Earthquakes, Micro-earthquakes and CO_2 injection at Weyburn field

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Conclusions

Micro-seismicity associated with water and/or CO_2 injection is very small

No seismic evidence that any injection-related fractures are developing

Small natural earthquakes have occurred in southern Saskatchewan
The closest was 39 km west of Weyburn in 1976, magnitude 3.3

No known natural earthquake nor potash mine induced earthquake has created a fracture on the surface in Saskatchewan.

It is unlikely, but should a natural earthquake greater than magnitude 2 occur inside the Weyburn oil field it could damage the casing of a deep well

Location of the Weyburn Field, set in the Williston Basin

Verdon et al., 2010a

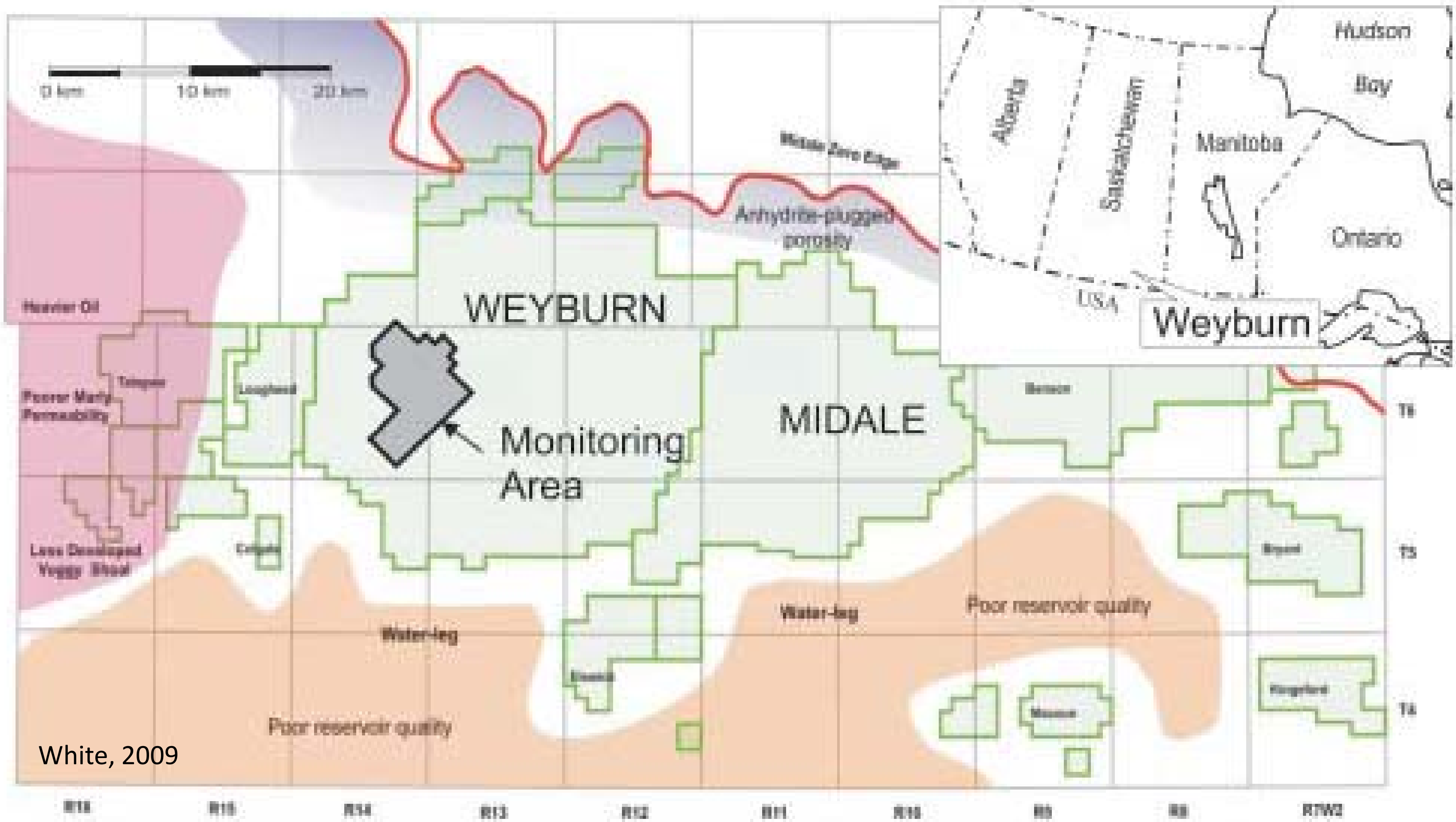
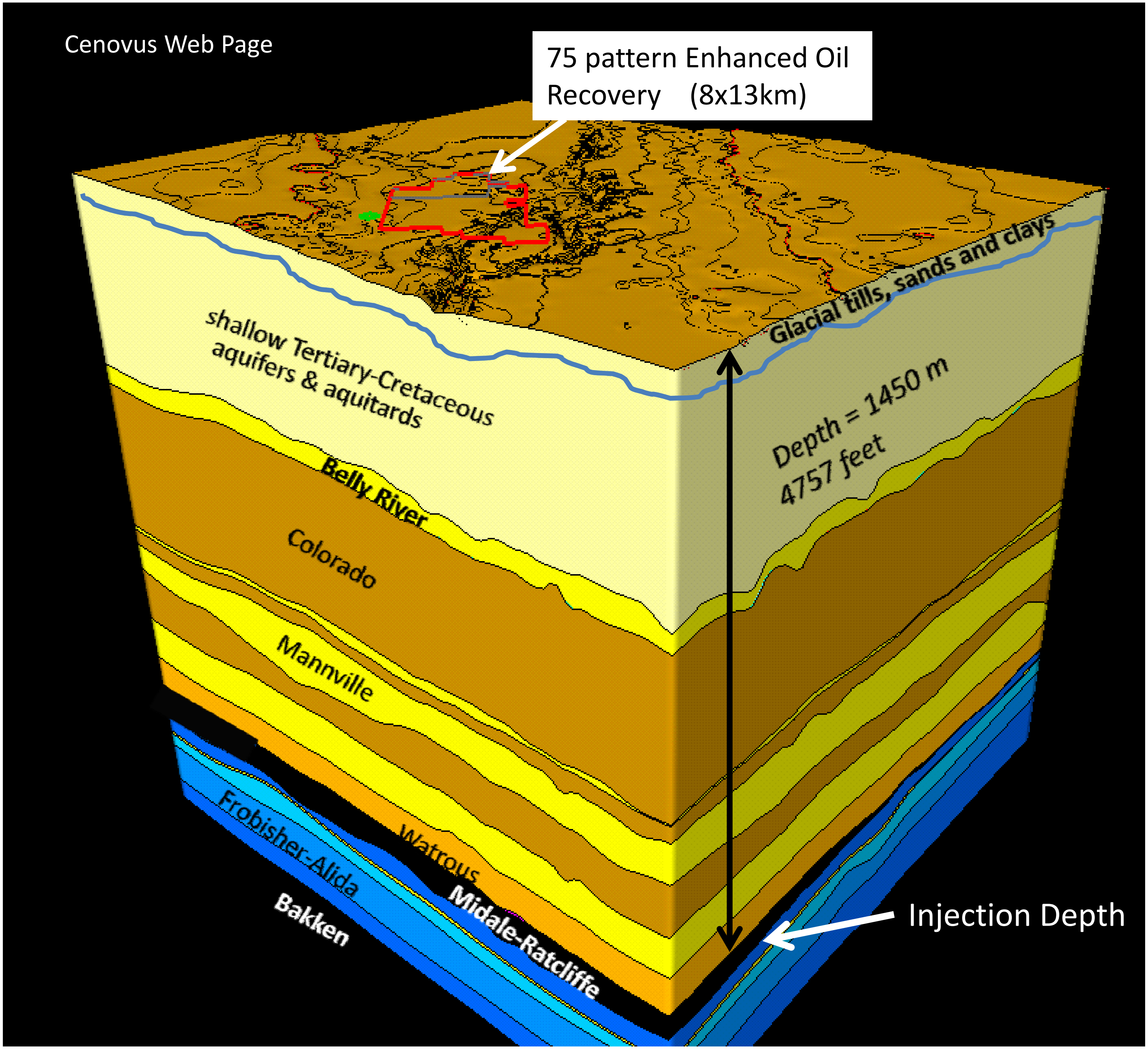
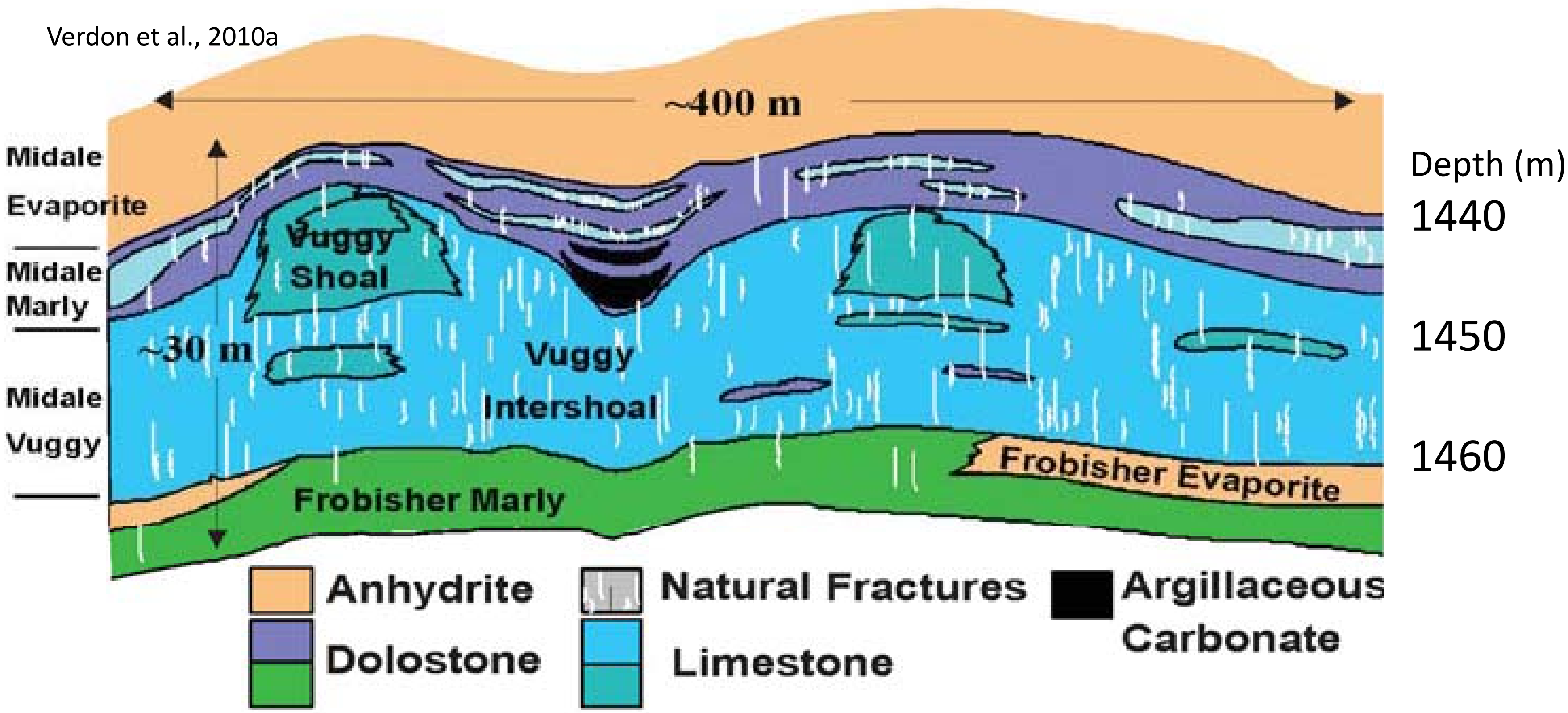


