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Subsurface fluid injection and induced seismicity in southeast Saskatchewan

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ABSTRACT

In order to mitigate CO_2 emissions while continuing to use fossil fuels as an energy source, CO_2 emissions from large point sources such as power stations can be captured and stored in suitable subsurface sedimentary formations. However, concerns have been raised that the injection of pressurized CO_2 may alter the subsurface stress state, leading to the re-activation of faults and generating induced seismic activity. Southeast Saskatchewan has seen extensive oil and gas activity since the 1950s. This activity includes, in recent years, a boom in shale oil production entailing hydraulic fracturing. It is also home to two world-leading CCS projects, the Weyburn-Midale CO_2 Monitoring and Storage Project, and the Boundary Dam/Aquistore Project. The aim of this paper is to assess whether any of the conventional oilfield operations, shale oil activity or CCS has caused induced seismicity in southeast Saskatchewan. We find that the region has a very low rate of natural seismicity, and that there is no evidence to suggest that any kind of oilfield activity has caused induced events. However, seismicity has been associated with potash mining activities in the region. It is not clear whether the potash mining-induced events are triggered by subsidence above the mined zones, or by re-injection of waste brines. It is of interest to compare the situation in southeast Saskatchewan with other areas that have seen substantial increases in the amount of injection-induced seismic activity. It is notable that in many areas that have seen injection-induced seismicity, fluid injection is into basal aquifers that are hydraulically connected to the crystalline Precambrian basement. In contrast, most oilfield activities in southeast Saskatchewan are in Carboniferous formations, while the only units to have experienced a net volume increase are of Cretaceous age. It is tentatively suggested that the lack of induced seismic activity is due to the fact that injection is hydraulically isolated from the basement rocks, although it is also possible that stress conditions in the region are less conducive to induced seismicity.

1. Introduction

It has been conclusively demonstrated that injecting fluids into the subsurface can trigger seismic activity (e.g., Raleigh et al., 1976). However, early research on Carbon Capture and Storage (CCS) was focussed on the danger that the buoyant CO_2 plume will migrate through the caprock and leak back to the surface. The potential hazard posed by injection-induced seismicity was generally downplayed (e.g. Damen et al., 2006) or not considered (e.g. Bickle, 2009). Even where microseismicity was observed at CCS sites, such observations were generally considered in terms of potential leakage through the caprock because of fracturing, rather than the hazard posed by injection-induced seismicity (e.g., Verdon et al., 2011).

However, these assessments were made prior to recent events in the mid-continental USA, where sharp increases in wastewater disposal volumes have lead to a dramatic increase in the number of recorded earthquakes (Ellsworth, 2013). Given that, on a well-by-well basis, injection volumes proposed for future CCS sites match or even exceed current wastewater injection volumes (e.g. Verdon, 2014), these observations have lead to a re-appraisal of the hazard posed by injection-induced seismicity at CCS sites (e.g. Zoback and Gorelick, 2012).

The Williston Basin underlies parts of Saskatchewan, North and South Dakota, Montana and Manitoba. It is a large (500,000 km^2) intra-cratonic basin of roughly oval shape, the origin of which is speculative. The Precambrian *trans*-Hudson Orogen trends in a NE-SW direction beneath the basin, sandwiched between the

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Archaean Wyoming and Superior Cratons. The oldest formation to be deposited on top of Precambrian crystalline basement is the Deadwood Formation, which is of late Cambrian/early Ordovician age. At its deepest, the thickness of sediments above the Precambrian basement is about 5 km. Most of the sediments are of Paleozoic age, although sedimentation continued through the Mesozoic. In Fig. 1 we show a stratigraphic column and schematic cross section of the area.

Oil and gas has been extracted from fields in southeast Saskatchewan since the 1950s, and production continues today. Substantial volumes of produced water are also generated by this extraction. Some of this water is re-injected for secondary recovery, while some are disposed of into saline aquifers. Additionally, the Bakken Shale underlies the conventional fields in southeast Saskatchewan. Within the past decade, this resource has been targeted for shale oil extraction using hydraulic fracturing.

CO_2 injection for the combined purposes of Enhanced Oil Recovery (EOR) and Carbon Capture and Storage (CCS) has been conducted at the Weyburn oilfield, in southeast Saskatchewan, since 2000. In 2015, CO_2 injection for CCS began at the Boundary Dam/Aquistore site, near to Estevan (approximately 85 km southeast of Weyburn). Southeast Saskatchewan is therefore home to two world-leading CCS projects, which provide an excellent opportunity to study the effects of CO_2 injection into the subsurface. At Weyburn, oil production is from, and CO_2 injection is into, Carboniferous rocks at a depth of approximately 1.5 km, while at Aquistore, CO_2 is injected into the Deadwood Formation, which sits on top of the Precambrian basement at a depth of approximately 3.5 km.

Therefore, there are and have been a range of oilfield activities conducted in southeast Saskatchewan that have the potential to induce seismic activity. The aim of this paper is to evaluate recorded seismicity in southeast Saskatchewan and to compare this activity with industrial activities in the area, thereby establishing whether oilfield activities have induced seismic activity. By doing so, we hope to better understand the tectonic setting in which these CCS sites are being developed, and thereby to assess the likelihood that they will lead to injection-induced seismicity as larger volumes of CO_2 are injected. Our principal study area extends northwards from the USA-Canada border approximately 1° of latitude (49°–50°N) and westward from the Saskatchewan-Manitoba border approximately 3.5° of longitude (101.4°–105°W). However, we also consider seismic activity across the broader southeast Saskatchewan-Montana-North Dakota region, which covers much of the Williston Basin.

