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EARTHQUAKES AND HYDROCARBON PRODUCTION IN THE FORT ST. JOHN AREA OF NORTHEASTERN BRITISH COLUMBIA

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ABSTRACT

Earthquakes as large as magnitude 4.3 have occurred near Fort St. John, B.C., since 1984 and show both spatial and temporal correlations with oil extraction and associated high-pressure water injection from the Belloy Formation (Permian) in the Eagle West and Eagle fields. The majority of the larger earthquakes can be grouped into three distinct clusters in time and space. Each has a duration of about one month. The first in November-December 1984 appears to have been centred near the western boundary of the Eagle West field. The second in January-February 1992 and the third in December 1992-January 1993 were both located about 10-15 kilometres (km) further east, presumably over the Eagle field. Earthquakes from the Eagle field may have begun as early as 1986. Fluid injection to increase recovery was initiated at Eagle West in 1980 and at Eagle in 1985, in both cases prior to the onset of seismicity. As production declined in the Eagle West field in the late 1980s, so too did the seismicity. Most of the larger earthquakes have occurred during the winter months but this is perhaps not significant if they are related to only a few episodes of strain release. This seasonal variation is not reflected by the production or injection rates. No earthquakes were located in the Fort St. John area before 1984. There are no reports of earlier felt events and the seismograph network in Western Canada would have permitted location of earthquakes with magnitudes equal to those in 1984 since the mid-1960s.

A field survey in January-March 1993 found epicentres of low-magnitude earthquakes exclusively in the Eagle field within a few kilometres of both production and injection wells. Focal depths could only be determined with an accuracy of 3-4 km but were consistent with injection depths of about 2 km. The high surface injection pressures of up to about 25 MPa, the faulted nature of this region of the Peace River Arch, and the spatial and temporal correlations indicate that fluid injection should be considered as a possible cause of this seismicity. The interval of up to 4-6 years between the onset of injection and seismicity might reflect the time it takes for pressures away from the injection wells to increase to levels that could initiate movement on preexisting faults. Although fluid pressure reduction does not appear to be significant, it is not possible to fully evaluate the influence of other potential factors with available data. Hydraulic fracturing indicates a compressive stress regime at depths of 1 to 2 km where $S_{Hmax} > S_{Hmin} > S_V$ and where thrust and/or strike-slip faulting would be expected.

The largest earthquakes to date have occurred in 1992, 1993 and 1994 and appear to reflect an increase in the frequency and magnitude of events over the Eagle field compared to the Eagle West field. Although there has been no significant damage, many of the earthquakes were felt with Modified Mercalli intensities as high as V. Felt areas were as large as 2000 km^2. The hazard presented by this seismicity still needs to be adequately assessed.

INTRODUCTION

Beginning in 1984, a number of felt earthquakes as large as magnitude (M) 4, have occurred near Fort St. John in the Peace River area of northeastern British Columbia. These are unusual events in a region of typically very low-level seismicity on the Interior Platform east of the Rocky Mountain Foreland Fold and Thrust Belt (Figure 1). This is also a major oil and gas producing area in British Columbia and the earthquakes appear to cluster near some of the fields just north of Fort St. John (Figure 2). The first gas discoveries were made in the early 1950s. Oil wells were first drilled in these fields in the mid-1970s; however, significant oil production and enhanced recovery by water injection did not occur until the early 1980s, just a few years before the earthquakes were first observed.

There are numerous instances of earthquakes induced by oil and gas production in other basins elsewhere in the world. They are usually attributed to fluid injection (Healy et al., 1968; Raleigh et al., 1972, 1976) or fluid pressure reduction (Yerkes and Castle, 1976; Pennington et al., 1986; Segall, 1989; Grasso and Wittlinger, 1990), but there may be a variety of factors (Doser et al., 1991, 1993). In Canada, the only documented case of induced seismicity by oil or gas extraction was at the Strachan gas field near Rocky Mountain House, Alberta (Rebollar et al., 1981; Wetmiller, 1986). Milne (1970) implied that a 1970 M 4.6 earthquake near Snipe Lake in northwestern Alberta was related to oil production but there were insufficient data to make a definite conclusion.

The purpose of this paper is to document the observed record of earthquakes near Fort St. John to September 1993 and to present results of an initial seismicity survey that was carried out from January to March, 1993. We make an initial examination of the possible relationship between the seismicity and hydrocarbon production and use hydraulic fracturing

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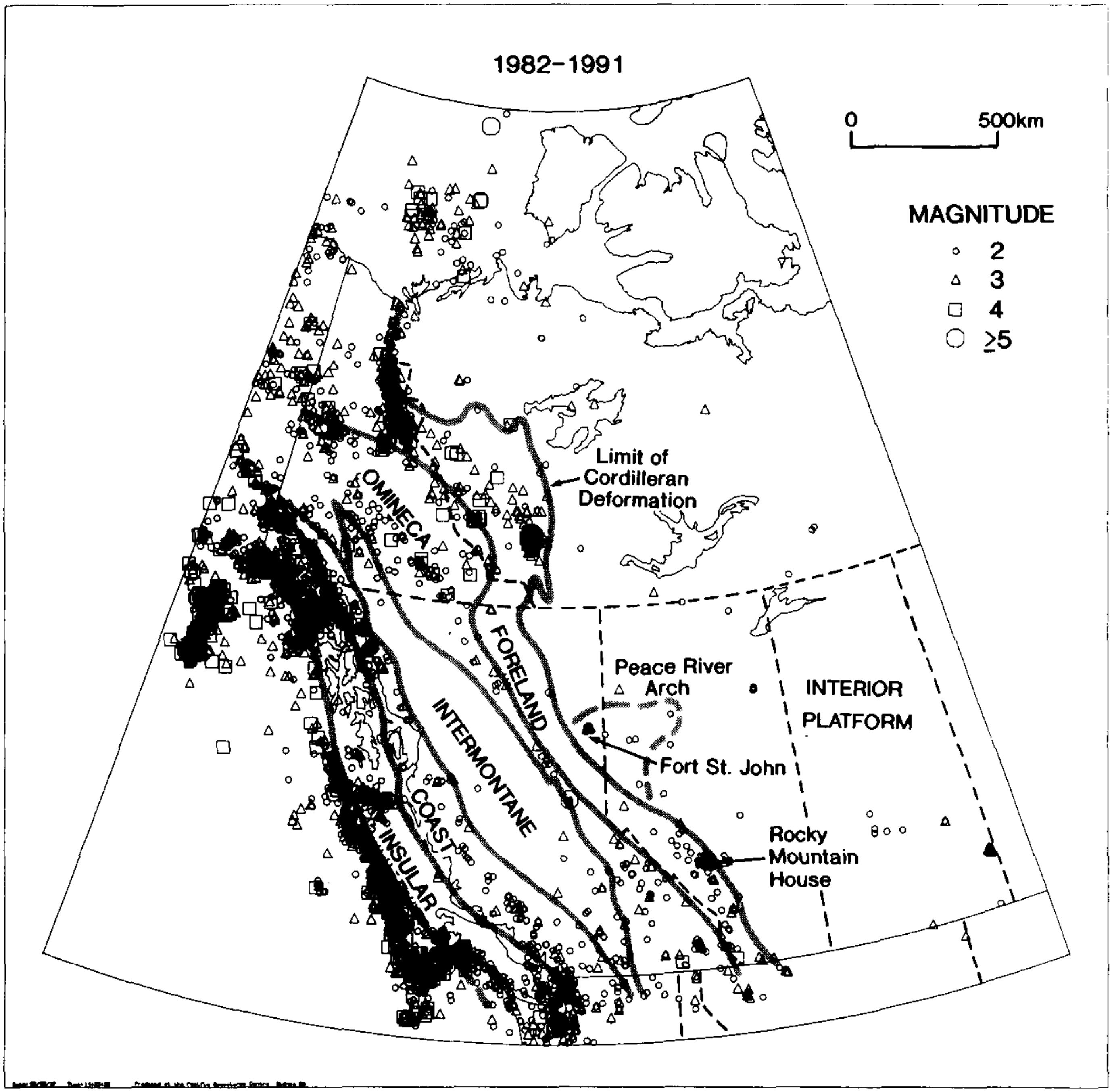