Figure 1. Map of the Weyburn and Midale EOR (Enhanced Oil Recovery) fields including reservoir quality.

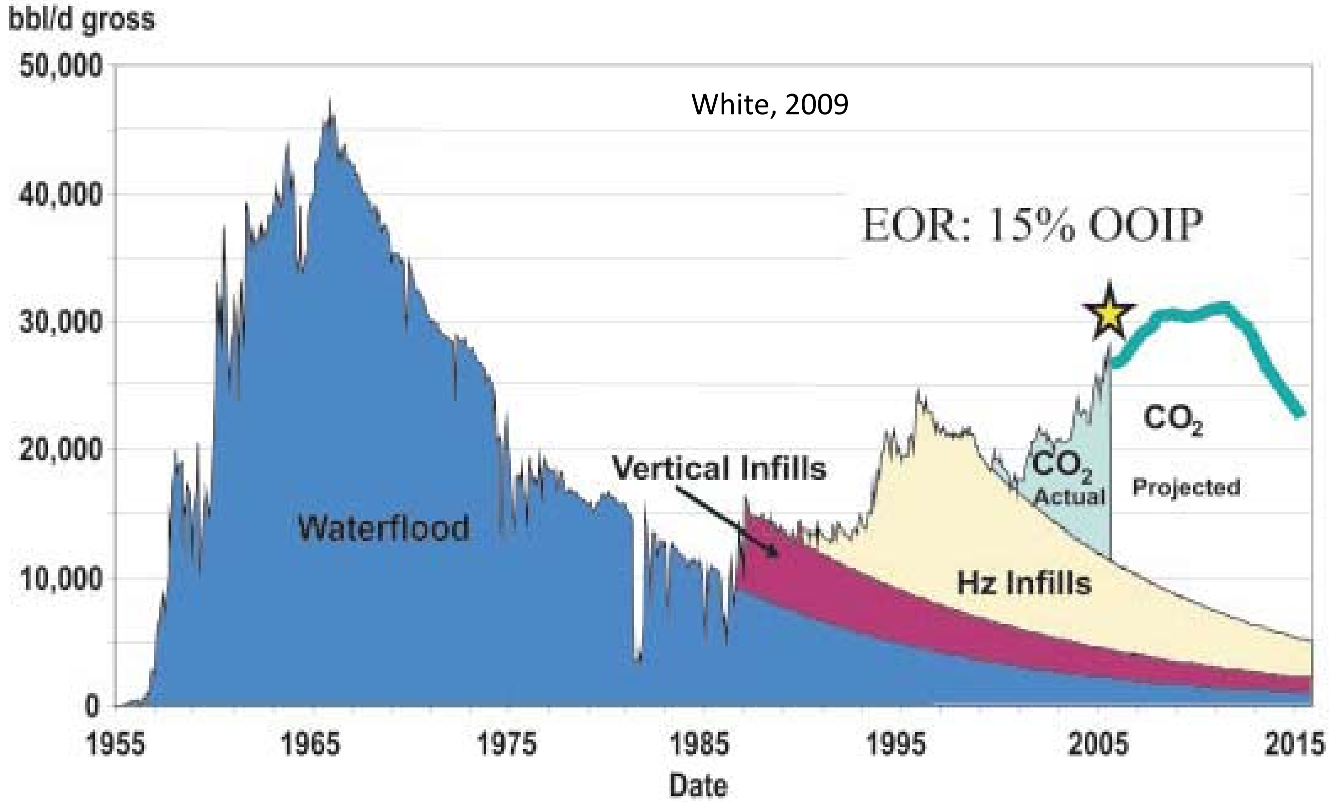

Cenovus Web Page
75 pattern Enhanced Oil Recovery (8x13km)
shallow Tertiary-Cretaceous aquifers & aquitards
Glacial tills, sands and clays
Depth = 1450 m 4757 feet
Belly River
Colorado
Mannville
Watrous
Frobisher-Alida
Midale-Ratcliffe
Bakken
Injection Depth

Verdon et al., 2010a



Schematic cross section through the naturally fractured Weyburn reservoir, lower vuggy and upper marly units.

Primary seal is the Midale evaporite.
An important secondary seal is the overlying Watrous member (not shown) of Jurassic age.



Why they are injecting water and CO_2 into the Weyburn field --

Production is returned to levels of 1970's

Life of the field is extended many years

524 million barrels produced 1955 to 2000

215 million barrels additional will be produced using CO_2

35 million tonnes of CO_2 sequestered

Why micro-seismic monitoring?

High pressure injection may fracture rock. Fractures may provide paths for fluid leakage to the atmosphere.

When rock fractures it sends out vibrations as in an earthquake; small fractures send out small vibrations.

Modern micro-seismic systems can :

1 Detect the vibrations
2 Locate where they came from
3 Estimate the size of the fracture
4 Determine the orientation of the fracture

If fractures are recognized, corrective action can be taken

Earthquakes vs Micro-earthquakes

During earthquakes, energy release breaks rock and moves earth, friction makes heat, and vibrations radiate outward.

Enormous amounts of energy cause large earthquakes

Small amounts of energy cause micro-earthquakes

Only a small fraction of the energy appears as vibration

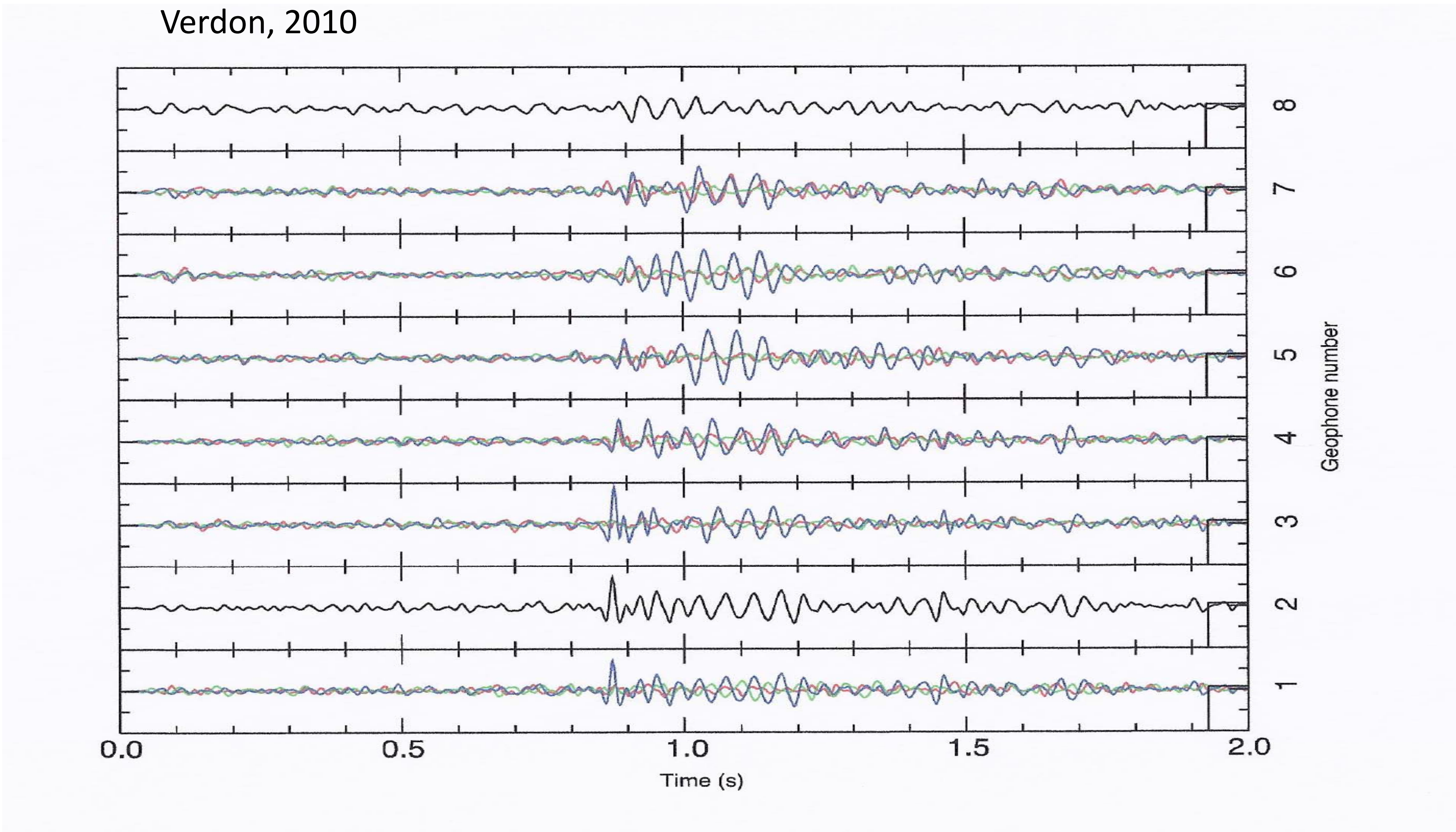
Distant seismometers can measure the vibration

