The Lodgepole Formation *Souris Valley Beds*: petroleum source rocks and potential self-sourced unconventional reservoir, an initial assessment

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Summary

Previous studies have indicated that organic rich rocks within the Souris Valley Beds could likely have been significant source rocks for Mississippian reservoirs in the Williston Basin (eg. Osadetz and Snowdon 1995; Chen *et al* 2009; Lillis 2013). Within the Souris Valley Beds, organic rich horizons up to 30 meters thick are generating petroleum within Saskatchewan. The name "Marker Bed" suggests regional continuity of this lithological unit, which cannot be established across the Williston Basin. Therefore this study proposes the term *Viceroy Unit* in place of "Marker Bed". Bitumen composition in the three cored locations are quite variable but show an increase in hydrocarbon yield with increasing depth; for example in the deeper buried and more mature samples (02-03-001-13W2 location, 2250 m burial) the associated bitumen contains up to 75% hydrocarbon. *In situ* generation, coupled with a brittle lithology and low differential stress has generated a very high natural fracture network. This study proposes a resource estimate for the organic rich *Viceroy Unit* suggesting that these beds are petroleum generating, possess a high density of natural fractures displaying brittle failure and represents a potential self-sourcing unconventional resource, in addition to functioning as a petroleum source rock. The proposed sub-facies could be used for unconventional completion targets.

Introduction

This study examines the petroleum potential of a predominantly carbonate, organic rich, bituminous and oil-charged, silicified and naturally-fractured horizon within the Souris Valley Beds (SVB) in Southern Saskatchewan, and using new data, looks at the self-sourced unconventional potential of these beds. The Mississippian SVB (Lodgepole Formation) in southern Saskatchewan is a 150 meter thick unit considered to be a mid-ramp to basinal carbonate, generally consisting of a thin to massively bedded lime packstone to mudstones, and argillaceous lime mudstones and represents the basinal unit of the Madison Group, conformably overlying the Upper Bakken Shale Member (Kent, 1984; Sereda and Kent 1987; Nickel, 2005). The lime-mudstones are the focus of this study as they are organic rich in some locations and consist they of bed-sets of alternating laminae-sets of bituminous and bitumen-deficient lime mudstone (Johnson and Bend, 2015; MacKnight 2015)

This horizon, informally referred to as "Marker Beds" was identified as organic-rich (avg. 5.49% TOC) carbonate rocks that contain good to excellent source rock potential (Osadetz and Snowdon, 1986; Brooks *et al* 1987; Osadetz *et al* 1992; Osadetz *et al* 1994; Burris *et al* 1996; Chen *et al* 2009; Lillis 2013). Brooks *et al* (1987) concluded that the carbonate sourced signature of oils found in Mississippian reservoirs were potentially derived from within the SVB. Subsequent analysis of the organic rich horizons within the SVB confirm them to be the likely source of *Family 'C'* oils (Osadetz *et al* 1992; Osadetz *et al* 1994; Jarvie 2001; Chen *et at* 2009).

The "Marker Beds" within the SVB vary in thickness from zero at the subcrop up to 30 meters thick in south central Saskatchewan and occur in a confined location that is coincident with the salt solution of the Prairie Evaporate, where salt solution potentially created topographical lows and sheltered sub-basins that allowed for the increase of bottom water hypoxia and the accumulation of organic rich sediments during deposition. However, the so-called "Marker Beds" are not laterally continuous regionally across the Williston Basin (MacKnight, 2015) and therefore *not* reliable as stratigraphic markers. Furthermore, “Marker Beds” are temporally heterogeneous on a macroscopic-, microscopic-, and geochemical-scale that makes any attempt at refined sub-unit correlation difficult where the “Marker Beds” do occur in the subsurface. The complex and at times cyclic nature of sedimentation and geochemical attributes indicates a complex interplay between the “organic matter factory” and sedimentation.

Previous research identified SVB source rocks to be immature to marginally mature in Saskatchewan, but this study indicates that the “Marker Beds” are thermally maturing and generating petroleum within Saskatchewan. This has a twofold significance; 1) the potential existence of potential reservoirs from unanticipated generated and migration of SVB petroleum, and 2) significant *in situ* petroleum within the “Marker Beds” as a potential ‘self-sourced unconventional reservoir’. Osadetz *et al* (1994) have confirmed the possibility of this westerly migration highlighting that Lower Cretaceous and Jurassic (Shaunavon) oils found in the west of Saskatchewan are geochemically identical to low-maturity Lodgepole sourced oils in reservoirs to the east. Similarly, Bend and Johnson (2016) have documented the occurrence of micro- to macro-scale natural fractures within oriented core (Silver Hawk Hardy Borehole 01/07-9-4-21W2) documenting a very high fracture saturation ratio (up to 2.4 per 5 cm of core) for macro-scale fractures, increasing to two fracture per one centimeter when micro-scale fractures are included; and the high fracture saturation ratio and fracture orientation suggest high pore-pressure and lower differential stress resulting in brittle failure (Johnson and Bend, 2015). The high frequency of natural macro sized fractures per unit distance is amongst the highest recorded in core (Aydin, 2014), this does not include the abundant micro-fractures measured in thin section.