Fig. 1. Seismicity in western Canada over a 10-year period from 1982-1991, superimposed on the morphogeological belts of the Canadian Cordillera.

data to infer the existing stress regime. This is extremely important in order to assess the potential hazard such seismicity might present, not only to the industry but to the public as well. Further analysis will await the results of a detailed seismicity survey conducted over the Eagle Field from November 1993 to March 1994.

Earthquake History

All of the earthquakes that have been located in the Fort St. John region to September 1993 are listed in Table 1. Most of the events over M 2.5 were felt locally. The largest earthquakes were generally felt to distances of about 25 km with Modified Mercalli intensities as high as V. There were reports of cracked plaster, fallen pictures and small objects knocked off shelves. In many cases, one strong thud was reported as though there had been an explosion or a vehicle had run into the building. People sleeping were awakened. An isoseismal map shown in Figure 3 for one of the large earthquakes on January 9th, 1993, is typical of the intensity distributions produced by the larger events. The felt area is about 2000 km^2.

The first earthquakes were not observed until 1984, even though the existing seismograph network would have permitted

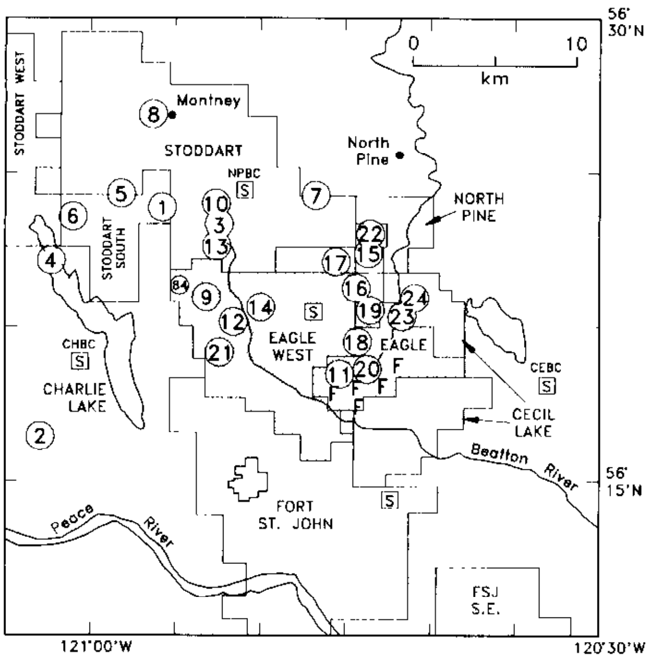

Fig. 2. Epicentres of all earthquakes located in the Fort St. John area in relation to the oil and gas fields. Event numbers refer to Table 1. "F" indicates an epicentre determined during the January-March 1993 field survey (see also Figures 6 and 11). "S" are locations of the temporary seismographs (Table 2). "84" marks the location where the first tremors in 1984 were mainly felt and represents the most accurate epicentre for these events.

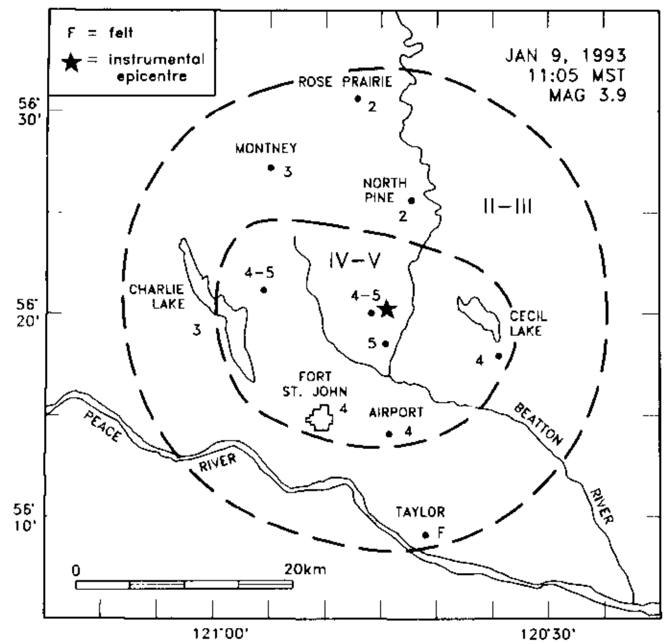

Fig. 3. Modified Mercalli intensities produced by the M 3.9 earthquake on January 9th, 1993, at 18:05 UT (event 19 in Figure 2 and Table 1).

the location of events like these, i.e., about M 2.5 and greater, since the mid-1960s (Figure 4). Stations at Fort St. James, Mica Creek, Edmonton and Yellowknife, installed within a few years of each other, dramatically lowered the location threshold from about M 5 that existed in the 1950s. There is no record of moderate or larger events before the 1960s. If they had occurred they would have been felt and reported.

The accuracy of the epicentres shown in Figure 2 (excluding those from the field survey) cannot be considered better than about 10 km because of the seismograph distribution (Figure 4) and the relatively low magnitudes. The nearest station to Fort St. John is Bennett Dam, about 100 km to the west; the others are all over 300 km away. Accurate focal depth determinations are also precluded, although the relatively high intensities do suggest a shallow, upper crustal source (e.g., Gendzwill et al., 1982).

Despite the uncertainty associated with the computed epicentres the macroseismic data confirm the general pattern shown in Figure 2 and suggest spatial correlations specifically with the Eagle West and Eagle oil fields. Although the epicentres of the initial sequence in 1984 (events 1-5) are scattered outside the Eagle West field in the Stoddart and Stoddart South fields, they were primarily felt on the east side of Charlie Lake near the west boundary of the Eagle West field and probably occurred within a few km of that location. At a residence in 10-85-19W6 ('84' in Figure 2), event 4, only M 2.8, was strong enough to knock ornaments from a shelf and felt like an explosion. Another small unlocated earthquake felt there the next day was not felt by neighbours about 2 km away (M. Smith, pers. comm., 1984). In contrast, the earthquakes in 1992-1993, and perhaps as early as 1986 (event 7), appear to be further east over the Eagle field. This is evident by both the overall 10-15 km eastward shift observed in the computed epicentres (Figure 2) and the intensity distributions determined from interviews conducted in January and February 1993. The isoseismal map shown for event 19 in Figure 3 is typical. In addition, residents on the east side of the Beatton River over the Eagle field reported many smaller felt events not detected by the regional seismograph network. Also, none of the larger earthquakes were felt strongly at North Pine, as would be expected if events 15, 16, 17 and 22 had occurred where they are plotted in Figure 2. In fact, all were felt with higher intensity at Fort St. John (Figure 3) suggesting true epicentres further south, over the Eagle field. As a result the apparent north-south epicentral trend over the Eagle field and other apparent lineations in Figure 2 cannot be considered real.