One Weyburn well was instrumented to detect micro-earthquakes caused by high pressure fluid injection

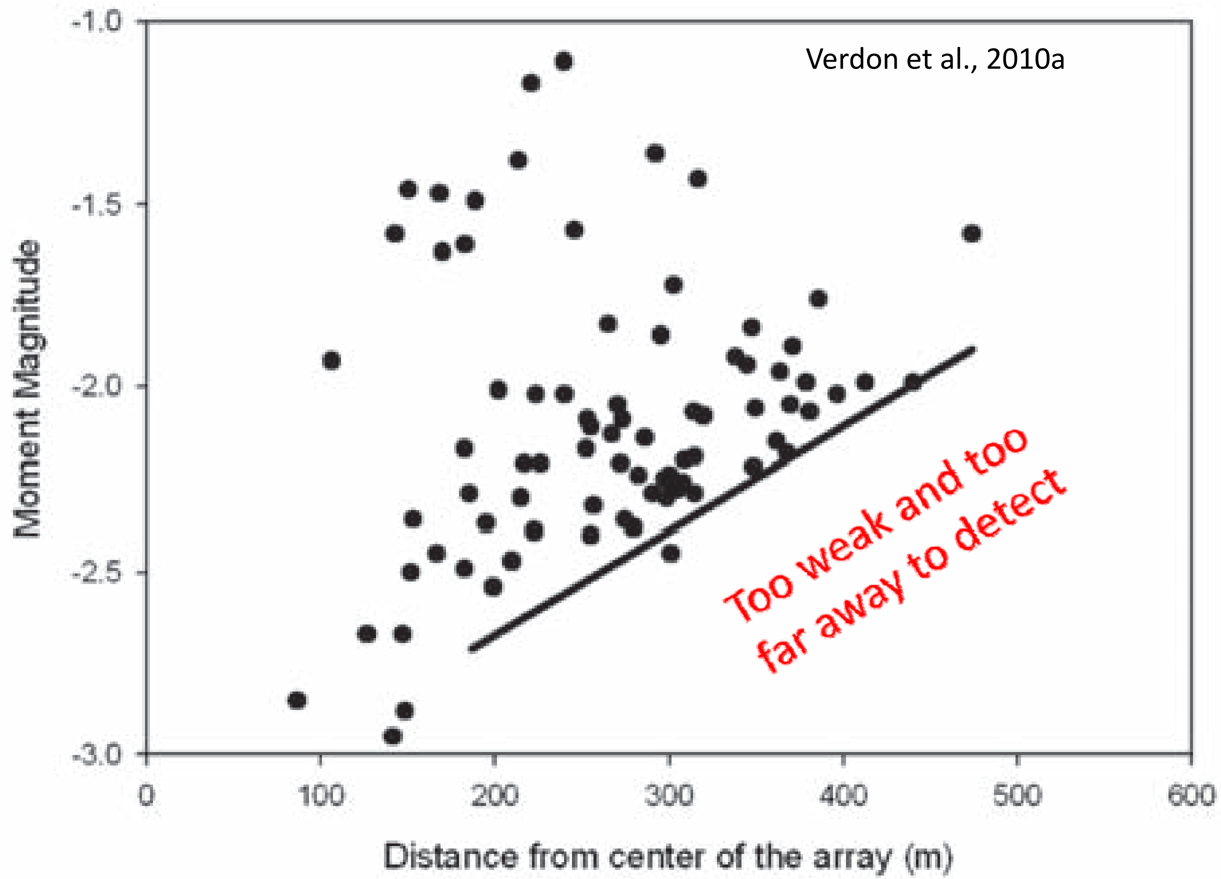
Earthquake and Micro-Earthquake Comparison

Magnitude	Equivalent TNT Radiated Energy	Energy Comparison
+3	480 kilograms	Large potash mine earthquake
+2	15 kilograms	Small potash mine earthquake
+1	480 grams	10 ton trucks collide
0	15 grams	Jump off a tall building
-1	**0.5 gram**	**30-30 rifle bullet**
-2	**15 milligram**	**Drop a large dictionary**
-3	**0.5 milligram**	**Break a small stick**

Red = Weyburn CO_2 injection micro-earthquake sizes



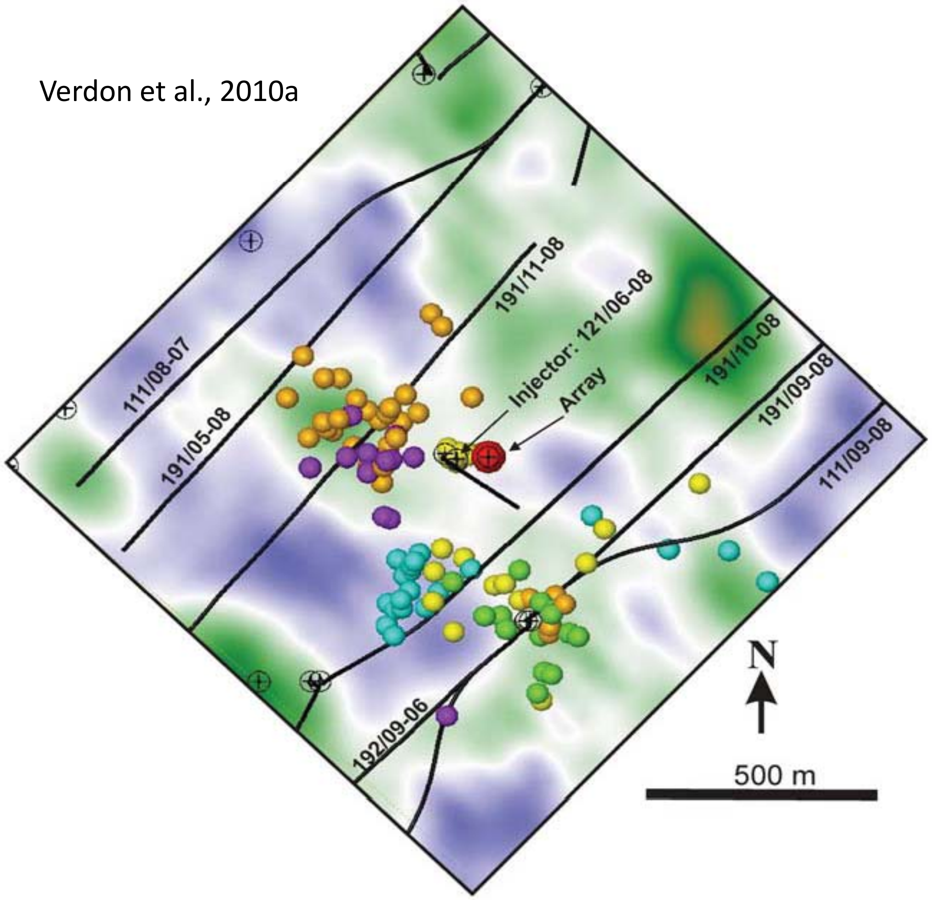
Example seismogram of a Weyburn micro-earthquake



About 100 micro-seismic events were detected during the monitoring period.

Negative magnitudes mean very small, detectable only by sensitive instruments.

