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DID (OR WILL) FLUID INJECTION CAUSE EARTHQUAKES? - CRITERIA FOR A RATIONAL ASSESSMENT

Scott D. Davis* and Cliff Frohlich

Institute for Geophysics
University of Texas at Austin
8701 North Mopac Blvd.
Austin, Texas 78759

ABSTRACT

Occasionally, the injection of fluids into deep wells causes or triggers earthquake activity. We propose two lists of yes-or-no questions to assess 1) whether an ongoing injection project has induced an earthquake that has already occurred; or 2) whether a proposed injection project is likely to induce a nearby earthquake. The answers to these questions form a descriptive profile of the injection project that facilitates comparison with other projects. To illustrate the application of these questions, we describe the answers in detail for the first set of questions at two sites: 1) the Rocky Mountain Arsenal near Denver, Colorado, where three significant earthquakes occurred in 1967; and 2) an injection site near Painesville, Ohio, near the epicenter of an earthquake that occurred 31 January, 1986. We also present a table of answers to these questions for several additional sites, and review other factors that may affect the potential for induced seismic activity. The profiles of injection sites presented herein provide a convenient tool for deciding whether an injection site more closely resembles other sites where injection does, or does not induce earthquakes.

INTRODUCTION

Since 1966, when Evans (1966) established that injection of waste fluids in a deep well near Denver induced earthquakes, scientists have generally agreed that injection may induce earthquakes in tectonically favorable situations. In the interim, there have been numerous other case studies where the injection of fluids into the crust apparently caused earthquakes. The primary objective of this paper is to suggest criteria that we as professional seismologists can apply to assess seismic hazard from fluid injection. Also, as a resource for assessing cases of possible induced activity, we provide relevant information for 20 case studies in which investigators have suggested a connection between injection and earthquakes.

Although felt earthquakes are rare in many areas, they do occur occasionally nearly everywhere; indeed, the historical record contains earthquake reports from all 50 states. The practice of fluid injection for waste disposal or petroleum recovery is also common; in some states there are thousands of injection wells. Thus when an earthquake does occur near a site of fluid injection, it is reasonable to ask whether the injection caused or triggered it. In addition, when an injection project is proposed there may be public concern that damaging earthquakes may result.

In particular, as earthquake seismologists we should be prepared to address the following questions:

Situation 1) If injection is ongoing and an earthquake has occurred: *Did this injection project induce the earthquake activity?*

Situation 2) If injection is proposed and earthquake hazard is uncertain: *Is this injection project likely to induce damaging seismic activity?*

In each case, there are compelling social and economic incentives for finding the best possible answers to these questions. We have assisted in the evaluation of several injection projects, both in the presence and absence of possible related seismic activity. The present paper summarizes our approach to providing reasonable answers to the questions posed above (Davis, 1985; 1989; Davis and Frohlich, 1987; 1988; Davis and Pennington, 1989).

We first present seven questions (Table 1) for assessing whether an ongoing fluid injection project may have induced an earthquake (Situation 1 above). These questions address four factors: 1) the historical seismicity of the region, 2) the presence or absence of correlation between injection

*Presently at U. S. Geologcial Survey, Memphis State University/CERI, Memphis, TN 38152

and seismic activity, 3) the geographical and geological relationship between the sites of injection and seismic activity, and 4) the expected effect of fluid injection on the stress regime at the injection sites. We have phrased these questions so that a "yes" answer supports injection as the cause of the earthquake, while a "no" answer suggests that injection is not the cause.

We then answer these seven questions for 20 earthquake sequences (Tables 2 and 3), including a fictional account of seismicity induced by injection down a deep well near Boston, Massachusetts (Franzen, 1992). Many of these earthquake sequences are clearly induced by injection, while for other sequences the causal relationship between injection and earthquakes is less clear. To illustrate the use of these questions we give detailed justifications for our yes-or-no answers at two injection sites: Denver, Colorado, and Painesville, Ohio. Although the individual yes-or-no questions may be somewhat subjective, we would argue that the cumulative effect of the entire series provides a basis for an informed judgement about the relation of the earthquakes to the injection. While there is no specific number of "yes" answers which constitutes proof that injection caused an earthquake sequence, generally more "yes" answers make it more likely that injection is responsible. Our practical result is that in every case we studied where five or more of the questions had "yes" answers, most professional seismologists would conclude that injection induced the earthquake sequence (Table 2).

Finally, we present a second list of ten questions (Table 4) that evaluate whether a proposed injection project is likely to induce an earthquake (Situation 2 above). From the profile developed above, we conclude that prior to injection, Denver would have received four "yes" answers to these questions. To further illustrate the method, we give answers for two other sites: Tracy, Quebec, and Texas City, Texas.

At present it is impossible to predict the effects of injection with absolute certainty. This uncertainty arises both because the underlying physical mechanisms of earthquakes are poorly understood, and because in nearly every specific situation there is inadequate or incomplete information about regional stresses, fluid migration, historical seismicity, etc. Clearly, a series of seven or ten yes-or-no questions oversimplifies many of these issues. Thus, these profiles should not be used as an absolute predictor of whether fluid injection at a particular site will induce earthquakes. Rather, they provide a means for comparing specific injection projects with others that have

Table 1
Seven Questions Forming a Profile of a Seismic Sequence

	Question	Earthquakes Clearly NOt Induced	Earthquakes Clearly Induced	I Denver, Colorado	II Painesville Ohio
	Background Seismicity				
1	Are these events the first known earthquakes of this character in the region?	NO	YES	YES	NO
	Temporal Correlation				
2	Is there a clear correlation between injection and seismicity	NO	YES	YES	NO
	Spatial Correlation				
3a	Are epicenters near wells (within 5 km)?	NO	YES	YES	YES?
3b	Do some earthquakes occur at or near injection depths?	NO	YES	YES	YES?
3c	If not, are there known geologic structures that may channel flow to sites of earthquakes?	NO	YES	NO?	NO?
	Injection Practices				
4a	Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?	NO	YES	YES	YES
4b	Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?	NO	YES	YES?	NO?
	TOTAL "YES" ANSWERS	**0**	**7**	**6**	**3**