An important feature of the earthquake distribution is the clustering in both time and space. Nineteen or 20 of the 24 events in Table 1 can be grouped into 3 distinct clusters, each having a duration of about 1 month and apparently constrained to a much smaller area than indicated by the computed epicentres on the basis of macroseismic data discussed above. The first in November-December 1984 (events 1-5) was centred near the western boundary of the Eagle West field. Event 6 in March 1985 could very likely have occurred

Table 1. Earthquakes located in the Fort St. John area to September 1993. Also included are preliminary details of the May 1994 event.

Event No.	Date yy-mm-dd	Time (UT) hh:mm:ss	Lat. Deg N	Long. Deg W	Depth km	Mag.	Comments
1.	84-11-09	05:30:18	56.398	120.929	5.0G	2.6	Felt at Fort St. John
2.	84-11-10	15:34:34	56.274	121.050	5.0G	2.2	
3.	84-11-26	02:35:52	56.391	120.878	5.0G	2.6	Felt on east side of Charlie Lake.
4.	84-12-09	04:17:32	56.367	121.041	5.0G	2.8	Felt (IV-V) on east side of Charlie Lake.
5.	84-12-12	12:07:40	56.405	120.967	5.0G	2.6	Felt on east side of Charlie Lake.
6.	85-03-13	20:19:36	56.394	121.017	5.0G	2.4	
7.	86-02-10	12:09:16	56.407	120.779	5.0G	3.1	Felt at Fort St. John.
8.	87-02-12	12:45:11	56.450	120.927	5.0G	2.5	
9.	87-11-12	05:30:19	56.354	120.885	5.0G	3.0	Felt in the Fort St. John area.
10.	89-01-23	07:35:53	56.397	120.878	5.0G	3.1	Felt in the Fort St. John area.
11.	92-01-23	04:44:22	56.311	120.760	5.0G	3.2	Felt in the Fort St. John area.
12.	92-01-23	05:52:20	56.337	120.854	5.0G	2.6	Felt in the Fort St. John area.
13.	92-02-08	21:51:12	56.375	120.877	5.0G	2.5	
14.	92-02-09	02:27:18	56.343	120.837	5.0G	2.6	
15.	92-02-11	10:25:09	56.378	120.723	5.0G	3.5	Largest earthquake to date. Felt strongly (IV) in Fort St. John. Many people awakened. No reports of damage.
16.	92-02-15	07:42:58	56.355	120.741	5.0G	3.2	Felt (IV) in Fort St. John.
17.	92-12-26	20:52:40	56.366	120.762	5.0G	4.1	Largest earthquake to date. Felt strongly (IV-V) in Fort St. John and area, similar to event 2 weeks later on Jan. 9, 1993. Several small aftershocks in next few days.
18.	93-01-08	08:32:50	56.326	120.741	5.0G	2.6	Not reported felt.
19.	93-01-09	18:05:47	56.348	120.725	5.0G	3.9	Felt strongly (IV-V) just north of Fort St. John; (IV) at Fort St. John; (III-IV) at Cecil Lake and Charlie Lake; (III) at Montney; and (II) at North Pine and Rose Prairie. Also felt at Taylor. Perceptible to distances of about 50 km. About 20 aftershocks observed in the next 5 hours including felt events at 18:41, 19:31 & 21:16. See Figure 3.
20.	93-01-09	18:12:13	56.310	120.730	5.0G	2.5	Not reported felt.
21.	93-01-09	18:41:39	56.321	120.877	5.0G	2.4	Felt mildly in the Fort St. John area.
22.	93-01-09	19:31:02	56.385	120.722	5.0G	3.7	Felt in the Fort St. John area. Less severe than event 19.
23.	93-01-09	21:16:04	56.344	120.694	5.0G	4.0	Felt strongly in the Fort St. John area. Similar to event 19.
24.	93-01-30	18:03:45	56.351	120.685	5.0G	3.5	Felt in the Fort St. John area.
—.	94-05-22	15:06:48	56.30	120.75		4.3	Felt (IV-V) in the area bounded by Fort St. John, Charlie Lake, North Pine and Cecil Lake. Similar to event 19. Foreshock at 15:02, M 2.8 was also felt.
January-March 1993 Field Survey							
25.	93-02-11	09:54:39	56.303	120.716	2.0G	<1	
26.	93-02-12	13:46:25	56.303	120.737	0.5	<1	
27.	93-02-13	09:43:12	56.312	120.699	4.0	1.6	
28.	93-03-16	03:03:26	56.292	120.736	4.0	1.8	
29.	93-03-29	06:35:31	56.303	120.753	0.0	1.3	

Regional solutions (1-24) are not accurate to much better than 10 km and there is no control on focal depth.
Field survey epicentres are accurate to better than 2 km, focal depths to 3-4 km.

at this location as well. The second and third clusters in January-February 1992 and December 1992-January 1993 (events 11-16 and 17-24, respectively) are centred over or very near the Eagle field. This distribution suggests a causal relationship, i.e., the earthquakes within each cluster are not independent events but are related to a common strain release episode, much like a main shock-aftershock sequence.

The seismicity over or near the Eagle field has also been the most intense and includes all of the larger earthquakes, M 3.5 and greater. This activity has continued with probably the largest earthquake to date occurring on May 22nd, 1994 at 15:06 UT. The preliminary magnitude is 4.3 and the epicentre appears to be in the same area as those in January 1993. The felt area is at least as large as that shown in Figure 3 with similar intensities.

Until the May 1994 earthquake occurred, an intriguing feature of the temporal distribution was the apparent confinement to the winter months. All of the larger earthquakes had occurred between November and March (Figure 5). This is now probably not significant, particularly if these events are related to only a few episodes of strain release.

JANUARY-MARCH 1993 SEISMICITY SURVEY

Following the January 9th, 1993 earthquakes, two seismographs were deployed in the epicentral region to improve monitoring of any low-level seismicity. In February a third seismograph was installed along with two portable instruments. Sites are shown in Figure 2; coordinates and operating times are listed in Table 2. About a dozen small earthquakes,

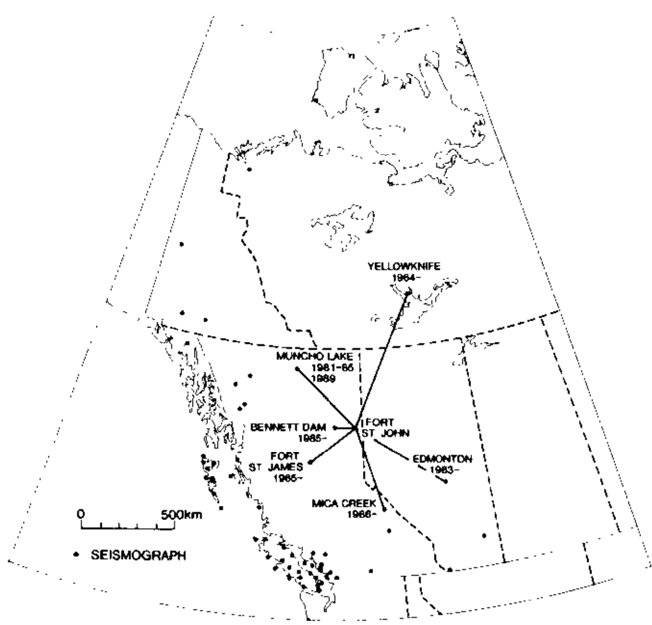

Fig. 4. The current distribution of seismograph stations in western Canada, showing the operating periods of those closest to Fort St. John.