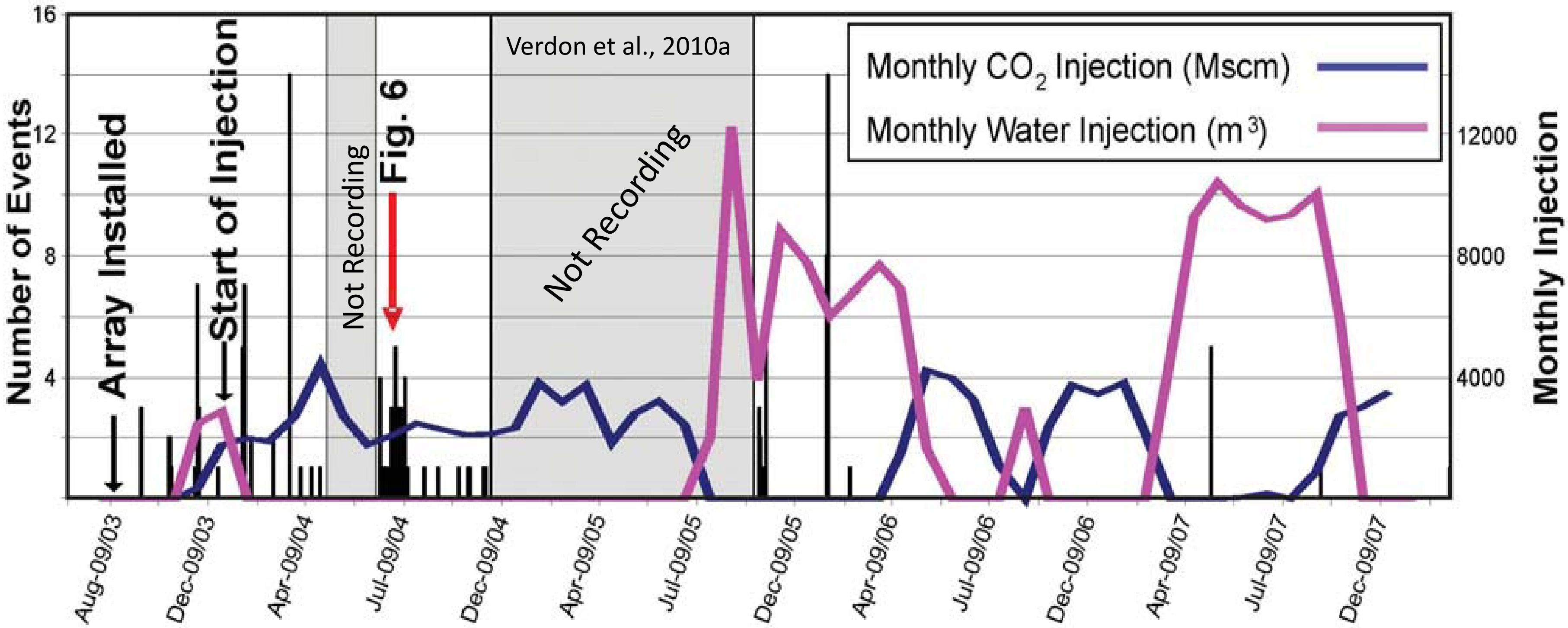
Verdon et al., 2010a



Map of one Weyburn field CO_2 injection area with micro-seismic monitoring.

Colored dots represent micro-seismic events at different time intervals from Aug. 2003 to Jan. 2006.

Blue and green background map is from 3D seismic.



Histogram of located micro-seismic events from August 2003 to January 2008.
Also shown are the alternating water and CO_2 injection volumes for well 121/06-08.

Seismic activity is very low whether water or CO_2 is injected.
Other injection oil fields have thousands of events.

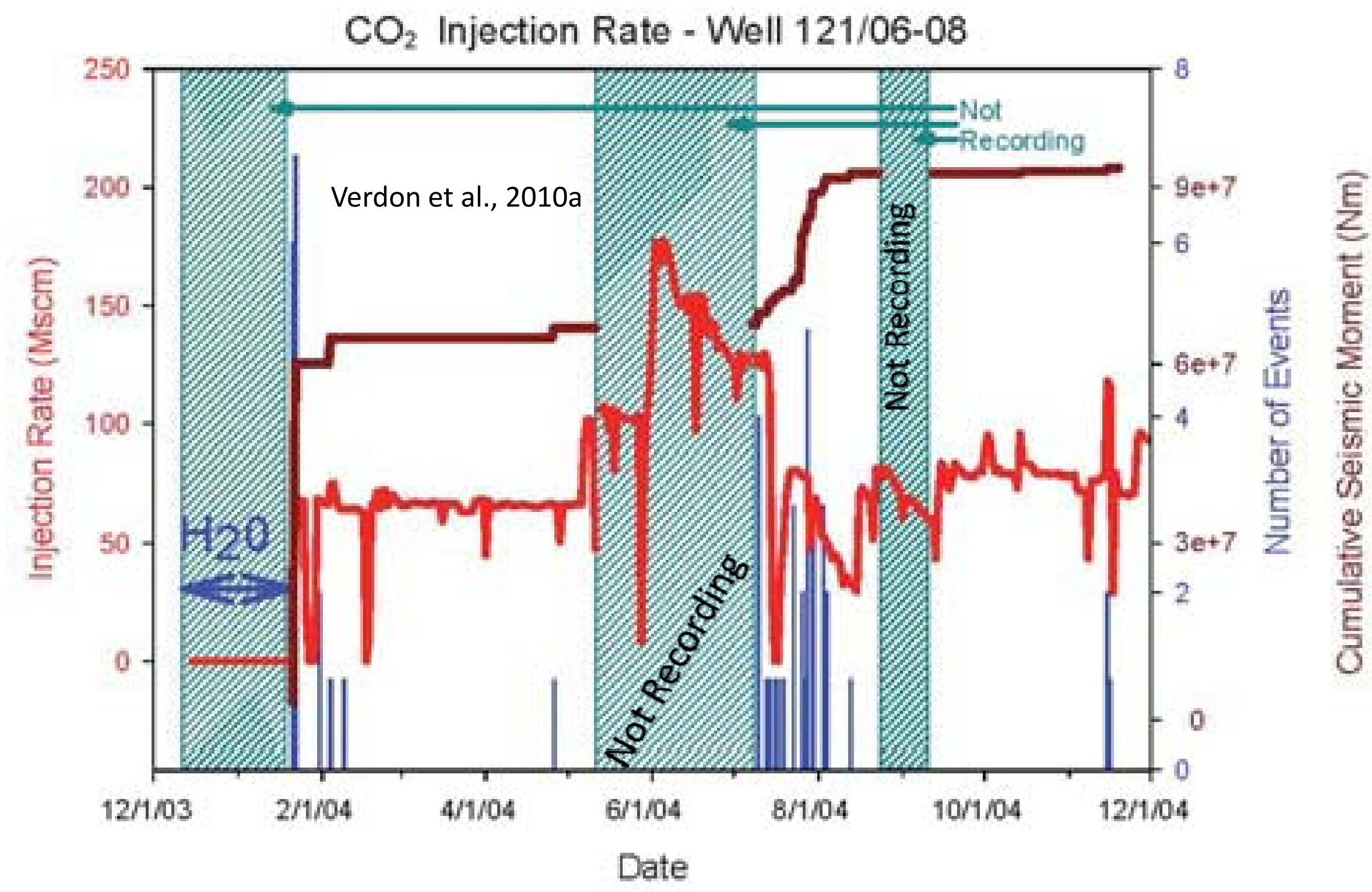
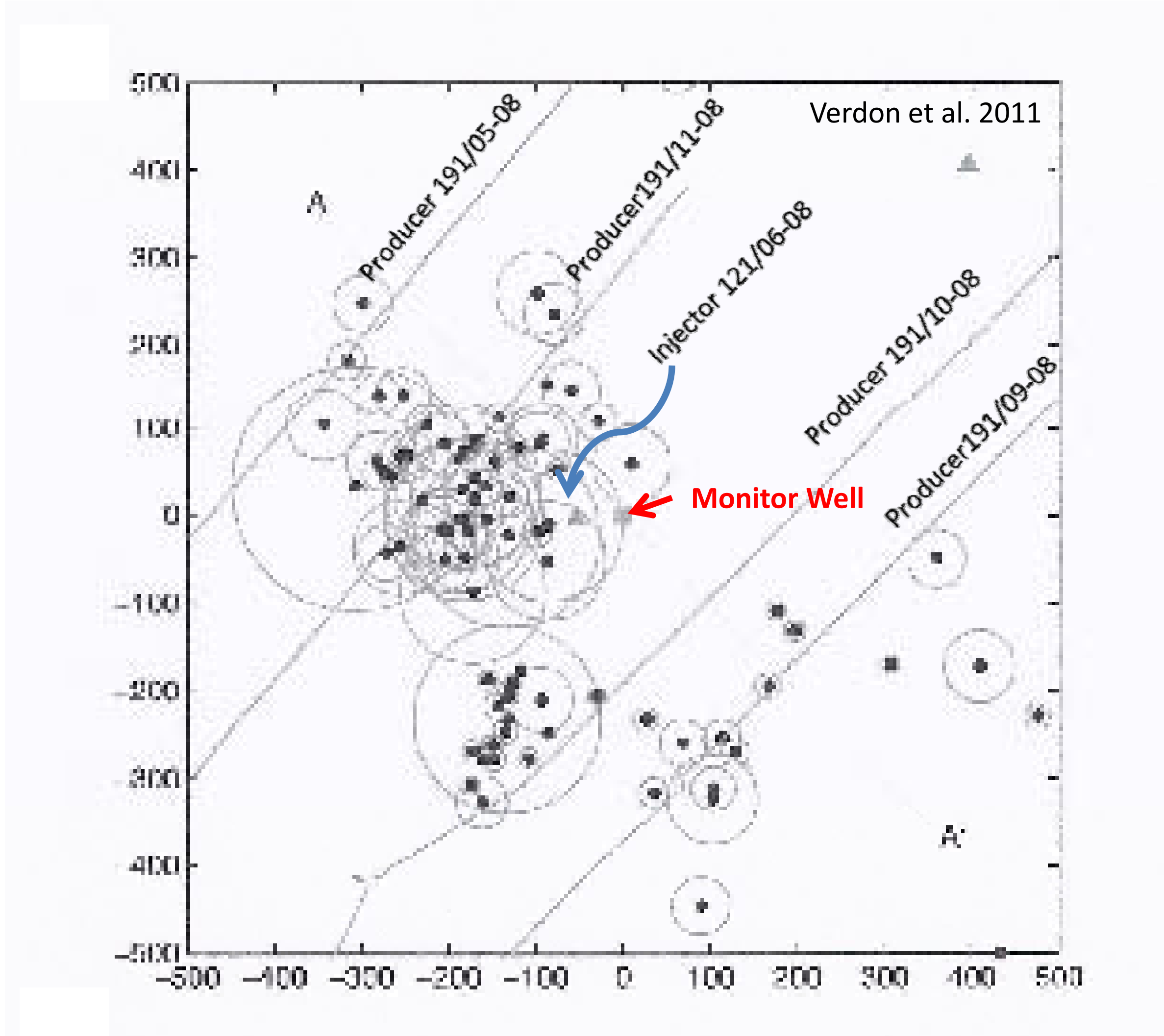
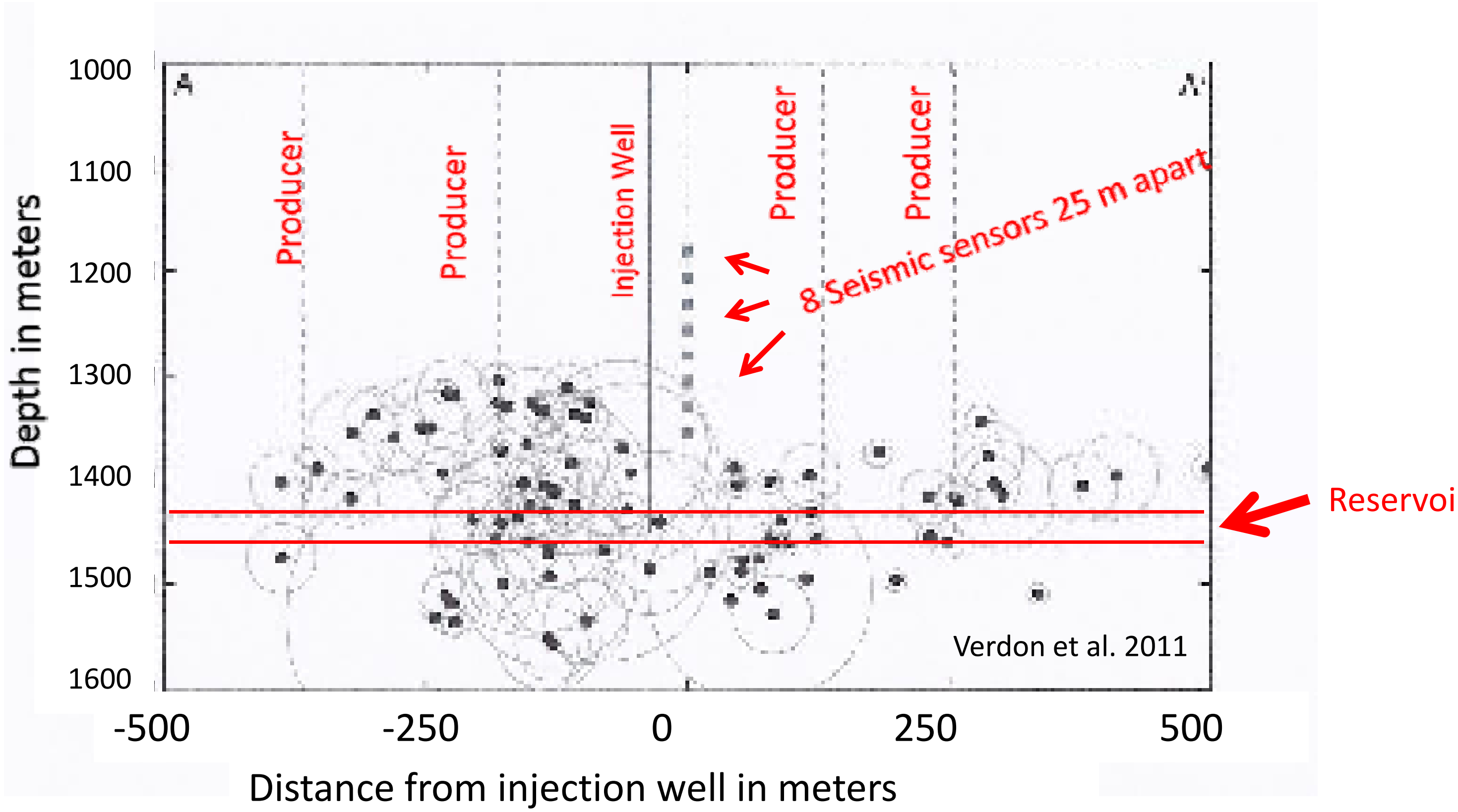