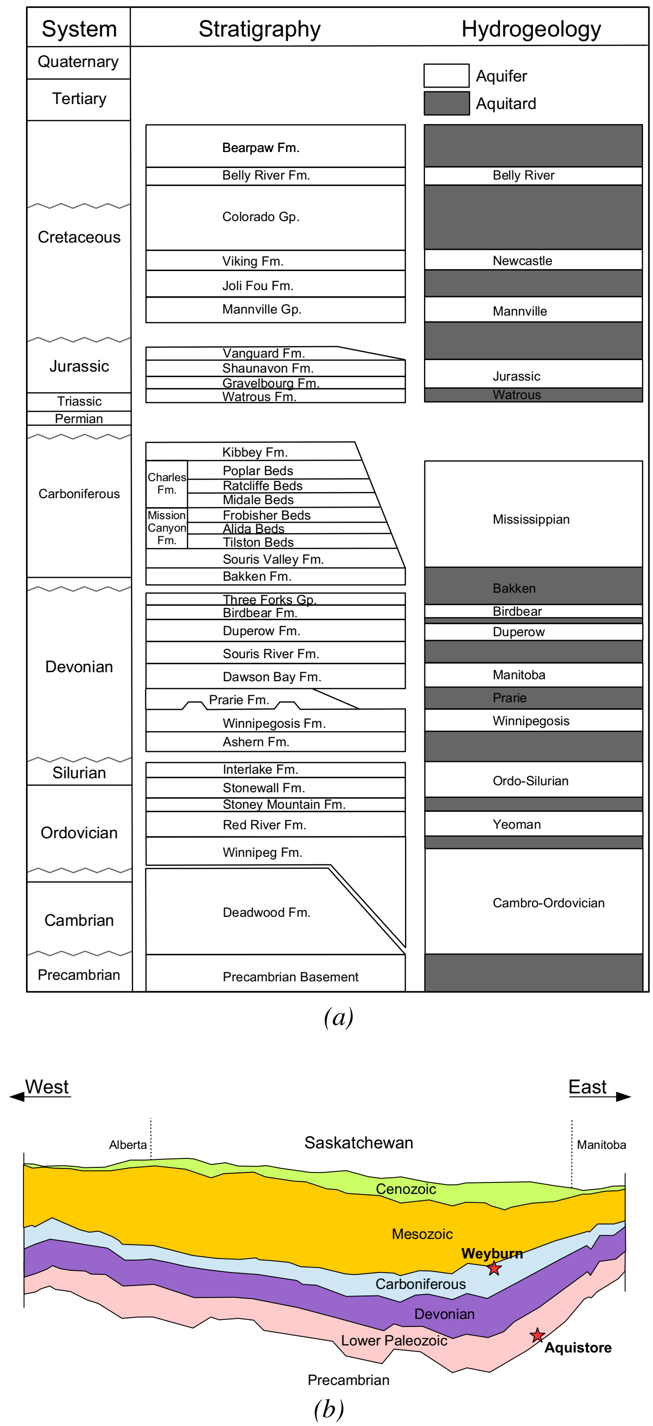

Fig. 1. In (a) we show a stratigraphic column showing the key lithologies in our study area. Each stratigraphic unit is categorised as being either an aquifer, through which fluids can flow relatively easily, or an aquitard, through which fluid flow is difficult or impossible, owing to the unit's low permeability. In (b) we show a schematic cross section running from west to east through southern Saskatchewan. The approximate positions and target depths of the Weyburn oilfield and Aquistore CCS project are both marked. Both figures are modified from Rostron et al. (2012).

2. Seismicity recorded in southeast Saskatchewan

2.1. Monitoring networks

We begin by curating a catalogue of seismic events recorded in the southeast Saskatchewan-Montana-North Dakota region. Broadly speaking, seismicity in this region is rare, and of low to moderate magnitude. However, for long periods, seismometer coverage has been equally sparse. Horner and Hasegawa (1978) describe the historical seismometer coverage in this area, and estimate detection thresholds of magnitude 6 prior to the 1950s, and of magnitude 5 until the mid-1960s. From this time onwards, detection thresholds are estimated to be magnitude 3, although the Large Aperture Seismic Array (LASA), which was deployed in Montana in 1966–67, provided a brief period of improved detection (Reinbold and Gillispe, 1974).

At present, several permanent stations of the USGS Advanced National Seismic System (ANSS) and Global Seismographic Network (GSN) provide the nearest real-time coverage. The nearest such station is at Dagmar, Montana (DGMT) which is approximately 130 km from the area of interest (Fig. 2a).

However, several studies have shown that such regional networks may not be able to detect small injection-induced events (e.g., Frohlich, 2012; Friberg et al., 2014; Frohlich et al., 2015). Therefore, in addition to events listed in National Earthquake Information Centre (NEIC) and National Earthquake Database of Canada