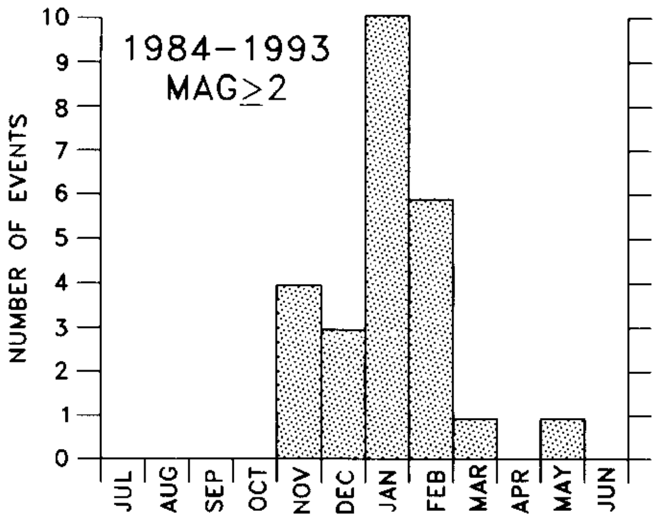

Fig. 5. The monthly distribution of earthquakes, M 2 and greater (Table 1), located near Fort St. John. Included is the M 4.3 event on May 22nd, 1994.

as well as the M 3.5 event on January 30th, were detected up to the end of March 1993. Five of these events were recorded on at least three of the seismographs and could be located. The hypocentres (Table 1) are considered accurate to better than 2 km horizontally and 3-4 km vertically. For this study we used a velocity model from a regional refraction survey (Zelt and Ellis, 1989). The seismograph distribution and analogue data precluded a more refined model.

The epicentres all lie in the Eagle oil field (Figures 2 and 6) at depths of less than about 5 km in what appears to be a somewhat ENE-WSW elongated zone, about 5 km in length. This distribution is also supported by the variation in *P* arrival time differences observed at CHBC and CEBC for a number of common events (Figure 7). The 1.1 second variation would translate to a horizontal distance of about 5 km assuming a *P* velocity of 5 km/sec. This zone is also very likely where the larger events in January occurred and supports the eastward shift discussed earlier. It is also important to note that there were no events located outside of the Eagle field. This seismograph network would have permitted location

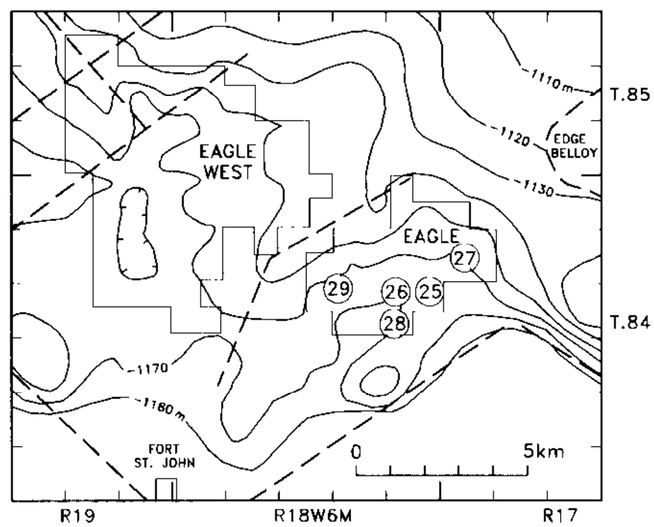

Fig. 6. Epicentres determined during the January-March 1993 survey (Table 1) superimposed on a structure map on the top of the Belloy Formation, also showing some of the inferred faults and the outline of the Eagle West and Eagle oil units (note that the unit boundaries are different from the field boundaries shown in Figure 2). Contours are metres below sea level. These epicentres are considered accurate to better than 2 km. Seismograph locations are shown in Figure 2.

Table 2. Operating parameters for the Fort St. John seismographs during the January-March 1993 seismicity survey. See Figure 2 for station locations.

Station Name	Code	Lat N	Long W	Elev m	Opened/Closed 1993	Paper Speed mm/min
Charlie Lake	CHBC	56.3146	121.0078	790	Jan 14 - Apr 1	60
Cecil Lake	CEBC	56.3006	120.5501	720	Jan 15 - Apr 1	60
North Pine	NPBC	56.4071	120.8473	750	Feb 9 - Apr 1	60
Airport	FSB1	56.2391	120.7074	695	Feb 9 - Feb 12	120
Pineview	FSB2	56.3412	120.7823	670	Feb 9 - Feb 12	120

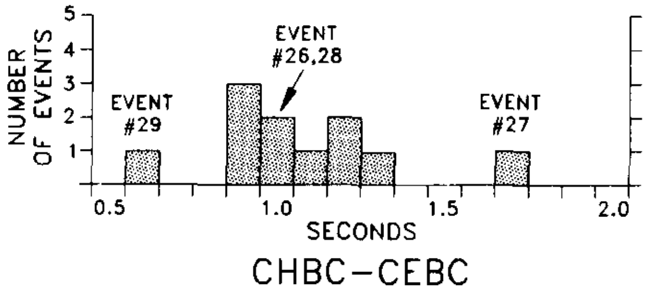

Fig. 7. Differences in *P* arrival times at CHBC and CEBC for 11 earthquakes recorded by both seismographs. See Figure 2 for station locations and Table 1 and Figure 6 for event numbers.

of similar magnitude events in the Eagle West, Stoddart, Fort St. John, Cecil Lake or North Pine fields – had they occurred during this period.

Geological Setting

This seismicity occurs in an area of the Western Canada Sedimentary Basin known as the Peace River Arch. The "Arch" is a Precambrian granitic basement-cored regional crustal structure covered with Proterozoic and Phanerozoic strata that display thickness and facies variations as a result of its tectonic activity. This cratonic arch is located near the western margin of the Basin and is oriented NE-SW, perpendicular to the depositional strike of the Basin (Figure 1). It has been tectonically active, although relatively stationary geographically, since the Proterozoic and perhaps earlier with a Proterozoic to Devonian uplift phase (Peace River Arch), a Carboniferous to Triassic downwarp phase (Peace River Embayment) and a Jurassic to Recent regional subsidence phase with some subtle uplift (Table 3). Numerous smaller episodic movements have also occurred during these three tectonic phases along numerous high-angle basement-rooted faults within two NW- and SE-trending orthogonal sets. These faults were continually active and appear to have absorbed the large-scale movements of the structure (Sikabonyi, 1957; Sikabonyi and Rodgers, 1959).