Figure 6. Daily CO2 injection volume (red), histogram of micro-seismic events (blue), and calculated cumulative seismic moment (maroon) for injection well 121/06-08. The period of high injection runs from May to July 2004, with elevated microseismic rates continuing through August 2004.



Map View of micro-seismic events detected Jan 2003 – Jan 2008
No events at the vertical injector well
Most events clustered over horizontal producer wells
Size of circle shows uncertainty in location of each event

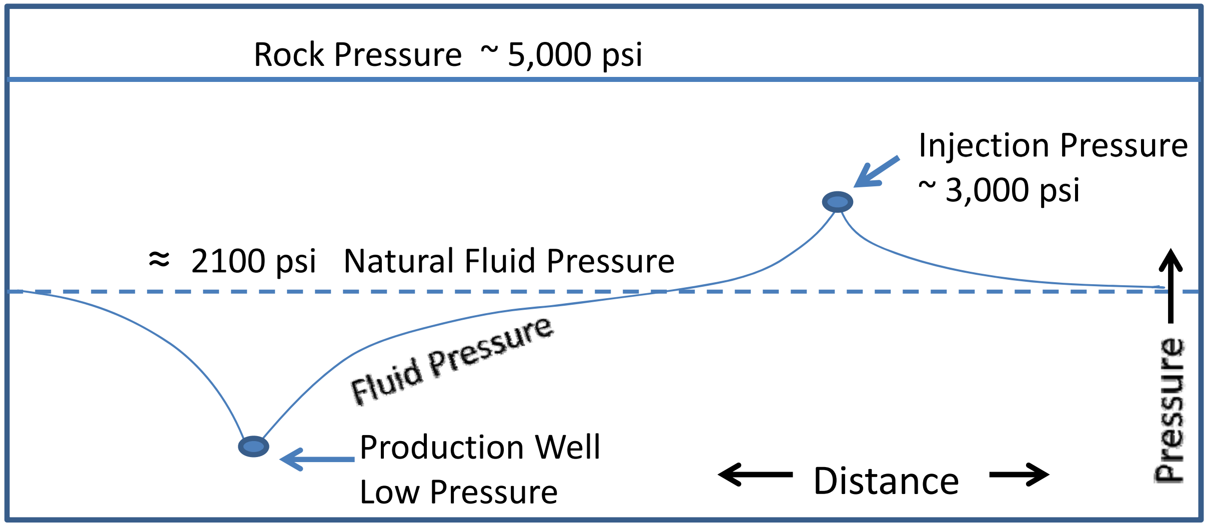


Vertical section through 121/06-08 injection well

Showing micro-seismic events near the injection depth

No events detected above the seismic sensors; no fracture pattern

Pressure reduction near the producer wells is thought to cause most events.



An explanation why micro-earthquakes occur close to production wells

Natural fluid pressure partly supports overburden weight

Pumping in production well reduces fluid pressure

Overburden weight is partly transferred from fluid to minerals in the rock

Weak spots in the rock fail under increased load, causing micro-earthquakes

--- natural fractures, large pores, thin clay layers, etc. ---

Pressure at injection well is too low to fracture rock.

- Geomechanical computer modelling of the Midale reservoir shows that pressure reduction at the producing wells is the main cause of micro-seismicity.
- Pressure reduction decreases stress above the well so rock beside the well takes up the load. The adjustment causes micro-earthquakes.
- Calculation agrees well with observations.
- No evidence of fracture growth.