Table 2
Locations of Possible Injection-Induced Earthquakes Examined

SITE	Maximum Magnitude	Date[1]	Injection Depth (km)	Focal[2] Mech	Surface[3] Pres. (bars)	YES[4] Answers
WASTE DISPOSAL						
Denver RMA, Colorado	5.3-5.5	08 / 67	3.7	N / SS?	?	6
El Dorado, Arkansas	3.0	12 / 83	2.2	?	20 - 60	7
Painesville, Ohio	5.0	01 / 86	1.8	SS	110	3
Peabody, Massachusetts[5]	6.1	06 / 92	7.6 ?	TH	?	(3)
SECONDARY RECOVERY / PRESSURE MAINTENANCE						
Ashtabula County, Ohio	3.6	07 / 87	1.8	SS	100	5
Cogdell Oil Field, Texas	4.6	06 / 78	2.1	N	184	5
The Geysers, California	4.0 ?	09 / 92	1.7 - 2.5	N / SS	0	6
Gobles Oil Field, Ontario	3+	08 / 81	0.9	N / TH	?	(2)
Los Angeles Basin, California	3.2	05 / 71	0.9 - 1.5	N?	?	(2)
Rangely, Colorado	3.4	08 / 64	1.7	SS	72	6
Sleepy Hollow, Nebraska	2.9	07 / 79	1.1 - 1.2	?	50	(3)
SOLUTION MINING / ACID TREATMENT						
Beowawe, New Mexico	-1	08 / 83	1.3	?	~ 100	(4)
Dale, New York	0.8	11 / 73	0.4	TH	129	7
EXPERIMENTAL / INJECTION TESTS / HYDRAULIC STIMULATION						
Baca, New Mexico	-2	05 / 82	1.7	?	?	6
Fenton Hill, New Mexico	-2	12 / 83[6]	2.7 - 3.5	N / LP	45 - 50	6
Matsushiro, Japan	2.8	01 / 70	1.8	SS	50	(3)
Orcutt Oil Field, California	3.5	01 / 91	0.1 - 0.3	TH	80	7
Puhagan field, Philippines	2.4	05 / 83	~ 1	N	< 10	6
Soultz-Sous-Forets, France	?	12 / 88	2.0	?	82	6
Wairakei, New Zealand	3.0	06 / 84	1.3	SS?	20 - 30	(4)

[1]Date of the largest event or injection experiment.
[2]Focal Mech is the focal mechanism: LP = Long Period Tensile Events, N = Normal, SS=Strike-Slip, TH = Thrust, ? = Unknown or not available.
[3]Surface Pres is a typical surface injection pressure (bars) for that site.
[4]YES Answers denotes number of criteria questions answered "Yes" in Table 3; parentheses indicate 3 or more questions were unanswered, or 5 or more questions were uncertain or unanswered.
[5] fictional account
[6] one of several injection periods

or have not induced earthquakes.

However, we make no apologies for our approach. In our experience these yes-or-no profiles do provide a convenient way of applying current scientific knowledge to these problems and communicating this information to the public. Moreover, our description of how we arrived at the profiles for sites in Colorado, Quebec, Ohio, and Texas provides examples of many of the difficulties one may encounter when assessing injection sites.

In some cases, it may be useful to make a distinction between earthquakes as either "triggered" or "induced", depending on what fraction of energy released in the earthquake was created artificially. Using the terminology of McGarr (1991), "triggered" earthquakes would include cases where most of the energy accumulated naturally by geologic forces, whereas "induced" earthquakes would only include those in which most of the energy release could be directly related to man-made sources. However, the magnitudes of in situ principal stresses are often poorly known (Zoback and Zoback, 1980); thus in practice this distinction is not always clear. Consequently, in this report we use the term "induced" to include both "triggered" and "induced" earthquakes.

Several recent studies also describe earthquakes caused by the withdrawal of fluids (Pennington et al., 1986; Segall, 1989; Grasso and Wittlinger, 1990; Doser et al., 1991). However, in this paper we will not discuss the effects of production or withdrawal on seismic activity, as our focus is the evaluation of seismic hazard from fluid injection.

SITUATION 1: DID INJECTION INDUCE EARTHQUAKES?

Seven Questions

In this section we discuss seven questions (Table 1) that address the four factors mentioned above concerning the relationship between an earthquake and ongoing injection activity. We have phrased these questions so that the answers will be "yes" for earthquakes clearly induced by injection, and "no" for an earthquake apparently unrelated to fluid injection. In many instances, the case for a particular "yes" or "no" answer is uncertain because of incomplete or conflicting information, and we denote these less certain answers with question marks -- "yes?" or "no?".

To illustrate the application of these questions, we discuss how we arrived at the answers for the earthquake sequence that occurred at the Rocky Mountain Arsenal near Denver, Colorado (Healy et al., 1968; Hsieh and Bredehoeft, 1981). In 1961, the Army Corps of Engineers drilled a well to a depth of 3671 m into crystalline Precambrian basement; injection for waste disposal began in 1962. Beginning in 1962, a series of earthquakes occurred near the well, with the three largest earthquakes having estimated magnitudes of 5 and above (Healy et al., 1968).

For contrast, we also discuss our answers for a sequence of earthquakes that occurred in 1986 near Painesville, Ohio. This sequence included an mb=5.0 event within 17 km of a nuclear power plant. While some (Ahmad and Smith, 1988) have suggested that injection at three waste disposal wells may have triggered the earthquakes, other studies have favored a natural, tectonic origin for the seismicity (Nicholson et al., 1988; Talwani and Acree, 1986; Wesson and Nicholson, 1986).

Question 1 (Background Seismicity): Are these events the first known earthquakes of this character in the region?

Clearly, if earthquakes occur regularly in the target region, the occurrence of an earthquake sequence near an injection well is not strong evidence for a causal relationship unless the character of the earthquake is unusual. In Denver, there may have been occasional very small earthquakes, and a possible larger earthquake occurring in 1882 (Coffman et al., 1982); however, the sequence beginning in 1962 was clearly anomalous in that the events were so numerous, and so widely felt.

Table 3

Yes-and-no profiles (as described in Table 1) for the 20 sites of possible injection induced seismicity listed in Table 2.

Site	1 Historical Earthquakes	2 Temporal Correlation	3a Earthquake Epicenters	3b Earthquake Depths	3c Geologic Structures	4a Pressures (Well)	4b Pressures (Hypocenters)
WASTE DISPOSAL							
Denver RMA, Colorado	YES	YES	YES	YES	NO?	YES	YES?
El Dorado, Arkansas	YES	YES?	YES	YES	YES	YES?	YES?
Painesville, Ohio	NO	NO	YES?	YES?	NO?	YES	NO?
Peabody, Massachusetts	NO?	NO?	YES?	YES?	YES?	?	?
SECONDARY RECOVERY / PRESSURE MAINTENANCE							
Ashtabula County, Ohio	YES	NO?	YES	YES	NO?	YES	YES
Cogdell Oil Field, Texas	YES	NO	YES	YES	-	YES	YES
The Geysers, California	NO	YES	YES	YES	YES	YES?	YES?
Gobles Oil Field, Ontario	?	NO	YES	YES	NO	?	?
Los Angeles, California	NO	NO?	YES	NO	YES?	?	?
Rangely, Colorado	?	YES	YES	YES	YES	YES	YES
Sleepy Hollow, Nebraska	?	NO?	YES	YES	YES?	?	?
SOLUTION MINING / ACID TREATMENT							
Beowawe, New Mexico	?	YES?	YES	YES	YES	?	?
Dale, New York	YES	YES	YES	YES	YES	YES	YES
EXPERIMENTAL / INJECTION TESTS / HYDRAULIC STIMULATION							
Baca, New Mexico	?	YES	YES	YES	YES	YES?	YES?
Fenton Hill, New Mexico	?	YES	YES	YES	YES?	YES	YES
Matsushiro, Japan	NO	NO?	YES	YES	YES	NO?	NO?
Orcutt Oil Field, California	YES	YES?	YES	YES	YES	YES?	YES?
Puhagan field, Philippines	YES?	YES?	YES	YES	YES	YES?	NO?
Soultz-Sous-Forets, France	?	YES	YES	YES	YES	YES?	YES?
Wairakei, New Zealand	NO?	YES?	YES	?	YES	YES?	?