Since the first well was drilled in the Arch area in 1949 (deMille, 1958), a variety of structural and structural-stratigraphic traps related to the active tectonic history have been investigated. Prolific oil and gas fields have been found, such as Normandville (Devonian), Dunvegan (Carboniferous), Eagle (Permian), Boundary Lake (Triassic) and Elmworth (Cretaceous), yet despite over 40 years of exploration and research in this area, researchers have not been able to singularly explain the origin(s) of the Arch and its several phases (e.g., O'Connell et al., 1990).

The Eagle, Eagle West and nearby Stoddart and Cecil fields (Figure 2) occur in one of the more tectonically active areas in late Paleozoic time. They are situated near the crest of the Proterozoic Arch and the north rim of the Carboniferous graben on the eastern flank of the Monias High, a north- and northwest-trending Cretaceous-Tertiary anticlinal fold which is an inversion structure imprinted on the downwarped Carboniferous-Permian graben (David G. Smith, pers. comm., 1990; Barclay et al., 1990). The main producing oil and gas reservoirs lie at depths (below surface) of about 2 km within the NW-trending shoreline-related deposits of the mainly Permian Belloy Formation. The Belloy consists of interspersed sandstone and carbonate units that were deposited on an elevated shallow marine shelf on the northern rim of the graben during its Peace River Embayment downwarp phase (Barclay et al., 1990; Leggett et al., 1993). During Permian time, while the graben was in its decaying phase and subsidence and block faulting was reduced compared to Carboniferous time, the northern rim appears to have persisted and was affected by significant continued faulting compared to other areas (e.g., Barclay et al., 1990, their figures 8b, c). Fault displacements were in the order of 30 m and may have been up to 150 m in some regions.

Production History

Petroleum and natural gas exploration and production have played an important role in the economic activity of northeastern British Columbia since the early 1950s. Significant gas discoveries in the Belloy Formation were made near the city of Fort St. John at the Fort St. John field in 1952 and 1953 (Figure 2), at the Fort St. John Southeast field in 1952, at the Stoddart field in 1957 and at the Stoddart West field in 1963. Significant Belloy oil discoveries were made in 1970 at the Stoddart West field, in 1972 at the Eagle field and in 1976 at Eagle West field.

The Belloy gas pools have produced in excess of 75% of their hydrocarbon resource originally in place. No pressure maintenance projects have been put into place in these pools and, as a result, average reservoir pool pressures have declined to 25% or less of their original pressure. The Stoddart West, Eagle and Eagle West Belloy oil pools were initially produced by solution gas drive – the primary expansion of the crude oil and dissolved solution gas in response to a controlled pressure release at the surface. This type of depletion mechanism is inefficient, so pressure maintenance by water injection was introduced into Eagle West in 1980, into Eagle in 1985 and into Stoddart West in 1991 to enhance the producing rate and oil recovery. In contrast to the gas pools, original reservoir pressures were not allowed to drop more than 50% before waterflooding was introduced. Since then pressures have been maintained or increased slightly from those that existed prior to the start of the flood.

Cumulative voidage (the total volume of fluid extracted minus that injected) taken from the two Eagle pools where the earthquakes appear to have occurred is shown in Figure 8 along with the earthquake history from Table 1. No direct correlation is noticeable, other than that the earthquakes start when approximately 1.7 x 10^6 m^3 of fluids or 4.4% of the hydrocarbon pore volume had been removed from these reservoirs. Waterflood start-up times are also indicated. At Eagle West there was a 4-year interval before the first earthquakes were observed. At Eagle the interval was 6 years if, in fact, the 1992 events were the first at that field. The 1986-1989 earthquakes (events 7-10) are not well located and the available macroseismic data are not sufficient to resolve which group they might belong to. It is also evident that earthquake frequency and

Table 3. Peace River Arch/Embayment history.

Time	Geometry	Description
ARCHEAN	?	Basement terranes & crust & mantle structures crosscut later "Arch" trends.
PROTEROZOIC	ARCH	Truncated Upper Proterozoic strata in outcrop.
CAMBRIAN	ARCH	Shallow water deposits; Middle, Upper Cambrian missing.
ORDOVICIAN	ARCH?	No sediments in region.
SILURIAN	ARCH?	No sediments in region.
DEVONIAN	ARCH	Basement emergent & fringed by reefs, sands. Terrestrial arkoses on crest areas. Progressive transgressive onlap throughout. 600 m total relief on Arch. Active NW & NE basement-rooted high-angle faults.
CARBONIFEROUS	EMBAYMENT & GRABEN	Old Arch blanketed by carbonates throughout embayment & graben. "Peace River Embayment" developed as broad NW-SE downwarp. Later, embayment shrunk to central, clastic-filled E-W graben. Old NW & NE faults very active in graben.
PERMIAN	EMBAYMENT	Sands & dolostones deposited throughout Peace River Embayment downwarp. Graben filled & less active. NW-SE faults locally active, e.g., in Eagle field area. Eagle fields in shoreline deposits.
TRIASSIC	EMBAYMENT	Return to broad Peace River Embayment downwarp. Clastic-carbonate-evaporite deposits. NW-SE faults active with reduced throws.
JURASSIC	REGIONAL SUBSIDENCE & SOME UPLIFT	Subtle extra subsidence more than rest of Western Canada Basin (Columbian foredeep). Middle Jurassic absent indicating uplift. Then westerly–derived mud and sand starting in Upper Jurassic.
CRETACEOUS	SUBSIDENCE & DRAPE STRUCTURES	Episodic extra foredeep subsidence. Drape folding & fracturing over old Arch & graben, reefs and faults.
CENOZOIC	SUBTLE ARCH	Laramide deformation inducing subtle uplift, persists into present. Tertiary removed from here & most of western Canada, Arch activity thus unclear. Recent earthquakes, Eagle field, production-induced rejuvenation of old faults?

Compiled from deMille, 1958; Lavoie, 1958; Williams, 1958; Pugh, 1973; Porter et al., 1982; Cant, 1988; Ross and Stephenson, 1989; Stephenson et al., 1989; Zelt, 1989; Barclay et al., 1990; Hart and Plint, 1990; Leckie et al., 1990; McMechan, 1990; Norford, 1990; O'Connell and Bell, 1990; O'Connell et al., 1990; Poulton et al., 1990; Ross, 1990.

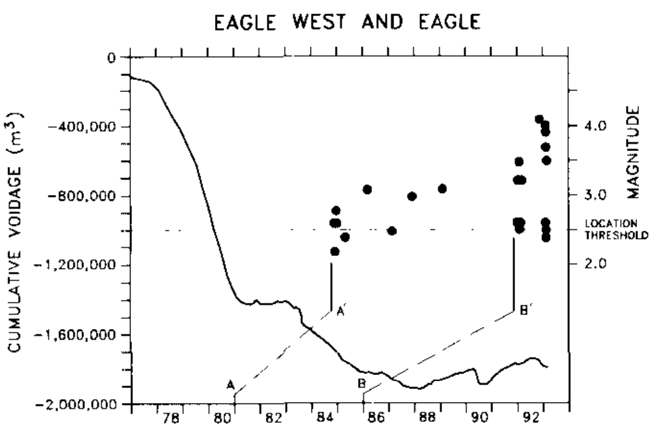

Fig. 8. Combined cumulative reservoir voidage for the Eagle West and Eagle units from January 1977 to March 1993, in relation to the observed seismicity. *Most earthquakes about M 2.5 and greater could* have been located by the existing seismograph network (Figure 4) since the mid-1960s. A-A' and B-B' indicate the commencement of enhanced recovery operations by water injection and the earthquakes possibly located in the Eagle West and Eagle fields, respectively. Earthquakes at the Eagle field may have begun as early as 1986.

magnitude are higher at the Eagle field. All of the M 3.5 and larger events have occurred there since 1992.