“at Weyburn injection pressures are 20-25MPa, with the intention of minimising fracture. “

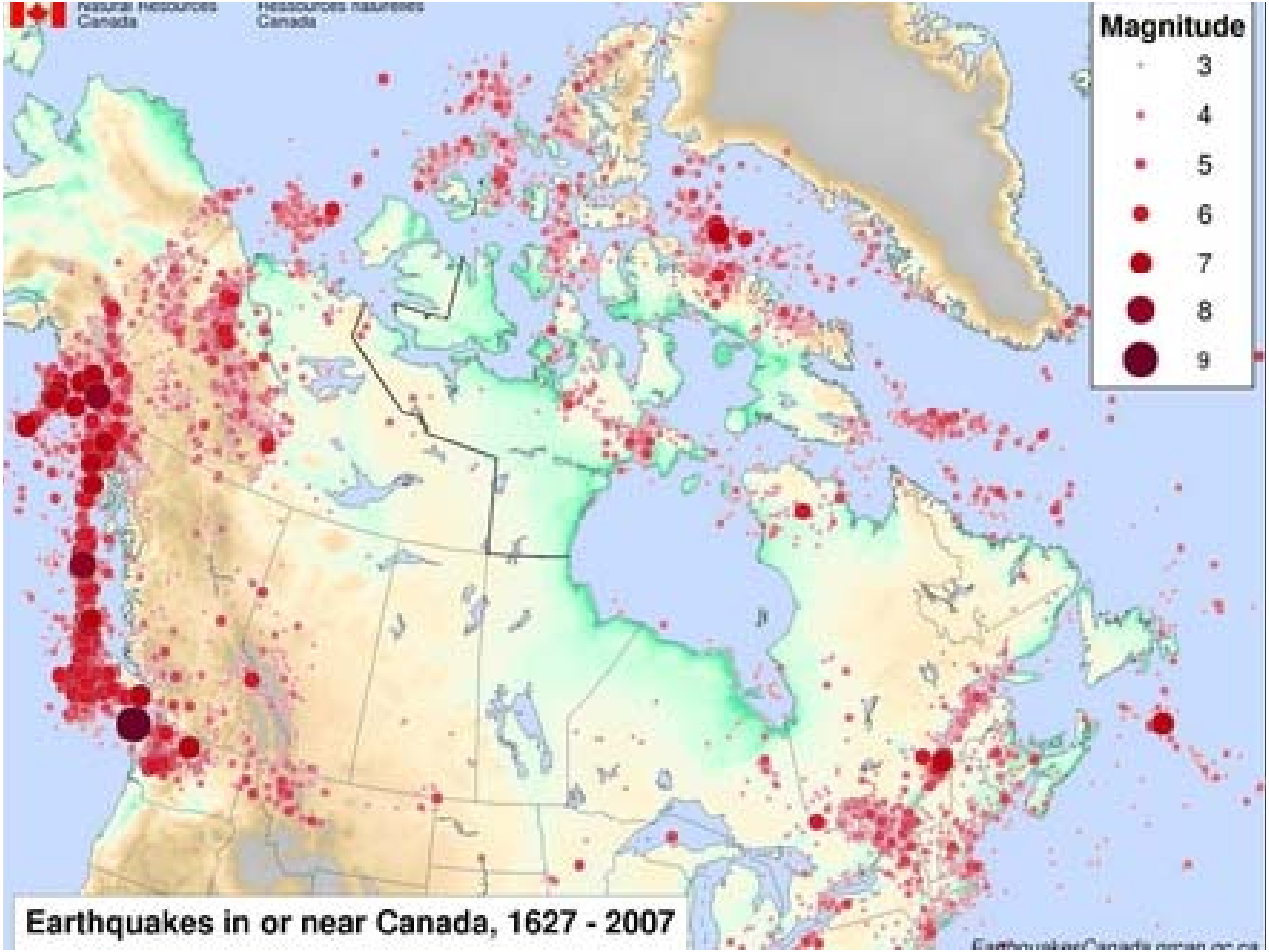
“rates and magnitudes of microseismicity are very similar during CO_2 injection and water injection, and very low compared to other places”

“The geomechanical model indicates that microseismicity observed in the overburden at Weyburn does not represent fluid migration through the caprock but stress transfer through the rock frame.”

3D seismic shows CO_2 fluid in the reservoir but not above the reservoir.

No evidence of fracture development

James Verdon, 2010, Ph.D thesis, University of Bristol, England.
Microseismic Monitoring and Geomechanical Modelling of CO_2 Storage in Subsurface Reservoirs


Natural Resources Canada
Ressources naturelles Canada
Magnitude
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Earthquakes in or near Canada, 1627 - 2007

Earthquake Magnitude

Magnitude is an estimate of earthquake size.
It is related to the wave energy radiated away from the epicentre.

Calculated by measuring the ground motion with a seismometer.

Earthquake motion diminishes with distance so a correction is needed for distance from the earthquake epicentre to the seismometer.

After the distance correction and other corrections, a seismograph anywhere should give the same magnitude for the same earthquake.

Charles Richter's original scale was valid only for California earthquakes and instruments used in California in the 1930's

Modern seismologists use other magnitude scales besides the historic Richter Scale

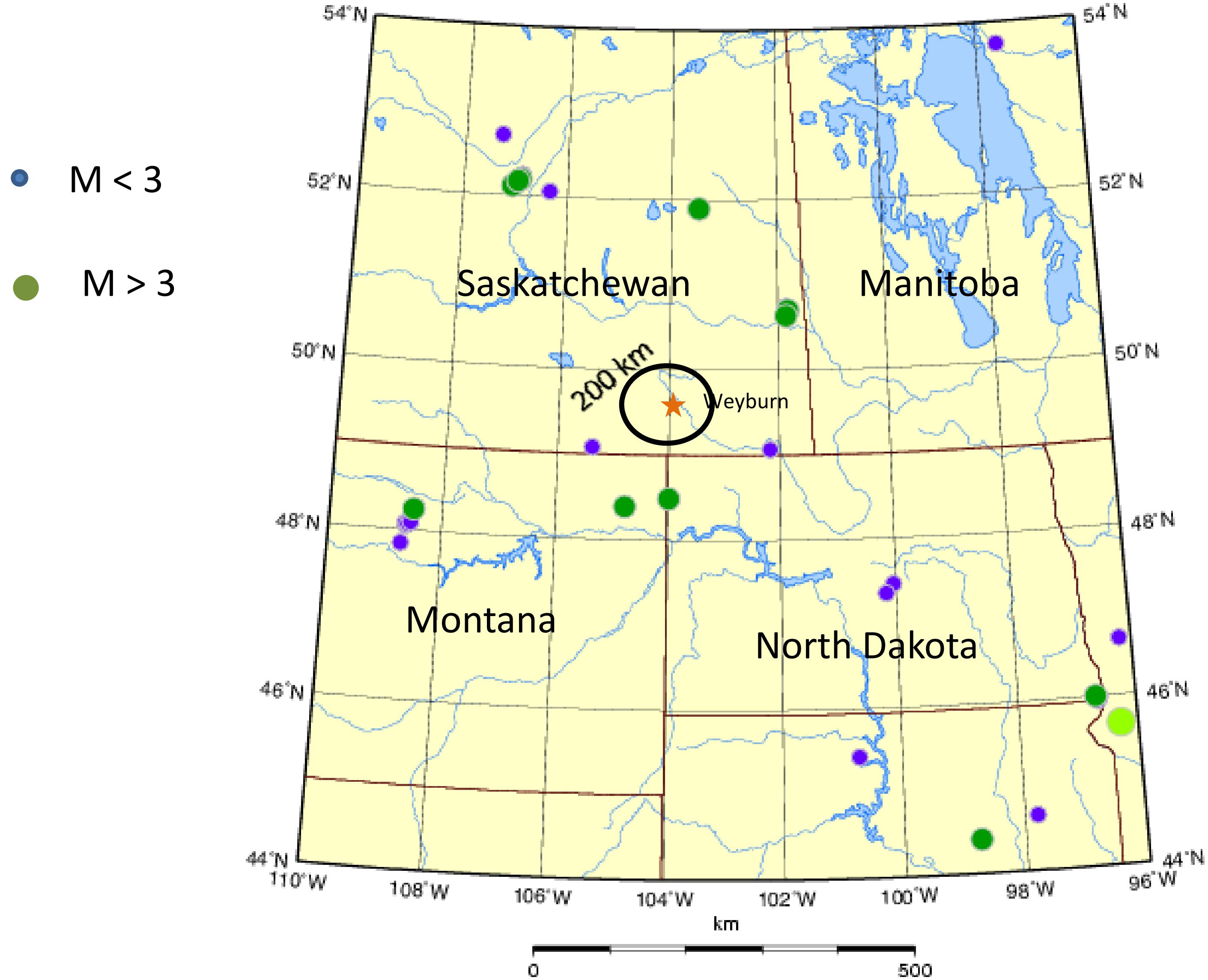
Earthquakes within 200 km of Weyburn up to 2012

Date	Latitude	Longitude	Magnitude	Comments
1998-11-11	48.49	-103.99	3.5MN	North Dakota - Montana border
1998-07-29	48.39	-104.77	3.4MN	North East Montana Felt
1998-07-28	48.40	-104.80	2.7MN	North East Montana Foreshock
1997-04-18	49.08	-105.38	2.9MN	Southern Saskatchewan Felt
1985-10-10	49.07	-102.17	2.9MN	60 km E from Estevan
1982-08-17	49.06	-105.38	3.9MN	130 km SW from Weyburn
1982-03-09	48.48	-104.09	3.4MN	Felt mildly at Grenora ND
1979-02-21	48.51	-105.06	2.8MN	156 km SW from Weyburn
1976-03-25	49.39	-104.27	3.5MN	43 km SW from Weyburn
1976-03-23	49.56	-104.37	3.3MN	39 km W from Weyburn
1972-07-26	49.35	-104.93	3.7MN	86 km SW from Weyburn
1968-10-11	49.61	-104.49	2.8MN	47 km W from Weyburn
1943-06-25	48.50	-105.00	5.0ML	145 km SE from Assiniboia
1909-05-16	49.00	-104.00	5.5MN	75 km S from Weyburn

Total = 14   Nearest in 1976 at 39 km west from Weyburn. None since 1998.