Table 4
Criteria to Determine if Injection May Cause Seismicity

	Question	NO APPARENT RISK	CLEAR RISK	Texas City, Texas	Tracy Quebec	Denver RMA, Colorado
	Background Seismicity					
1a	Are large earthquakes ($M \geq 5.5$) known in the region (within several hundred km)?	NO	YES	NO	YES	YES
1b	Are earthquakes known near the injection site (within 20 km)	NO	YES	NO	YES	NO?
1c	is rate of activity near the injection site (within 20 km) high?	NO	YES	NO	NO	NO
	Local Geology					
2a	Are faults mapped within 20 km of the site?	NO	YES	YES	YES	NO?
2b	If so, are these faults known to be active?	NO	YES	NO	NO	NO
2c	Is the site near (within several hundred km of) tectonically active features?	NO	YES	NO?	YES	YES
	State of Stress					
3	Do stress measurements in the region suggest rock is close to failure?	NO	YES	NO	NO?	YES[1]
	Injection Practices					
4a	Are (proposed) injection practices sufficient for failure?	NO	YES	NO?	YES	YES[1]
4b	If injection has been ongoing at the site, is injection correlated with the occurrence of earthquakes?	NO	YES	NO	N.A.	N.A.
4c	Are nearby injection wells associated with earthquakes?	NO	YES	NO	N.A.	N.A.
	TOTAL "YES" ANSWERS	**0**	**10**	**1**	**5**	**4**

[1]Assumes stress measurements completed prior to survey

This was clearly the first documented sequence of this character for the region. [Answer: DENVER = YES]

In Ohio, the historical record shows that earthquakes having Mercalli Intensity IV or V were felt in northwestern Ohio in 1906, 1928, 1943, and 1958 (Coffman et al., 1982). The 1943 event, with intensity V, has been relocated near the epicenter of the 1986 event (Dewey and Gordon, 1984), and had a comparable magnitude. These data suggest that similarly felt earthquakes occur approximately every twenty years in this region, and thus the occurrence of an intensity VI event in 1986 is not in and of itself unusual. [Answer: OHIO = NO]

Question 2 (Temporal Correlation): Is there a clear correlation between the time of injection and the times of seismic acitivity?

Even if we lacked a clear scientific understanding of the processes causing earthquakes, most people would be convinced of a causal relationship if the seismicity "turned on" when injection began and "turned off" when injection stopped. In Denver, scientists were able to establish a clear relationship between the volume of injection and the number of seismic events, with a time lag of about ten days (Healy et al., 1968). More recently, Hsieh and Bredehoeft (1981) were able to explain the spatial and temporal extent of seismic activity in Denver in terms of the flow of fluids along a permeable semi-infinite rectangular region which approximately contained the activity. Earthquakes occurred when fluid pressures in the model had increased approximately 32 bars or more above hydrostatic. [Answer: DENVER = YES]

In Ohio, injection had been ongoing for about 15 years before the recent sequence of earthquakes began. As felt earthquakes have occurred approximately every 20 years in this area, we cannot easily attribute the 1986 event to the onset of injection. [Answer: OHIO = NO]

Question 3a (Spatial Correlation): Are epicenters near the wells?

It is more plausible that deep well injection triggers earthquakes if we can establish that the injection would cause fluid pressure increases at hypocentral distances. In Denver, most of the epicenters were within 8 km of the well, and several were within 2 km. The average distance was about 4 km. There was also an apparent migration of activity away from the well as time passed. [Answer: DENVER = YES].

In Ohio, two small earthquakes in 1983 (magnitudes 2.5 and 2.7) had reported epicenters within 5 km of one of the injection wells; however, these locations are uncertain (Nicholson et al., 1988). The mainshock on 31 January 1986 and all but one of its immediate aftershocks occurred at distances of about 10 to 15 km from the well. The single exception was an aftershock with magnitude -0.2 which occurred on 12 March 1986 about 3 km from the well. Between April 1986 and April 1987, several small (magnitude 1.0 or less) earthquakes were located near one of the injection wells (see addendum in Nicholson et al., 1988). Apart from these events, which may not have been detected if the network had not been installed due to the 31 January 1986 event, the aftershocks seem too distant to have been affected by fluid injection if the fluids behave as expected for radial fluid flow models. Nevertheless, we assign a tentative "yes?" answer as some earthquakes do occur near the injection site, although it is not clear if these earthquakes are related to the magnitude 5.0 earthquake. [Answer: OHIO = YES?]

Question 3b (Spatial Correlation): Do some earthquakes occur at depths comparable to the depth of injection?

Induced earthquakes would be most likely to occur close to the injection well or nearby at similar depths if the injectate flows along approximately horizontal strata. In Denver, earthquakes did occur near the injection depth, although some occurred at shallower depths and some occurred up to about 3.3 km deeper than the well. [Answer: DENVER = YES]

In Ohio, the majority of aftershocks occurred in the vicinity of the hypocenter of the 31 January 1986 earthquake, with depths about 3 km deeper than the injection point. However, several small earthquakes were also subsequently located near the injection well, and at depths of 2 km or less. Although it is not clear if there is a connection between the two sets of earthquakes, we assign a tentative "yes?" on the basis of these shallow events. [Answer: OHIO = YES?]

Question 3c (Local Geology): If some earthquakes occur away from wells, are there known geologic structures that may channel fluid flow to the sites of the earthquakes?

Fluid pressure might affect activity at considerably greater distances if there are geological structures that channel pressure increases toward the hypocentral region, making a radial flow model inappropriate. At Denver no such structure has been mapped, although some investigators have postulated the existence of a fault or fracture system on the basis of earthquake focal mechanisms, hypocentral locations, and fractures observed in well cores and in neighboring rocks (Hsieh and Bredehoeft, 1981). A seismic reflection survey reported several minor faults with displacement less than 30 meters in the epicentral region (Healy et al., 1968), although the nearest well-mapped faults are over 30 km to the northwest (Hsieh and Bredehoeft, 1981). [Answer: DENVER = NO?]