Figure 9 shows oil, gas and water volumes produced from the Eagle West and Eagle pools from January 1977 to March 1993. Peak oil production of about 40 000 m^3/month, reached in the early 1980s in Eagle West, started to decline about 1987 and by the beginning of 1993 was d own to about 12 000 m^3. In Eagle, peak oil production of about 12 000 m^3/month was not reached until 1986. In both Eagle West and Eagle the earthquakes lagged peak production periods. The seasonal variation exhibited by the earthquakes (Figure 5) is not evident in the production rates.

Figure 10 shows average monthly injection rates and average wellhead injection pressures over the same period as Figure 9. At Eagle West there was an increase in average surface injection pressure from about 20 MPa to 23 MPa in 1984, just before the first earthquakes were observed. Injection pressures were reduced in 1987 and appear to be reflected by a coincident decline in seismicity. At Eagle, slightly higher injection pressures of about 25 MPa were attained near the end of 1988 and have been maintained

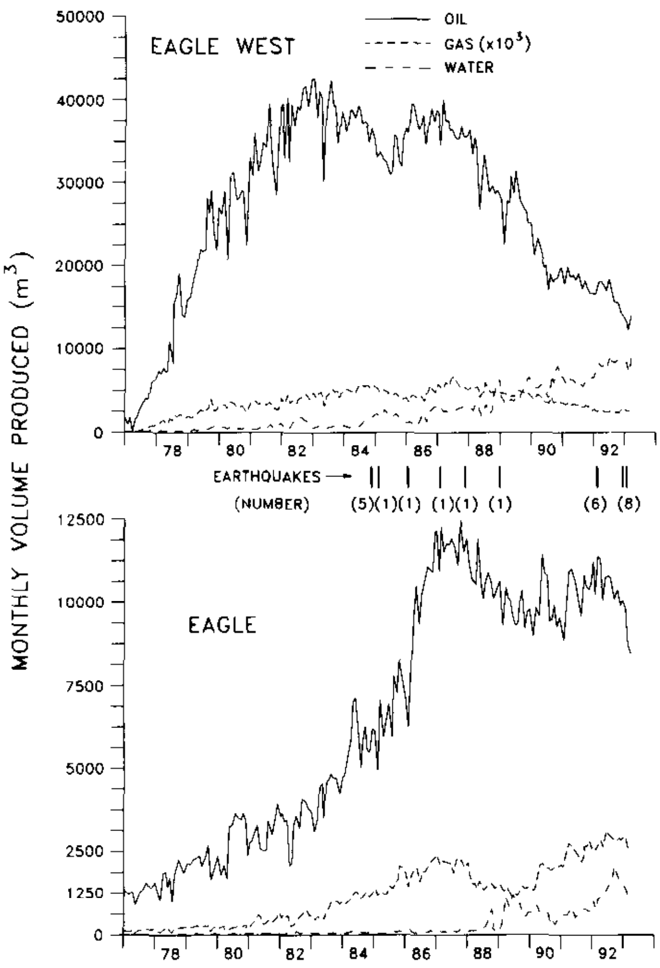

Fig. 9. Monthly oil, gas and water volumes produced from the Eagle West and Eagle units from January 1977 to March 1993. Note the scale differences. The times and number of earthquake occurrences are marked.

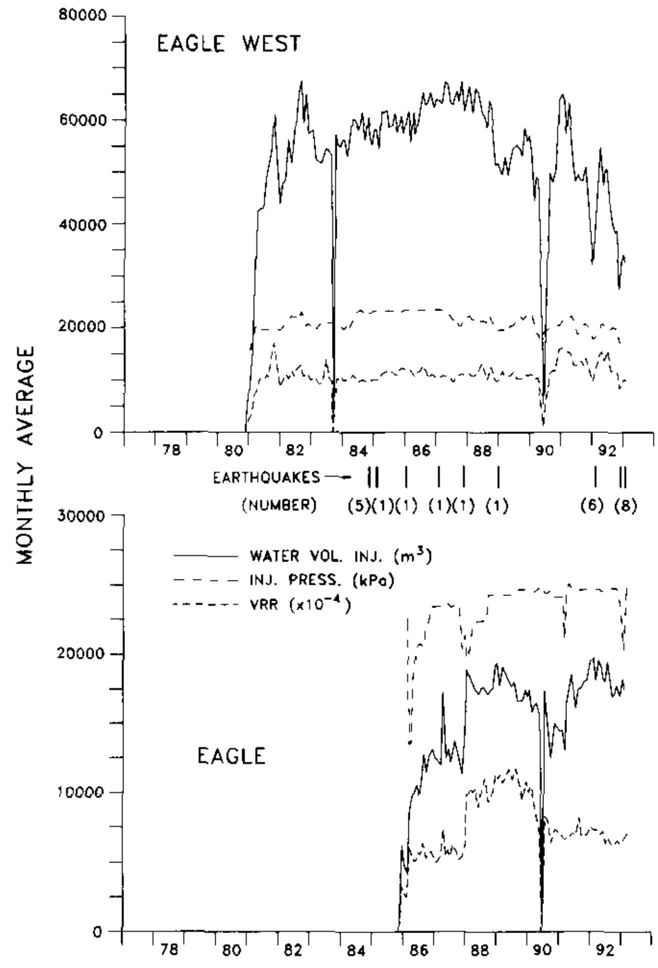

Fig. 10. Monthly water volumes injected, average monthly injection pressures and voidage replacement ratios in the Eagle West and Eagle units from January 1977 to March 1993. Note the scale differences. The times and number of earthquake occurrences are marked.

since. Again, there is no evident seasonal variation in pressure, nor is there the same apparent direct correlation between seismicity and increased injection pressure observed in Eagle West.

Also included in Figure 10 is an approximate estimate of voidage replacement. Voidage replacement ratio (VRR) is the ratio of monthly fluid volumes injected at reservoir temperature and pressure divided by the total fluids produced. A ratio of one indicates that replacement equals withdrawals. In contrast to Eagle West where VRR was maintained near 1, VRR at Eagle was only about 0.5 except for a 2-year period from 1988 to 1989 when it was 1 or slightly higher. During this time there was only one earthquake.

Discussion

Although a detailed analysis is precluded by the relatively poor location accuracy of the larger magnitude events and the absence of any mechanism solutions, there do appear to be spatial and temporal correlations between the earthquakes and oil production in the Eagle West and Eagle fields. Fluid injection in particular must be considered as a possible cause. The surface injection pressures of about 25 MPa are much higher than injection pressures in other oil fields that have been demonstrated to induce seismicity (e.g., Davis and Frohlich, 1993) and the earthquakes located during the January-March 1993 field survey all lie within about 0-4 km of both injection and production wells (Figure 11), taking into account epicentral uncertainty of 1-2 km. Focal depths are less accurate but are consistent with injection depths of about 2 km.