Before 1965 no seismographs were able to detect a small earthquake in Saskatchewan

Geological Survey of Canada, Earthquake internet site



Northern Plains Earthquakes 1985 – 2009 35 Events

NRC Canada

Horner and Hasegawa, 1978

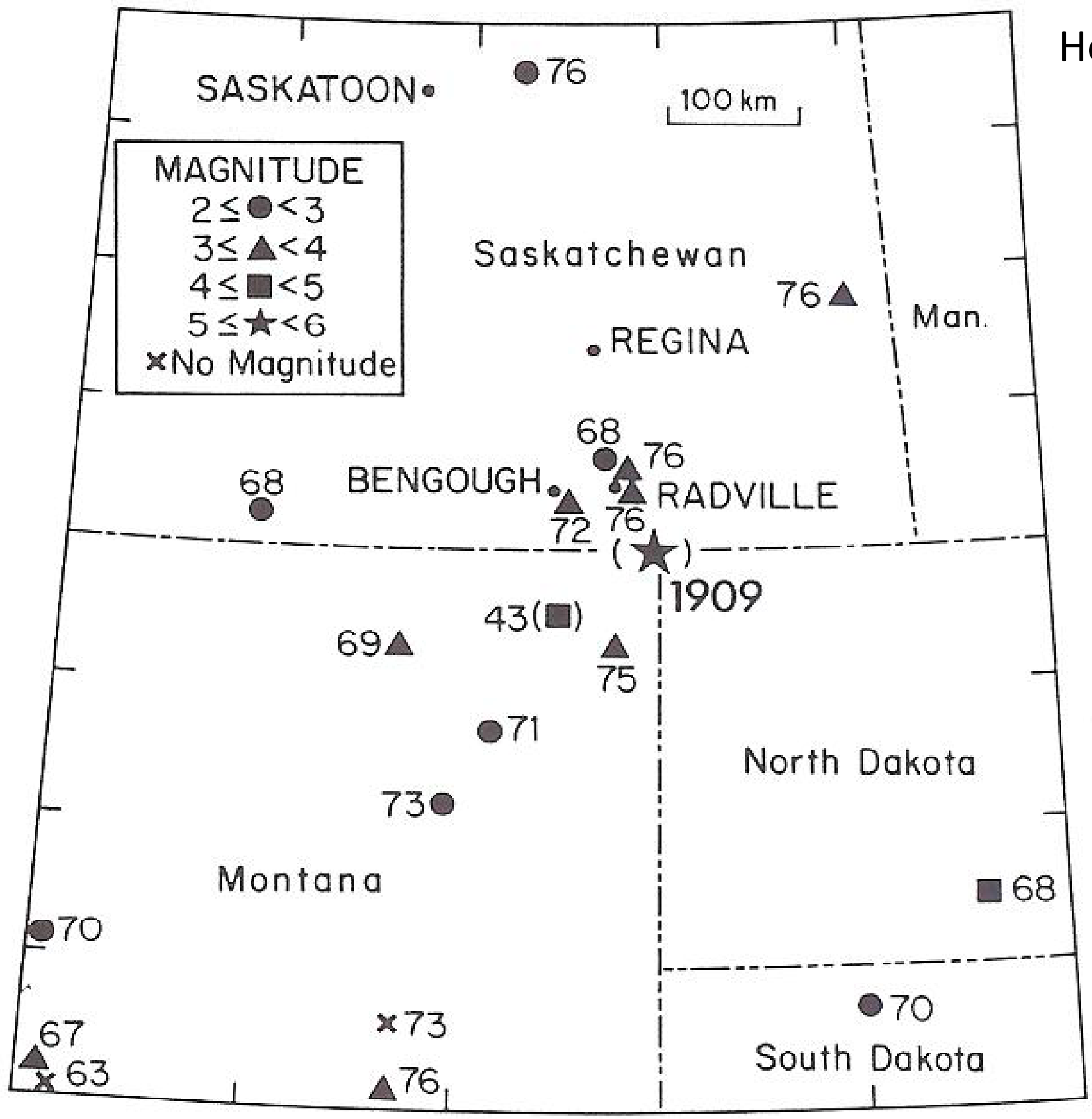


FIG. 5. Known seismicity in southern Saskatchewan and adjacent areas in the north-central United States.

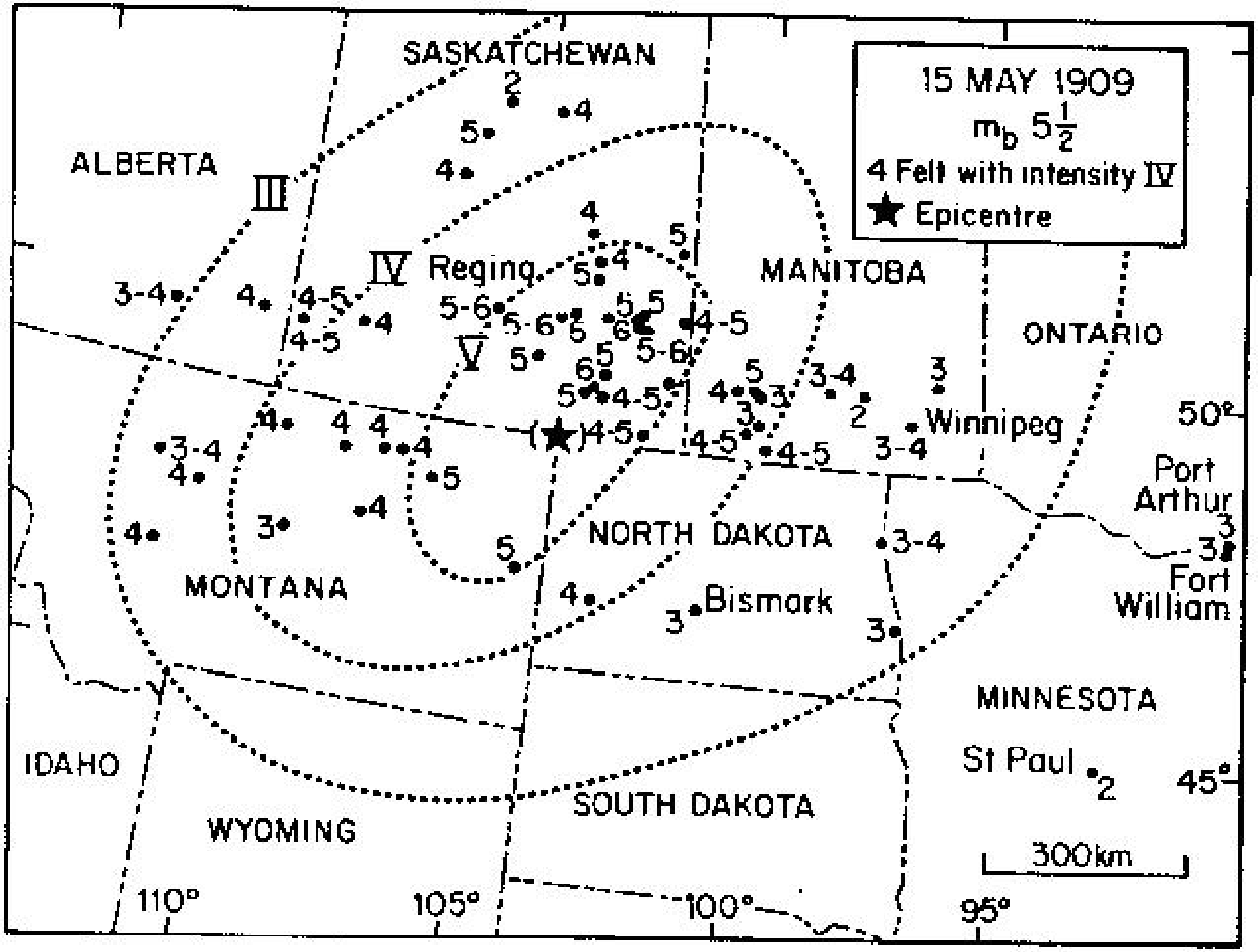


FIG. 3. Isoseismal map of the May 15, 1909, earthquake

Horner and Hasegawa, 1978

Average Maximum ground velocity In cm/s	Intensity	Ground Displacement For 5 cycle/sec. wave
1–2	IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably. (IV to V Rossi-Forel scale)	0.3 – 0.6 mm
2–5	V. Felt by nearly everyone, many awakened. Some dishes, windows, and so on broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel scale)	0.6 – 1.5 mm
5–8	VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight. (VI to VII Rossi-Forel scale)	1.5 – 2.5 mm

Part of the Modified Mercalli Earthquake Intensity Scale

Describes the Effects of Shaking And relates it to Ground particle Velocity and Acceleration

Bruce Bolt, 1993

Estimating seismic flexure on a well casing

Mercalli Intensity	Acceleration m/s/s	Velocity cm/s	Displacement mm
IV	0.147	1	0.8
IV	0.196	2	1.6
V	0.294	2	1.6
V	0.392	5	4
VI	0.588	5	4
VI	0.686	8	6.4

For a 5 Hz seismic shear wave
Shear wavelength in shale is about 280 m

So for seismic intensity VI (1909 event), 280 m of well casing could be flexed 6.4 mm (1/4 inch) at the center 5 times each second during an earthquake

More than 50 potash mine induced earthquakes since 1976

Magnitudes up to 3.7
Maximum Intensity V
Hypocentre located in Dawson Bay Fm at depth ≈ 900 m
Probably due to horizontal slip above the mine.
Damage restricted to falls of loose rock in the mine, vibrations and occasionally cracked plaster in houses near the epicentre.
No damage to mine shafts or operating wells.

For IMC K-2 event July 11, 1994
Magnitude = 3.05
Fault diameter = 174 m
Average displacement on fault = 15 mm, enough to damage a well if badly located.
J. Long, 1998

Surface subsidence over all underground potash mines (900 to 1100 m depth) reaches about 1 m over older mined areas. Deformation is gradual, no fractures are observed at the surface, due to plastic deformation of Cretaceous shales.

Dec. 25, 1985 earthquake at IMC-K-2 coincided with a brine inflow that continues to this day.   High mine extraction under a porous Dawson Bay Fm is thought to be the cause.   Despite roof collapse into the mine and high subsidence rates on the surface, no fractures are observed at the surface. All the brine is derived from the Dawson Bay Fm. Gendzwill and Unrau, 1996.