In Ohio, there are no known structures that should channel fluid flow in either the Precambrian basement or in the overlying Paleozoic strata. Ahmad and Smith (1988) propose the existence of a fault zone on a weak linear trend in the aftershock locations, an observed magnetic anomaly, the isoseismal pattern of the 31 January earthquake, and slight variations in basement topography. However, Roeloffs et al. (1989) find no evidence for anisotropic permeability in their hydrologic modelling. As the contact between the Precambrian and the Paleozoic strata is very nearly horizontal and there are no mapped faults in this region, we assign a tentative "no?". [Answer: OHIO = NO?]

Question 4a (Injection Practices): Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the bottom of the well?

Clearly, for any reasonable hydrological model, the largest pressure increases will occur in close proximity to the well bottom. If well bottom pressures are insufficient to induce failure, it is unlikely that the lower fluid pressures found at hypocentral distances will induce earthquakes. The Mohr-Coulomb model is the most common method for evaluating shear failure induced by increases in pore fluid pressure (e.g. Davis and Pennington, 1989; Nicholson and Wesson, 1990). According to the Mohr-Coulomb failure criterion, the critical shear stress t_{crit} needed to cause slip on a fault is related to the normal stress σ_n across the fault, the fluid pressure p, the coefficient of friction μ_f, and the inherent shear strength τ_0 of the rock by the equation:

$$\tau_{crit} = \tau_0 + \mu_f(\sigma_n - p)$$

This criterion appears as a straight line on a Mohr circle diagram (Figure 1), and the crustal state of stress can be described as a circle that intersects the normal stress axis at $(\sigma_1 - p)$ and $(\sigma_3 - p)$, where σ_1 and σ_3 are the maximum and minimum principal stresses, respectively (Hubbert and Rubey, 1959). Thus, an increase in fluid pressure has the effect of shifting the Mohr circle to the left, or closer to failure.

In both Denver (Healy et al., 1968) and Ohio (Nicholson et al., 1988), calculations that utilize the available estimates of tectonic deviatoric stresses, the known or probably injection pressures, and the Mohr-Coulomb failure law, suggest that it is plausible that failure would occur near the bottom of the injection well. [Answer: DENVER = YES, OHIO = YES]

Question 4b (Injection Practices): Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the hypocentral locations?

In order to determine if fluid pressures at the locations and depths where earthquakes occur are sufficient for failure, it is usually necessary to perform some kind of hydrologic modelling. Because the geologic settings at different injection sites are so varied, no single hydrologic model will be appropriate for every case study. Nicholson et al. (1988) present a detailed account of fluid pressure calculations for the Painseville, Ohio site, and compare results for two models: one for an infinite, isotropic reservoir; and one for a reservoir of infinite length but finite rectangular cross section.

In both Denver and Ohio, hydrologic calculations suggest that if the fluid flows in a radial pattern the change in pressures would be too small to induce seismic activity. However, in both cases it was possible to achieve a sufficient increase in pressure at the hypocenter if fluid flow was confined to a favorably oriented zone of rectangular cross sectional area, in approximate coincidence with the zone of earthquake activity. For Denver, a reservoir of 3.35 km width, based on earthquake locations and on long term declines in fluid levels, was sufficient to explain the observed seismicity (Hsieh and Bredehoeft, 1981). For Ohio, the calculations only achieved large pressure increases if flow was confined to a narrow strip approximately 1 km wide; however, the observed well response was more consistent with radial flow (Nicholson et al., 1988). [Answer: DENVER = YES?, OHIO = NO?]

Profile of Induced Seismic Activity

We now apply the above seven questions to 20 seismic sequences which are possibly related to well injection (Tables 2 and 3). Our purpose is to obtain a profile of induced seismic activity as measured by these questions. To answer these questions we thoroughly evaluated the available published literature concerning these sequences (see Appendix).

Of the 20 sequences considered, profiles for twelve sites (Ashtabula, Baca, Cogdell, Dale, Denver, El Dorado, Fenton Hill, The Geysers, Orcutt, Puhagan, Rangely, and Soultz-Sous-Forets) have five or more "yes" answers. We conclude that there is strong evidence that these sequences are related to the injection process. At two other sites (Beowawe and Wairakei), there were four "yes" answers, suggesting a link between injection and seismicity, although incomplete or conflicting evidence makes the relation somewhat more ambiguous.

For the remaining seven sequences, we found three or fewer "yes" answers. In many of these cases the only strong evidence favoring an injection-induced cause is that earthquakes occurred near injection wells. Thus the presently available data do not encourage us to conclude that these sequences are induced by injection.

Several of the answers listed in Table 3 are open to some interpretation. For example, at Matsushiro, Ohtake (1974) reports a correlation between the timing of activity and injection as well as an apparent migration of activity away from the well following injection. However, we have carefully read Ohtake's paper, and we feel the correlation between injection and seismic activity is not nearly so clear as he reported (see Appendix). Thus, with only three "yes" answers, we conclude that it is questionable whether the Matsushiro events are induced by injection.

In several cases, incomplete information prevents us from answering one or more of the questions, and thus the relationship between injection and seismicity remains inconclusive. For example, we assigned only three "yes" answers for the fictional account by Franzen (1992). However, no injection data (volume or pressures) were available in that account, although it seems probable from the novel that injection volumes were substantial. If a study of the injection showed it to be sufficient to cause failure, the additional "yes" answers for questions 4a and 4b would produce a profile suggesting the earthquakes were induced.

Finally, we note that any profile is open to revision if new information or evidence becomes available. For example, a profile of the Painesville site made shortly after the 31 January 1986 earthquake (Frohlich and Davis, 1987) contained 6 "no" answers and only one "yes" answer, with the sole "yes" answer given because well-bottom pressures were high enough to cause failure (question 4a). During the following year, however, several small (magnitude 1.0 or less) earthquakes were located in the vicinity of the injection well, making a stronger (but still inconclusive) case for relating the earthquakes to injection.

SITUATION 2: WILL INJECTION INDUCE EARTHQUAKES?

Ten Questions

In this section we present ten questions (Table 4) which concern whether a proposed injection project may induce damaging earthquake activity. The questions in Table 4 are similar to those in Table 1 in that they again evaluate four factors related to possible earthquake hazard: historical background seismicity, local geology, the regional state of stress, and the nature of the proposed injection. However, the focus of these questions is somewhat different. In the first case (Table 1), an earthquake has already occurred, and the question to be evaluated is whether or not the earthquake

was caused by injection. In the second case (Table 4), the problem is trying to evaluate the potential for future, damaging earthquakes at a specific injection site.

To illustrate the application of these questions, we discuss results for two proposed or ongoing injection sites we have previously evaluated (Frohlich and Davis, 1988, 1990): a proposed injection project near Tracy, Quebec, and an injection well near Texas City on the Texas Gulf Coast. As before, "yes" answers support the hypothesis that injection may induce seismic activity while "no" answers oppose this hypothesis.

