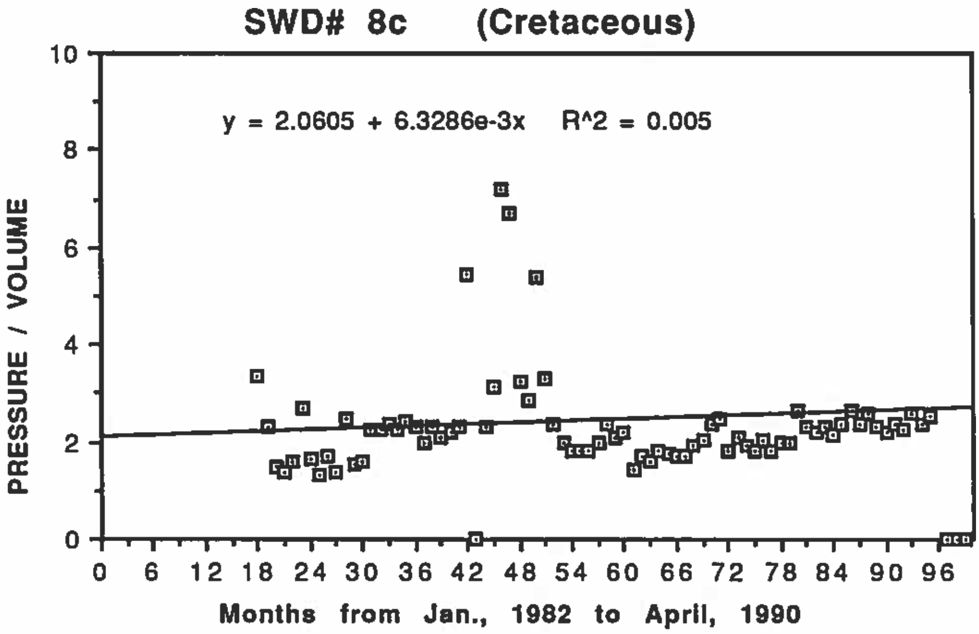
Average monthly injection pressure (psi) per volume (barrels) for wells SWD# 6, 7, 8t and 8c. See Figs. 2 and 4 for well locations (8t and 8c are both located at SWD# 8 on the maps). SWD# 6, 7, and 8t inject into the Jurassic Smackover Formation, and SWD# 8c injects into the Cretaceous Ozan and Pine Island Formations. Horizontal axis units are months from January, 1982 through April, 1990. Best-fit linear regression lines of the data are shown.

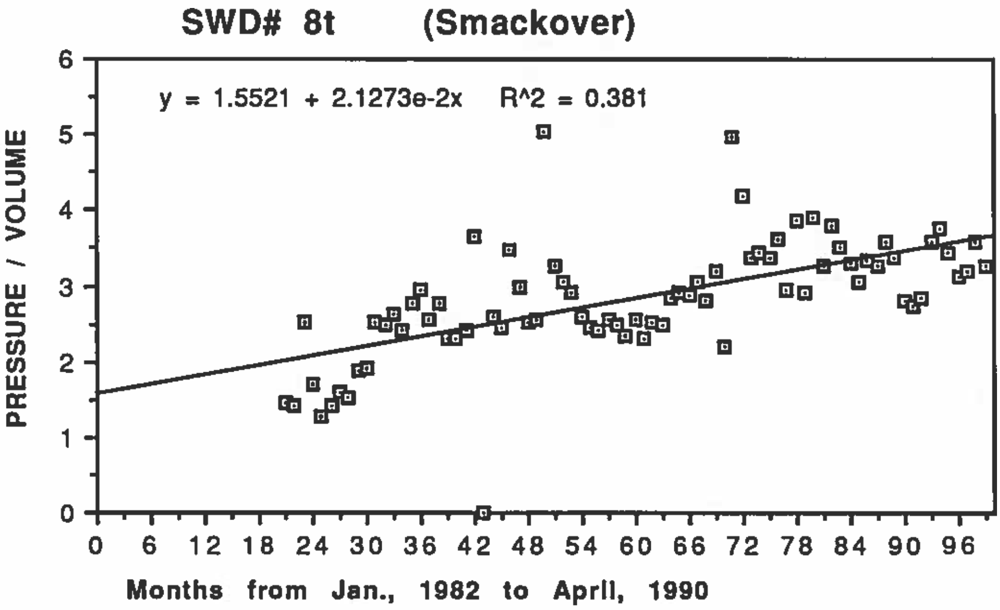


SWD# 6 (Smackover)
y = 0.62023 - 8.1051e-4x R^2 = 0.010
PRESSURE / VOLUME
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96
Months from Jan., 1982 to April, 1990



SWD# 7 (Smackover)
y = 0.48481 + 5.9242e-3x R^2 = 0.211
PRESSURE / VOLUME
2.0
1.6
1.2
0.8
0.4
0.0
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96
Months from Jan., 1982 to April, 1990


SWD# 8c (Cretaceous)
y = 2.0605 + 6.3286e-3x R^2 = 0.005
PRESSURE / VOLUME
0
2
4
6
8
10
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96
Months from Jan., 1982 to April, 1990


SWD# 8t (Smackover)
y = 1.5521 + 2.1273e-2x R^2 = 0.381
PRESSURE / VOLUME
0
1
2
3
4
5
6
0 6 12 18 24 30 36 42 48 54 60 66 72 78 84 90 96
Months from Jan., 1982 to April, 1990