In 1976 the Potash Company of America mine at Patience Lake intersected the glacial-age Saskatoon Low salt-collapse structure with fractures that extend upward.   The fresh-water inflow was controlled until 1987 when the mine was forced to close.   A magnitude 2.4 earthquake was observed in July, 1988 when the mine was completely full. Mohr-Coulomb failure is thought to be the cause as pressure increased in the rock. No fractures appeared on surface.   Gendzwill and Martin, 1996.

These potash examples show that fractures did not propagate from limestones into Cretaceous shales.

Conclusions

Micro-seismicity associated with water and/or CO_2 injection is very small

No seismic evidence that any injection-related fractures are developing

Small natural earthquakes have occurred in southern Saskatchewan
The closest was 39 km west of Weyburn in 1976, magnitude 3.3

No known natural earthquake nor potash mine induced earthquake has created a fracture on the surface in Saskatchewan.

It is unlikely, but should a natural earthquake greater than magnitude 2 occur inside the Weyburn oil field it could damage the casing of a deep well

Main Sources:

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The Leading Edge, vol. 29, pages 200–206.

Verdon. J.P., Kendall, J.M., White, D.J, Angus, D.A., 2011. Linking microseismic event observations
with geomechanical models to minimise the risks of storing CO_2 in geological formations,
Earth and Planetary Science Letters 305, pages 143–152.

White, D. J., 2009. Monitoring CO_2 storage during EOR at the Weyburn-Midale Field.
The Leading Edge, July 2009 v. 28 no. 7 p. 838-842

http://en.wikipedia.org/wiki/Weyburn-Midale_Carbon_Dioxide_Project

http://www.cenovus.com/operations/oil/docs/Cenovus-summary-of-investigation.pdf


Thanks For Listening

Horner and Hasegawa, 1978

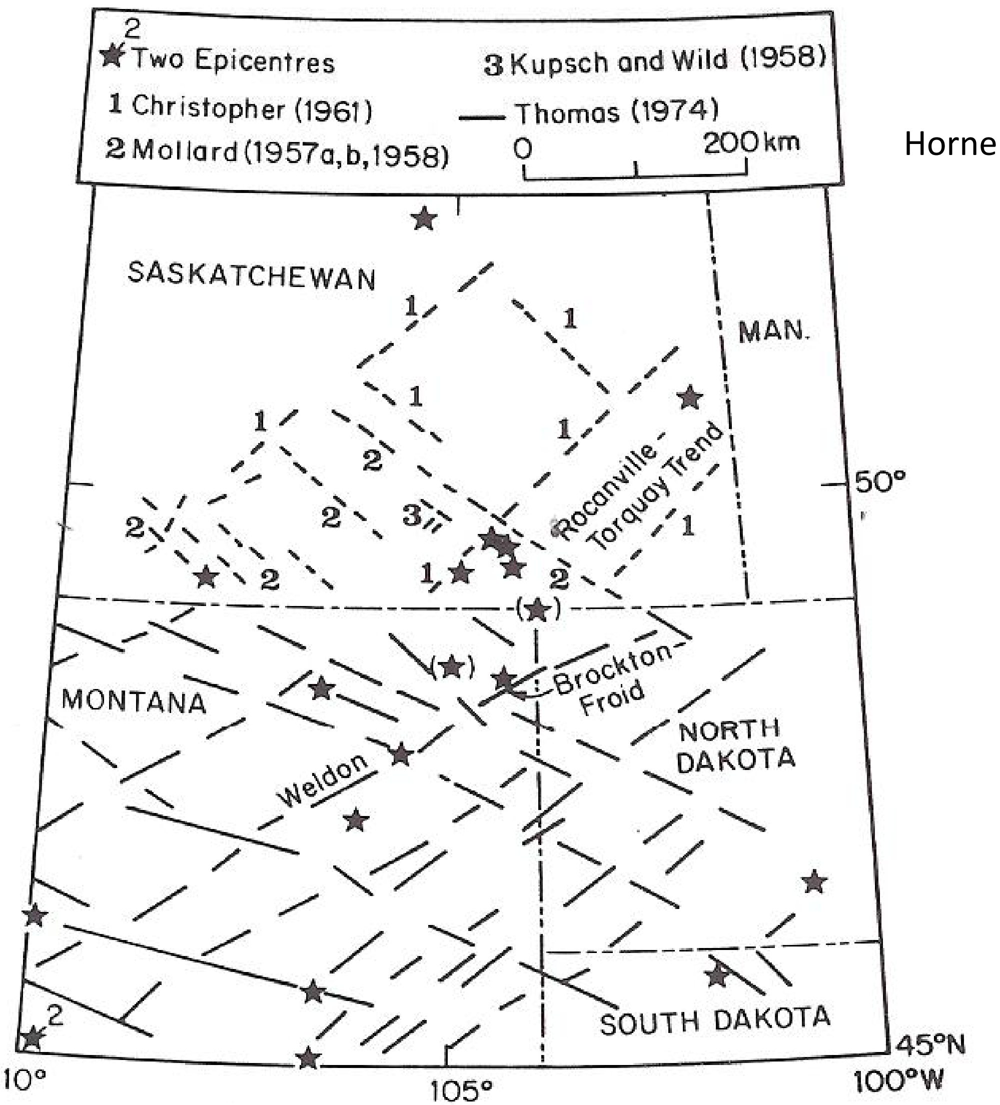

FIG. 12. Map showing the spatial correlation between the observed seismicity and linears, lineations, and bedrock trends (after Kent 1974) in the Williston Basin region.

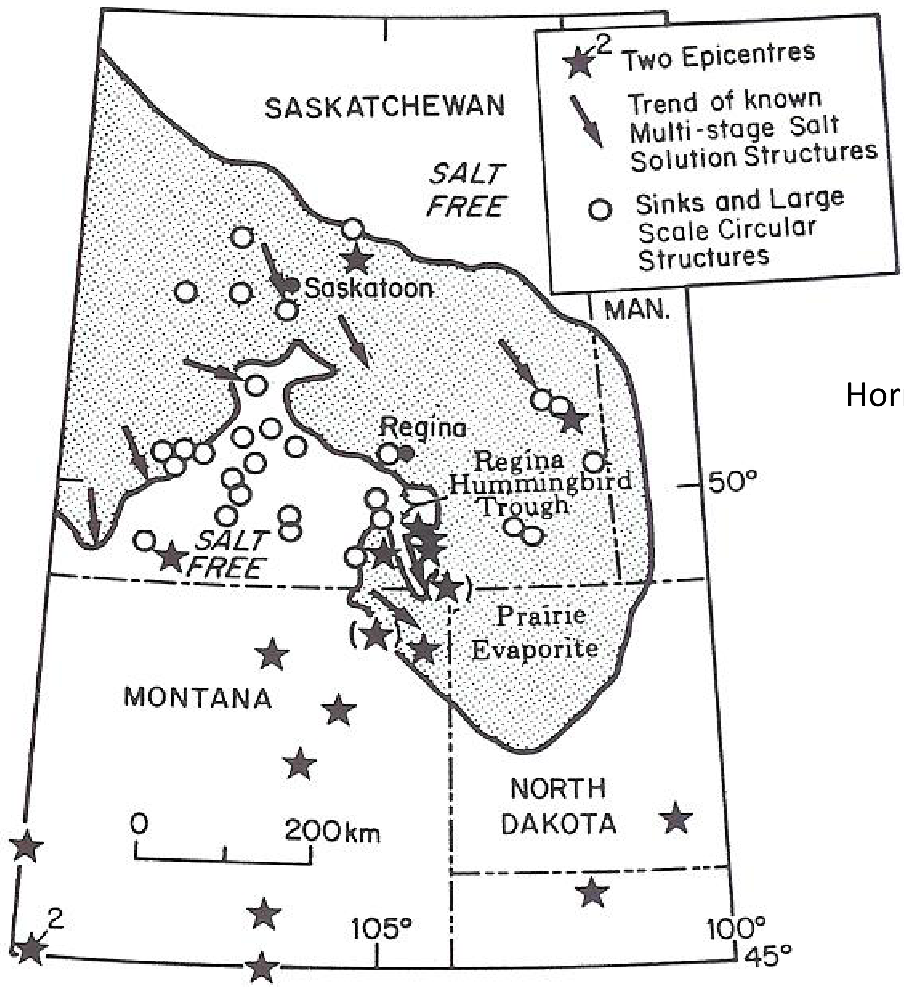

FIG. 11. The spatial correlations between the observed seismicity, the present-day distribution of the Prairie Evaporite, and the principal salt-solution features (Kent 1973; Simpson and Dennison 1975) in southern Saskatchewan and adjacent regions of Montana, North Dakota, and Manitoba.

Horner and Hasegawa, 1978

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Magnitude	Equivalent TNT Radiated Energy	Energy Comparison
+5	480 tonnes	1909 Earthquake
+3	480 kilograms	Large potash mine earthquake
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Red = Weyburn CO_2 injection micro-earthquake sizes

Average Maximum ground velocity In cm/s	Intensity		Average Maximum Ground Acceleration In g = 9.8 m/s/s
1–2	IV.	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably. (IV to V Rossi-Forel scale)	0.015g–0.02g
2–5	V.	Felt by nearly everyone, many awakened. Some dishes, windows, and so on broken; cracked plaster in a few places; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel scale)	0.03g–0.04g
5–8	VI.	Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster and damaged chimneys. Damage slight. (VI to VII Rossi-Forel scale)	0.06g–0.07g

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