As a further illustration, we also present the profile for the Denver Rocky Mountain Arsenal project as if injection had not yet taken place there. This allows us to "test" the criteria at a site where seismologists generally agree that injection has induced earthquakes. We chose the Denver site as it is the most well-known case study of injection induced earthquakes.

Using our ten-question profile (Table 4), we find only one "yes" answer for the Texas City site: there are known faults within 20 km of the injection site. However, the faults appear to be currently inactive, and in view of the lack of local and regional seismicity, the low deviatoric stresses in the Gulf Coast, and the lack of seismicity associated with nearby injection projects, we would find the Texas City site an unlikely candidate for large induced earthquakes.

In contrast, we find four "yes" answers at the Denver site. We could not answer two of the questions with the available data, and we assigned "no" answers to the other four questions. However, the presence of large regional earthquakes, nearby active tectonic features, and an in situ stress state near failure suggest that Denver might be a reasonable candidate for injection induced earthquakes. In this hypothetical evaluation, note that several of the questions receive "no" answers because we are presuming that our assessment takes place prior to injection. In actuality, if one were to propose injection at a site near Denver today, the existence of the earthquake activity between 1962 and 1972 would alter the profile, and there would be six or more "yes" answers.

At the Tracy, Quebec site we find five "yes" answers. This site lies within several hundred km of the Charlevoix seismic zone, the site of several large ($M \geq 6$) historical earthquakes. Moderate seismicity occurs near Tracy itself (Wahlstrom, 1987). This area overlies a failed rift arm; such structures represent planes of weakness in the crust and are often associated with large, damaging earthquakes (Sykes, 1978; Keller at al., 1983; Johnston and Shedlock, 1992). While calculations of the in situ stress from hydrofracture do not suggest that rocks at the proposed depth of injection are naturally close to failure, bottom hole pressures following injection would place the rock at or near failure (Frohlich and Davis, 1988). We would thus conclude that the situation is more similar to Denver than the Texas Gulf Coast.

OTHER CONSIDERATIONS

The yes-and-no profiles described above, in conjunction with the Mohr-Coulomb failure model (Figure 1), provide a useful way to evaluate the possible seismic hazard at injection sites. In particular, it allows one to make comparisons to other sites, and to communicate these comparisons to non-seismologists. However, to effectively evaluate a site one must consider the possibility that rock failure will occur aseismically, and determine the faulting characteristics expected for possible "worst-case" earthquakes that might be induced.

Rock Failure Without Earthquakes

When stress analyses suggest that rock failure is likely, this does not necessarily indicate that earthquakes will occur. There is considerable evidence that rocks can, and do, fail aseismically, as by stable sliding. For example, Byerlee and Brace (1972) and Lockner et al. (1982) found in the laboratory that there was a transition from stick-slip (earthquake-like) behavior to stable sliding behavior as pore pressures increased. Indeed, in some oil and gas fields near San Antonio, Texas, Pennington et al. (1986) concluded that small ($M \leq 3.9$) earthquakes began to occur only when ambient pore pressures decreased due to fluid withdrawal. They suggested that a transition from aseismic to seismic behavior, caused by decreased fluid pressures from oil and gas production, may have played a role in the timing and location of the earthquakes. In California, networks of "creepmeters" document that aseismic motion occurs along sections of the San Andreas Fault (Louie et al., 1985; Schulz et al., 1982). These creep events last hours to days, accommodating fault slip a few mm at a time, and can occur in the complete absence of earthquakes.

Elsewhere there are thousands of injection wells in regions where no earthquakes are known to occur, but where an analysis of injection pressures and probable principal stresses suggests that rock failure occurs. Davis (1989) and Davis and Pennington (1989) analyzed Railroad Commission data summarizing injection activity from 2420 injection projects in Texas. For these projects, the Mohr-Coulomb model predicted rock failure at well bottoms for somewhere between 5% and 36% of the sites that inject under pressure, depending on the failure criteria used (Figure 2). However, earthquakes were only clearly identified with one project, the Cogdell Oil field near Snyder, Texas. No earthquakes are known at numerous other sites

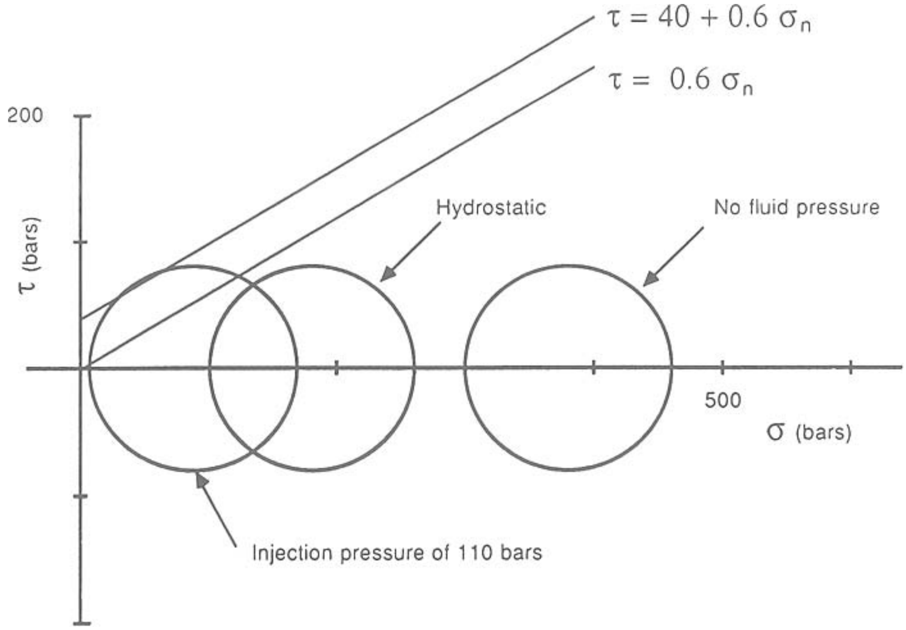

Fig. 1. Mohr circle diagram showing inferred state of stress at the bottom of the injection wells (1.8 km depth) for the Painesville, Ohio site, from Nicholson et al. (1988). Each point on the perimeter of a Mohr circle represents the stress field for a fault plane of a particular orientation; σ is the normal stress across the plane, while τ is the shear stress along the plane. The two lines indicate failure criteria for Mohr-Coulomb failure (see text); failure occurs if the Mohr's circle intersects (or lies to the left of) the failure line. The circle at the right indicates in-situ stresses (typically estimated from the inferred overburden pressure, hydrofracture measurements, and other stress indicators such as earthquake focal mechanisms) in the absence of fluid pressure. In the center Mohr's circle, the principal stresses have been shifted to the left by the hydrostatic fluid pressure in accordance with the effective stress law. The leftmost circle indicates stresses at the well bottom during injection (fluid pressure = hydrostatic + surface injection pressure). The fact that the circle intersects both lines indicates that pressures at the well bottom are not only sufficient for failure if pre-existing faults with zero strength exist (failure line at right), but are sufficient to cause failure even in intact rock with a shear strength of 40 bars (failure line at left).

in Texas, even where injection pressures exceed the Mohr-Coulomb failure criterion.