Earthquakes induced by fluid injection are usually explained by the theory of effective stress (Hubbert and Ruby, 1959). Increasing fluid (pore) pressure will reduce the frictional resistance to fracture by decreasing the effective normal stress across the fault plane according to the equation (e.g., Davis and Pennington, 1989):

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

where τ_{crit} *is the critical shear stress needed to cause slip on a* fault, τ_0 is the inherent shear strength of the rock, σ_n is the normal stress across the fault, p is the pore pressure and μ_f is

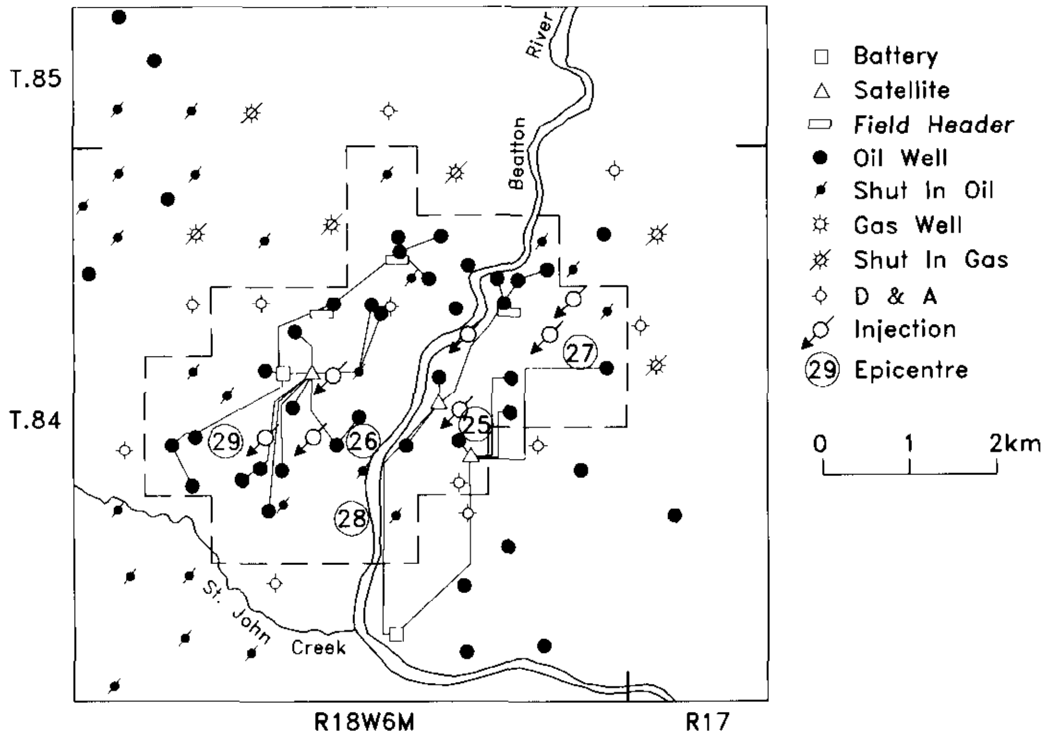

Fig. 11. Distribution of well-determined field epicentres (Table 1) in relation to production and injection wells in the Eagle field.

the coefficient of friction. In Figure 12, Mohr circles are used to illustrate the inferred state of stress at the bottom of injection wells in the Eagle field and for comparison at Rangely, Colorado, where seismicity was clearly related to fluid injection (Raleigh et al., 1972). At Rangely, surface injection pressures above about 6.5 MPa combined with hydrostatic pressures of about 19 MPa were sufficient to exceed the Mohr-Coulomb failure criterion and induce earthquakes. These ranged in magnitude up to M 3.5 and occurred at depths of about 1.8-3.7 km.

In situ stress magnitudes in the Fort St. John area can be inferred from hydraulic fracturing data in the Eagle and Stoddart fields (Table 4). Instantaneous shut-in pressure (ISIP) in three different formations at depths of 1-2 km yield estimates for the minimum compressive horizontal stress, S_{Hmin}, (Haimson and Fairhurst, 1970) that are an average of about 3 MPa higher than corresponding vertical stress values, S_V, calculated assuming a lithostatic gradient of 25 kPa/m (Figure 13). No direct measurements of the larger horizontal compressive stress (S_{Hmax}) are available but Kry and Gronseth (1983) calculate S_{Hmax}:S_{Hmin} ratios of 1.3-1.6:1.0 in the Peace River Arch area (see also Bell and McCallum, 1990). At injection depths of about 1900 m, assuming a lower S_{Hmax}:S_{Hmin} ratio of 1.3:1.0, we obtain

$$\begin{aligned} \sigma_1 &= S_{Hmax} = 65.0 \text{ MPa} \\ > \sigma_2 &= S_{Hmin} = 50.0 \text{ MPa} \\ > \sigma_3 &= S_V \quad = 47.5 \text{ MPa} \quad , \end{aligned}$$

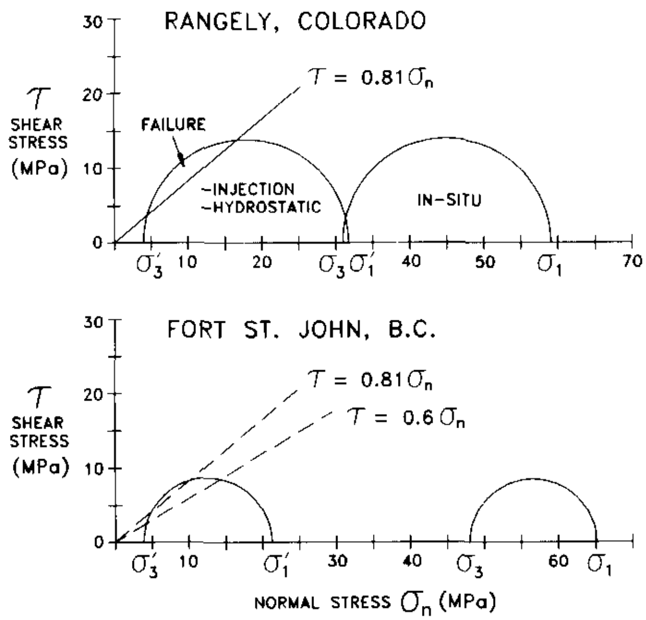

Fig. 12. Mohr circle diagrams showing the inferred stress conditions at the bottom of injection wells at Rangely, Colorado (Raleigh et al., 1972) and at the Eagle field near Fort St. John, B.C. (Table 4 and Figure 13). σ_1 and σ_3 are maximum and minimum principal stresses, respectively. σ_1' and σ_3' are effective stresses indicating the combined influence of hydrostatic and surface injection pressure. Portions of the circle to the left of the Mohr-Coulomb failure line indicate pressures are more than sufficient to induce movement on favourably oriented preexisting faults with zero strength. The failure criterion for Fort St. John is not known so two lines are plotted to indicate a possible range.

where σ_1, σ_2 and σ_3 are the maximum, intermediate and minimum principal stresses, respectively. These values indicate a compressive stress regime where thrust and/or strike-slip faulting would be expected (since σ_2 and σ_3 have similar magnitudes).