Earthquake Magnitudes and Fault Characteristics

Even at sites where earthquakes are known to occur, the earthquakes may be of such small magnitude as to make the possibility of damage unlikely. For example, profiles for the Baca and Fenton Hills sites (Tables 2 and 3) strongly indicate the earthquakes are related to injection. However, all of the earthquakes observed have been small (approximate magnitude -2 or less) and would be unlikely to produce damage. Although one cannot rule out the possibility of larger earthquakes occurring at these sites, the presently available evidence suggests that the induced seismicity is limited to small, non-damaging earthquakes.

Two useful parameters for describing the physical nature of earthquakes are the fault area A of the rupture and the slip S that takes place over this area as the earthquake occurs. Suppose an injection project induces an earthquake with magnitude M. Does the associated fault area and slip pose a hazard? The generally accepted method for evaluating the slip and fault area involves analysis of seismic moment, M_0, of an earthquake:

$$M_0 = \mu A S$$

where μ is the rigidity of crustal rocks (approximately 3×10^{11} dyne/cm^2). The most commonly used relationship (Hanks and Kanamori, 1979) between moment magnitude **M** and seismic moment M_0 is:

$$\log_{10} M_0 = 1.5\mathbf{M} + 16.05$$

Empirical studies (Abe, 1978; Kanamori and Anderson, 1975) of the relationship between fault dimension R and fault slip S find that $S \sim 10^{-4} R$. If R is the radius of a circular fault, then combining the above equations we obtain the relationship between fault dimension R (in meters), fault slip S (in mm) and moment magnitude **M** as:

$$\log_{10} R\ (meters) = 0.5\mathbf{M} + 0.7$$
$$\log_{10} S\ (mm) = 0.5\mathbf{M} - 0.3$$

Thus for earthquakes with magnitudes **M** between 0 and 2, we would expect fault dimensions of 5 to 50 meters, and slips of 0.5 to 5 mm. However, for an earthquake with magnitude of 5.0, similar to the largest of those earthquakes in the Denver sequence, R and S would be 1.6 km and 16 cm, respectively.

Whether the faulting associated with an earthquake poses a hazard depends on the situation. For example, an earthquake with magnitude 2 would be unlikely to pose a risk to any man-made structure, while even aseismic failure in an area with considerable preexisting faulting might allow chemical wastes to enter a nearby aquifer. However, seismologists are usually asked only to evaluate the characteristics of past or possible future seismic activity, and other experts must decide whether these conditions represent a significant risk.

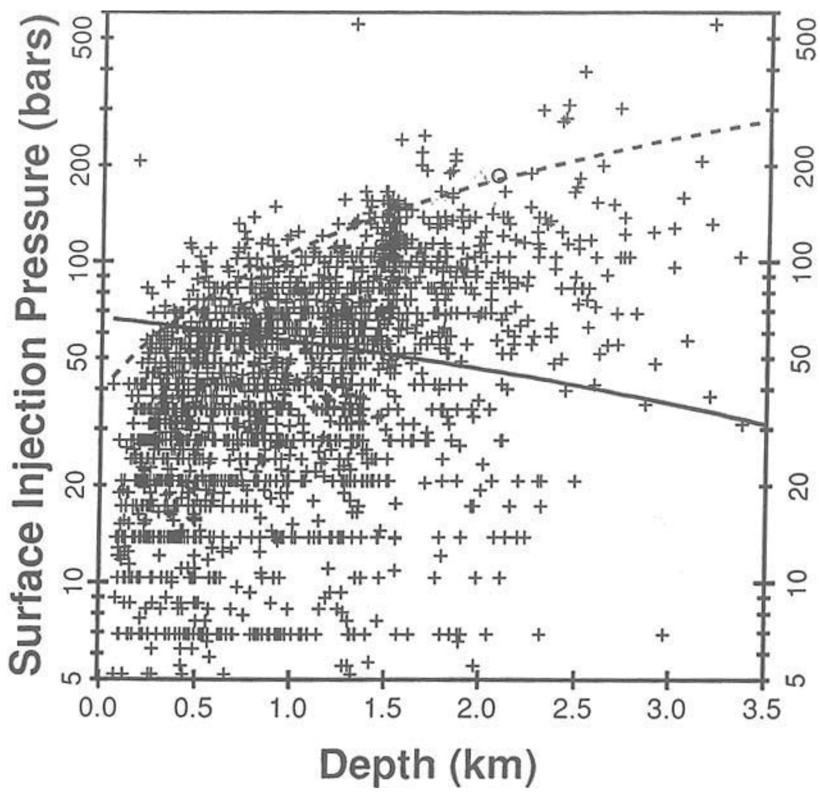

Fig. 2. Injection pressure versus depth for 2420 projects in the state of Texas which inject water under pressure at depths of 0 to 3.5 km. The two lines represent failure curves with different assumptions about deviatoric stresses, friction, and rock shear strength (see Davis and Pennington, 1989 for details). In each case, failure is estimated for conditions at the well bottoms; we correct these to surface injection pressures as recorded by the state of Texas (Railroad Commission of Texas, 1983). Projects which plot above the lines should be in failure at well bottom conditions. The solid line is a typical failure curve, whereas the dashed line is an extremely conservative failure curve (high friction and low deviatoric stresses). 877 projects lie above the typical failure line, and 112 projects should be in failure even by the conservative failure law. Nevertheless, induced earthquakes are only unambiguously associated with the Cogdell Oil Field (open circle).

DISCUSSION

Liability and Public Concern

While there are thousands of injection projects, there is surprisingly little available information about the effects of these projects on seismic activity. In places such as Ohio and Quebec, the fact that fluid injection might affect seismic activity has only recently become a factor in obtaining permits for injection projects. While this has created an inducement for companies to study seismicity prior to a proposed injection project, after injection begins the recording of any earthquake, no matter how small or how distant, can only add expense or delay to the project. Often, individuals and groups in the community may oppose the injection, because of either real or misguided environmental concerns, or simply because the development is not in their interest. Thus after injection begins there is little inducement for a company to operate a seismic network or publicize recorded activity.

However, these companies may be held liable for any resulting damage or interference from induced earthquakes under the legal concepts of strict liability, negligence, and/or nuisance (Cypser and Davis, 1993). Evaluation of the potential for injection-induced earthquakes (e.g. Frohlich and Davis, 1988; 1990; Nicholson and Wesson, 1990) can help companies avoid the possibility of costly lawsuits and the adverse publicity which would accompany induced seismic activity. In addition, it is economically more efficient to determine the potential for induced seismicity in the early stages of a project rather than dealing with the consequences of induced earthquakes, including the possibility of abandoning the site, after injection begins.

As previously mentioned, there may be cases where one can make a distinction between "induced" and "triggered" earthquakes, in which the energy release from "triggered" earthquakes primarily resulted from stresses built up over time by natural tectonic processes (McGarr, 1991). One might be tempted to argue that "triggered" earthquakes would not be a cause for legal concern, as the triggering mechanism (e.g., injection) has only hastened the release of tectonic energy, and the earthquakes would have happened anyway. However, a study on liability for induced earthquakes (Cypser and Davis, in preparation) shows that this argument does not hold. Rather, it is possible that human intervention could release energy that might have remained stored in the crust for centuries (Allen, 1982). Further, one could argue that such perturbations might influence the character of seismicity, perhaps creating earthquakes of larger magnitude than would have occurred naturally (Pennington et al., 1986). There are reasons to find legal causation even in the case where the triggering process merely hastened the release of stored energy, and the inducer would still be held liable for any resulting damage (Cypser and Davis, 1993).

While the potential for a damaging earthquake is often real, in some situations the threat of damage may be as costly to society as any damage from the earthquake itself. For example, these societal costs may be in the form of lawsuits, or they may arise from public concern over seismic hazard in situations where the possibility of damage from induced earthquakes is remote. The application of the criteria presented in this paper may help provide a framework for determining when such concern is warranted.

Other Characteristics of Induced Earthquakes

It is possible that there exist other characteristics that are diagnostic of induced seismic activity in addition to the characteristics addressed in Tables 1 and 4. In Table 2 we have compiled additional information about each of the 20 sequences studied. These data show that the induced earthquakes have either strike-slip, thrust, or normal focal mechanisms, and can occur over a large range of depths. However, future research may determine other factors that might be of use in determining if seismic activity is natural or induced.

There is some indication that the rate of seismic activity is higher in sequences clearly attributed to injection than not (Talwani and Acree, 1986; Frohlich and Davis, 1987). This is not too surprising, as swarm-like behavior is often observed where fluid movement or fluid pressure changes are thought to cause earthquake activity. These include earthquakes induced by the filling of reservoirs (Gupta, 1992) and those associated with volcanic activity and magma intrusions (e. g., Stuart and Johnston, 1975; Malone et al., 1983).

Finally, we note that the literature on injection-induced earthquakes is surprisingly large. In addition to those listed in Tables 2 and 3 and in the Appendix, other cases have been made for injection-induced earthquakes in a variety of settings. Earthquakes possibly related to injection at oil and gas fields have been found in East Texas (Carlson, 1984), the Texas Panhandle (Davis et al., 1989), and in Alberta (Milne, 1970; Milne and Berry, 1976). Earthquakes associated with injection at geothermal sites are common; these include the Salton Sea field, California (Hutchings et al., 1988), the Texas Gulf Coast (Knutson, 1981; Mauk, 1985), the Tongonan field, Philippines (Sarmiento, 1986), the Cambourne Hot Dry Rock site in the United Kingdom (Pine and Batchelor, 1984; Crampin and Booth, 1989; Parker, 1989), and the Larderello-

Travale geothermal area in Italy (Batani et al., 1985). Solution mines where earthquakes have been related to injection include those in southeastern Utah (Wong et al., 1985) and Iraq (Terashima, 1981). Other locations where earthquakes have been related to injection for experimental or other purposes include central France (Cornet et al., 1992), the Buffelsfontein Gold Mine in South Africa (Board et al., 1992), the Lucky Friday Mine in Idaho (Whyatt et al., 1992), and a small-scale experiment at the Canadian Underground Research Laboratory (Majer and Doe, 1986). Finally, injection at the Inglewood Oil Field, California, has been related to surface faulting which led to the destruction of the Baldwin Hills Reservoir (Hamilton and Meehan, 1971). Note that this is not intended to be a complete list, as there exist other locations where a connection between deep well injection and earthquakes has been suggested (e.g., see Nicholson, 1992).

CONCLUSIONS

The question "Is it possible that injection may induce (or may have induced) seismic activity?" is often a difficult one for the professional seismologist to answer, as it is impossible to rule out a connection between earthquakes and injection with complete certainty, even in the absence of evidence linking the two. Rather, the profiles described answer the question, "How similar is this injection situation to other situations where injection did cause seismic activity?" We emphasize that this analysis does not, by itself, determine whether or not injection should take place. However, by using criteria such as those presented in this paper, seismologists can provide information to assist industry and government in making responsible decisions concerning the initiation of injection, continued injection, or, after an earthquake, about whether it is plausible that injection was a contributing factor.

We note that differences in the quality of data sets for injection histories, historical seismicity, and geology and hydrology between different sites precludes the use of a consistent, quantitative set of criteria for evaluating these questions. Thus, most of the questions in Tables 1 and 4 are inherently subjective. However, their usefulness is that they do provide a framework for comparing different injection projects to one another, utilizing whatever information is available at a particular site.

In evaluating the seismic hazard from fluid injection projects, we encourage people to assess the magnitudes of potential earthquakes. Many injection situations are similar to those where small earthquakes may be induced, but the likely fault areas and fault slips would pose little or no hazard for most engineering applications. However, where there are concerns about the possible damage from induced seismic activity, it would be prudent to take appropriate precautions (Nicholson and Wesson, 1990; Cypser and Davis, 1993). These precautions might include evaluating the site for the potential of induced seismic hazard, and monitoring the injection site for seismic activity.

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APPENDIX

Listed below are the sources used in preparing entries for Tables 2 and 3. Explanations for entries are given only if there is some conflicting information that requires justification.

Ashtabula, Ohio (waste disposal): Seeber and Armbruster (1988, 1993), Nicholson and Wesson (1990)

2) Injection at Ashtabula had been ongoing for about a year prior to the magnitude 3.6 earthquake on 13 July 1987. Although there is no clear correlation between injection and seismicity, the fairly short lag between the start of injection and the earth quake is suggestive. The detection threshold prior to the installation of the temporary network to locate the aftershocks to the 13 July earthquake was about 1.5, and it is possible that smaller events may have begun before July 1987. Seismic activity has occurred at least through March 1992. [NO?]

3c) The epicenters delineate a possible fault that extends from the injection formation into the basement, where most of the earthquakes occur. A composite fault plane solution is consistent with strike-slip motion on the inferred fault. However, there are no mapped faults in the region, and a reflection survey failed to resolve the fault plane. [NO?]

Baca Location Geothermal Site, New Mexico (hydraulic stimulation / geothermal): Pearson et al. (1982)

4a,b) We did not calculate pressure changes, but volumes were sufficient for hydraulic stimulation. [YES?, YES?]