The Eagle surface injection pressure of 25 MPa and a hydrostatic pressure of about 18.6 MPa are both subtracted from the maximum and minimum principal stresses in Figure 12. Since the failure criterion is not known for this case, two failure lines are plotted to indicate a possible range and illustrate the effect of different coefficients of friction. The resulting Mohr circle lies to the left of both lines. If a larger $S_{Hmax}:S_{Hmin}$ ratio had been used both failure criteria would have been exceeded by an even larger degree. On the other hand, friction losses that would lower bottom-hole pressures by about 0.5 MPa have been ignored. Nonetheless, it does appear that injection pressures at the Eagle field could be sufficient to promote failure on favourably oriented preexisting faults.

Waterflooding was initiated on the west side of the Beatton River in 1985 and extended east of the Beatton River in 1986 (Figure 11). The delay of up to 4-6 years after injection was initiated and before earthquakes were observed might be related to the time it takes for pressures away from the injection wells to increase to levels that could initiate movement on preexisting faults. There is abundant evidence for faults in this region of the Peace River Arch (such as displacements seen on seismic sections and displacements seen on thickness, structure and facies maps of stratigraphic units; see Cant, 1988; Barclay et al., 1990; O'Connell et al., 1990; and others listed in Table 3) and the Eagle field itself is dissected by small NE- and NW-trending normal faults (Leggett et al., 1993).

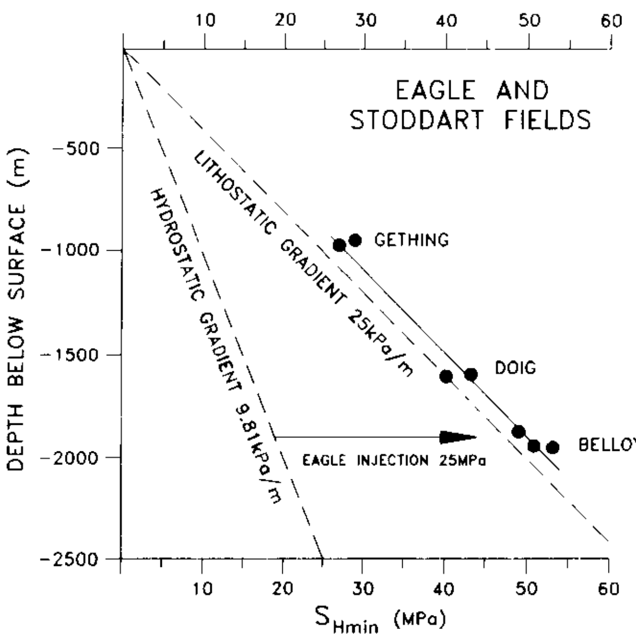

Fig. 13. Minimum horizontal compressive stress values, S_{Hmin}, from hydraulic fracturing data in the Eagle-Stoddart area of Fort St. John (Table 4). S_{Hmin} values are an average of about 3 MPa higher than comparable lithostatic pressures. Also indicated is Eagle injection pressure of 25 MPa at a depth of about 1900 m.

Table 4. Minimum compressive horizontal stress (S_{Hmin}) from hydraulic fracturing data in the Eagle-Stoddart area of Fort St. John. ISIP is instantaneous shut-in pressure at the surface. Pressure gradients of the fluids used for hydraulic fracturing range from about 7.8-10.0 kPa/m. Ignored are friction losses that would lower S_{Hmin} values by about 0.5 MPa.

Well Location	Formation	Depth m	ISIP MPa	Static Pressure MPa	S_{Hmin} MPa
05-26-84-18W6M	Gething	−946	21.2	7.4	28.6
10-22-84-18W6M	Gething	−973	19.5	7.6	27.1
12-04-86-20W6M	Doig	−1601	27.2	16.0	43.2
06-04-86-20W6M	Doig	−1608	27.9	12.5	40.4
02-36-84-18W6M	Belloy	−1873	34.0	14.7	48.7
14-19-85-19W6M	Belloy	−1940	34.0	19.0	53.0
15-35-85-20W6M	Belloy	−1940	36.0	15.2	51.2

Davis and Frohlich (1993) developed a criterion to assess whether injection is likely to have induced the observed seismicity. They pose seven questions based on the historical earthquake record, temporal and spatial correlations and injection practices and state "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". Their questions are:

1. Are these events the first known earthquakes of this character in the region?
2. Is there a clear temporal correlation between injection and seismicity?
3. Are epicentres within 5 km of injection wells?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to the sites of earthquakes?
6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?
7. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?

In this study we can address the first six questions and would answer "yes" or "apparently yes" to all of them.

It is difficult to evaluate the possible influence of other factors with available data. Pool depletion does not appear to be as significant as high-pressure fluid injection. If the large volumes of gas that have been produced from nearby gas pools have had no precipitating effects for earthquakes it is unlikely that the relatively small amount of unreplaced voidage in the Eagle pools would have an effect either.

CONCLUSIONS

There are several observations that point to a correlation between earthquakes and oil production in the Fort St. John area.

1. These earthquakes occurred in a region of typically very low-level seismicity.

2. The majority of the larger earthquakes are grouped into three distinct clusters, each with a duration of about one month and located over or very near to the Eagle West or Eagle oil fields.
3. The first cluster in November 1984 was apparently centred near the west side of the Eagle West field. This field was discovered in 1976; however, peak production and associated high-pressure water injection to enhance recovery did not occur until 1980. Average surface injection pressures were increased from about 20 MPa to 23 MPa in 1984, just before the first earthquakes were observed. As injection pressures and production declined in the late 1980s, so too did the seismicity.
4. In January-February 1992 and December 1992-January 1993 most of the earthquakes and all M 3.5 and greater occurred in two clusters over or very near the Eagle field. Although this field was discovered in 1972, significant production was delayed until Eagle West production started to decline. Water injection was initiated here in 1985 and 1986 with pressures reaching about 25 MPa, about 2 MPa higher than at Eagle West. Earthquakes possibly occurred at the Eagle field as early as 1986.
5. A field survey in January-March 1993 found low-magnitude events exclusively in the Eagle field. Epicentres were within a few km of both production and injection wells and although focal depths were not accurate to better than 3-4 km they were consistent with reservoir depths of about 2 km.
6. The injection pressures of about 25 MPa are perhaps high enough to induce failure on favourably oriented preexisting faults. The delay of up to 4-6 years after injection has been initiated and before earthquakes are observed is perhaps attributable to the time it takes for fluid pressure away from injection wells to rise to the level necessary to initiate failure. Hydraulic fracturing indicates a compressive stress regime at depths of 1 to 2 km where $S_{Hmax} > S_{Hmin} > S_V$ and where thrust and/or strike-slip faulting would be expected.
7. There is abundant evidence for faults in this region of the Peace River Arch that has been tectonically active since at least the Proterozoic.

Although high-pressure fluid injection must be considered as a possible cause of this seismicity, we cannot rule out the possible contribution of other factors until more accurate hypocentre and mechanism solutions, in particular, are available.

The earthquakes in December 1992, January 1993 and, most recently, in May 1994, with magnitudes up to M 4.3, would be among the largest associated with any secondary recovery or pressure maintenance program. All were strongly felt with Modified Mercalli intensities as high as V and felt areas up to about 2000 km^2. Davis and Frohlich (1993) report magnitudes as high as M 4.6 in the Cogdell oil field in Texas. How large the earthquakes in the Fort St. John area could become is not known. Also, the hazard presented by this seismicity still needs to be adequately assessed and warrants further investigation.

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