Beowawe Geothermal Field, Nevada (acid treatment / geothermal): Batra et al. (1984)

2) A burst of seismicity accompanied an injection phase on August 21, 1983, but a second injection stage the following day occurred without seismicity. [YES?]

Cogdell Oil Field, Texas (secondary recovery / oil field): Davis (1985, 1989), Davis and Pennington (1989), Harding (1981)

3c) Earthquakes occur within the injection zone. [NOT APPLICABLE]

Dale, New York (solution mining): Fletcher and Sykes (1977)

1) Although the Attica area of western New York state has experienced a moderate amount of historic seismicity, historic compilations and more recent instrumental locations indicate a low level of background activity near the brine field. A permanent station in Attica recorded an average rate of less than one event per month prior to injection, which increased to up to 80 events per day during injection. Many of these later events were felt or heard by residents in the immediate area. [YES]

Denver RMA, Colorado (waste disposal): Bardwell (1966), Evans (1966), Frohlich and Davis (1987), Healy et al. (1968), Herrmann et al. (1981), Hsieh and Bredehoeft (1981)

see text for comments

El Dorado, Arkansas (waste disposal): Cox (1991)

2) The two principal periods of seismic activity were preceded by increased disposal rates. [YES]

4a,b) Cox (1991) reports that in situ stresses were close to failure. [YES?, YES?]

Fenton Hill Hot Dry Rock Site, New Mexico (hydraulic stimulation / geothermal): Bane and Fehler (1986), Cornet and Julien (1989), Fehler (1989), Fehler and Phillips (1991), Fehler et al. (1987), Ferrazini et al. (1990), House (1987), House et al. (1992), Pearson (1981), Talebi and Cornet (1987)

The Geysers, California (pressure maintenance /

geothermal): Allis (1982), Eberhart-Phillips and Oppenheimer (1984), O'Connell and Johnson (1988), Oppenheimer (1986), Stark (1990)

Maximum Magnitude -- The largest earthquakes in the field have been approximately magnitude 4.0, although it is not clear if the largest earthquakes are associated with injection.

4a,b) The high background rate of seismic activity in the field suggests that in situ stresses are close to failure. [YES?, YES?]

Gobles Oil Field, Ontario (secondary recovery / oil field): Mereu et al. (1986)

Los Angeles Basin, California (secondary recovery / oil fields): Teng et al. (1973), Nicholson and Wesson (1990)

2) Teng et al. (1973) suggest a possible relation between number of earthquakes and net volume of fluid injected at the Inglewood Oil Field for 1971, but the correlation is slight. [NO?]

3c) The Newport-Inglewood Fault may channel fluids to greater depths. [YES?]

Matsushiro, Japan (experimental): Ohtake (1974)

2) Ohtake (1974) purports to see a correlation between the time of injection and seismic activity, with bursts of activity seen 4.8 to 9.3 days following injection periods. However, swarms in the area are not uncommon before and after the injection periods (see figure 3 in Ohtake), and we do not see the proposed correlation. However, the hypocenters do exhibit an apparent migration away from the well following the first injection period (figures 4 and 5 of Ohtake's report). [NO?]

Orcutt Oil Field, California (hydrofracture induced earthquake / oil field): Kanamori and Hauksson (1992)

1) The unusually shallow depth (300 m, based on field evidence) and long duration (2 minutes) of the magnitude 3.5 earthquake was clearly anomalous. [YES]

2) The earthquake occurred a few hours after the hydrofracture. [YES?]

4a,b) We did not calculate pressure changes, but they are presumed to have been sufficient for hydraulic fracturing. [YES?, YES?]

Painesville, Ohio (waste disposal): Ahmad and Smith (1988, 1989), Evans (1987), Frohlich and Davis (1987), Nicholson et al. (1988), Roeloffs et al. (1989), Talwani and Acree (1986), Wesson and Nicholson (1986)

see text for comments

Peabody, Massachsetts (fictional account of waste disposal): Franzen (1992)

1) Historical events are known, although the swarmlike nature of the earthquakes may have been anomalous. [NO?]

2) There was a 16 year lag between the assumed start of injection and the first earthquakes. The second earthquake swarm may have closely followed a second injection period. [NO?]

3a) The closest epicenters are approximately 5 km from the assumed injection site. [YES?]

3b) The injection depths are unknown but are presumed deep. The book mentions an early report suggesting a drilling goal of 25,000 feet [7.6 km]. [YES?]

Puhagan Geothermal Field (injection tests / geothermal): Bromley et al. (1987)

1) Bromley et al. (1987) report a "near-quiescent background" prior to geothermal development. [YES?]

4a,b) Although injection pressures may have been sufficient to induce earthquakes, Bromley et al. (1987) report that most of the seismicity occurs in the production sector of the field, where pressures have decreased. [YES?, NO?]

Rangely Oil Field, Colorado (secondary recovery / oil field): Gibbs et al. (1973), Haimson (1972), Raleigh et al. (1972, 1976)

1) There are possible felt reports of earthquakes prior to injection but no reliable station coverage. [UNKNOWN]

2) An early study (Gibbs et al., 1973) could find no clear relation between injection and monthly numbers of earthquakes, although injection and annual activity were more clearly correlated. However, later studies (e.g. Raleigh et al., 1976) demonstrated a very clear correlation between earthquake activity and fluid pressures in the field. [YES]

Sleepy Hollow Oil Field, Nebraska (secondary recovery / oil field): Evans and Steeples (1987), Frohlich and Davis (1987), Rothe and Lui (1983)

2) No clear correlation exists, although Evans and Steeples (1987) note that the conversion of ten producers to injectors was followed by an increase in activity. However, this may have been an artifact of the catalog (Evans and Steeples, 1987). [NO?]

3c) Contour maps of the Precambrian basement show several vertical faults. However, Evans and Steeples (1987) suggest that the unusually high permeability of the Reagan sandstone (2.9 darcies) would be likely to divert fluid flow horizontally rather than into the basement. [YES?]

Soultz-Sous-Forets Hot Dry Rock Site, France (hydraulic stimulation / geothermal): Beauce et al. (1991)

4a,b) We did not calculate pressure changes, but volumes were sufficient for hydraulic stimulation. [YES?, YES?]

Wairakei Geothermal Field, New Zealand (reinjection test / geothermal): Hunt and Latter (1982), Sherburn (1984), Sherburn et al. (1990)

1) The Wairakei region exhibits low to moderate background seismicity (Hunt and Latter, 1982), although the numbers of earthquakes associated with the 1984 injection test was somewhat anomalous. [NO?]

2) A 1984 injection test at Wairakei was clearly associated with microearthquake activity. However, a later injection test at lower pressures did not appear to significantly increase earthquake activity. [YES?]

3b) Microearthquake depths were not well determined. [UNKNOWN]