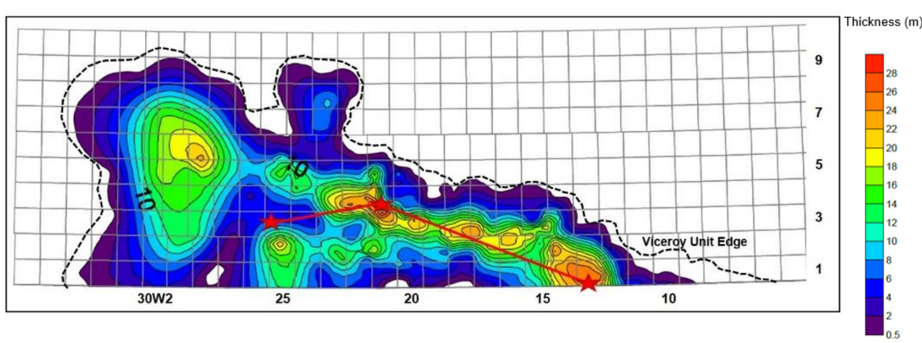
Method

The study area extends from the 9th township down to the U.S. border, and from 28W2 to the Manitoba border. The data set is comprised of 1300 petrophysical wireline logs and core samples obtained from ten different borehole, which were also logged. Detailed analysis of rock texture, bedding characteristics, and composition using the criteria of Lazar et al (2015) was used to identify and develop sub-facies units.

A total of 150 samples (15-21-003-25W2, 07-09-004-21W2, 02-03-001-13W2 identified by red stars; **Figure 1**) were solvent extracted using a Foss Industries Soxtech (DCM/Methanol: v/v 93/7) and subsequently fractionated into saturate hydrocarbon, aromatic hydrocarbon, and non-hydrocarbon fractions using column chromatography.

Results and Discussion

Correlation of these so called “Marker Beds” is difficult, and issues of internal stratigraphy of the SVB have been noted by previous authors (Heck, 1974; Carlson and Lefever 1987, Osadetz and Snowdon, 1995); issues that are confounded by limited core and well control, compounded by problems with the general interpretation of fine-grained sedimentary rocks and ineffective geological models. As these so called “Marker Beds” are only found in a confined geographical area in the Williston basin, this study proposes the term ***Viceroy Unit*** in place of “Marker Bed”. Although there are problems with regional stratigraphic correlation, this study recognises and presents three delineated sub-facies; termed Sub-facies ‘A’, Sub-facies ‘B’, and Sub-facies ‘C’ that are based upon texture, bedding characteristics and mineral and organic matter composition that appears to have a substantial influence upon petroleum potential and fracture characteristics.



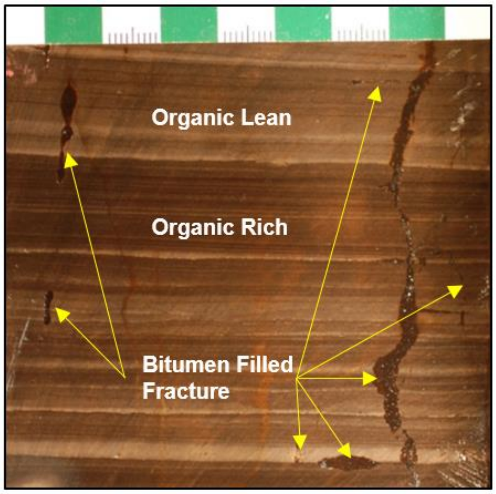


Fig. 2 Core micrograph showing bed-sets characterized by alternating lamina-sets of light (silty bases lacking OM) versus dark (mud tops rich in OM) and bitumen infilled fractures 07-09-004-21,

The Souris Valley Bed organic-rich Viceroy Unit isopach attains a maximum thickness of 30 m, trends NW-SE, and contains zones of local thinning and thickening (**Figure 1**). The Viceroy Unit consist of bed-sets that are composed of alternating light grey and brownish-dark grey in colour laminae-sets consisting of continuous and discontinuous planar to wavey bedded medium to coarse lime-mudstone with with filled natural fracture network (**Figu** mm in size) and thin walled Brachiopod shells are found throughout the horizon, while bioturbation is rare and generally absent. Core is silicified and brittle, and has a very high density of natural macro-, meso- and micro-fractures.

Fig. 1 Isopach map of the organic rich Viceroy

The average TOC is 5.49 wt% (Osadetz and Snowdon 1995), although the organic matter exhibits considerable temporally and geographically variation exhibiting a clear zoneation of high and low bitumen yield. Bitumen content varies from 3 to 47 mg bitumen per gram of rock, averaging 21 mg/g within the subcrop although reaching an average 28 mg/g within the most thermally mature sample set. Bitumen composition (in terms of saturate

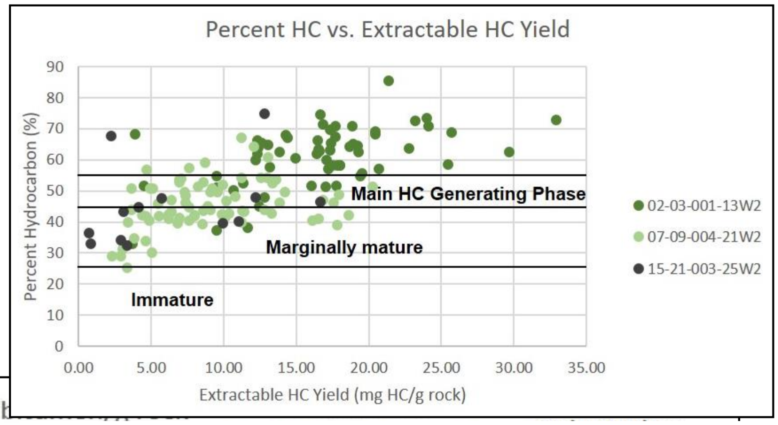


Fig. 4, Thermal Maturity Cross-plot after Osadetz and Snowdon (1995) for organic rich Viceroy Unit, Souris Valley Beds

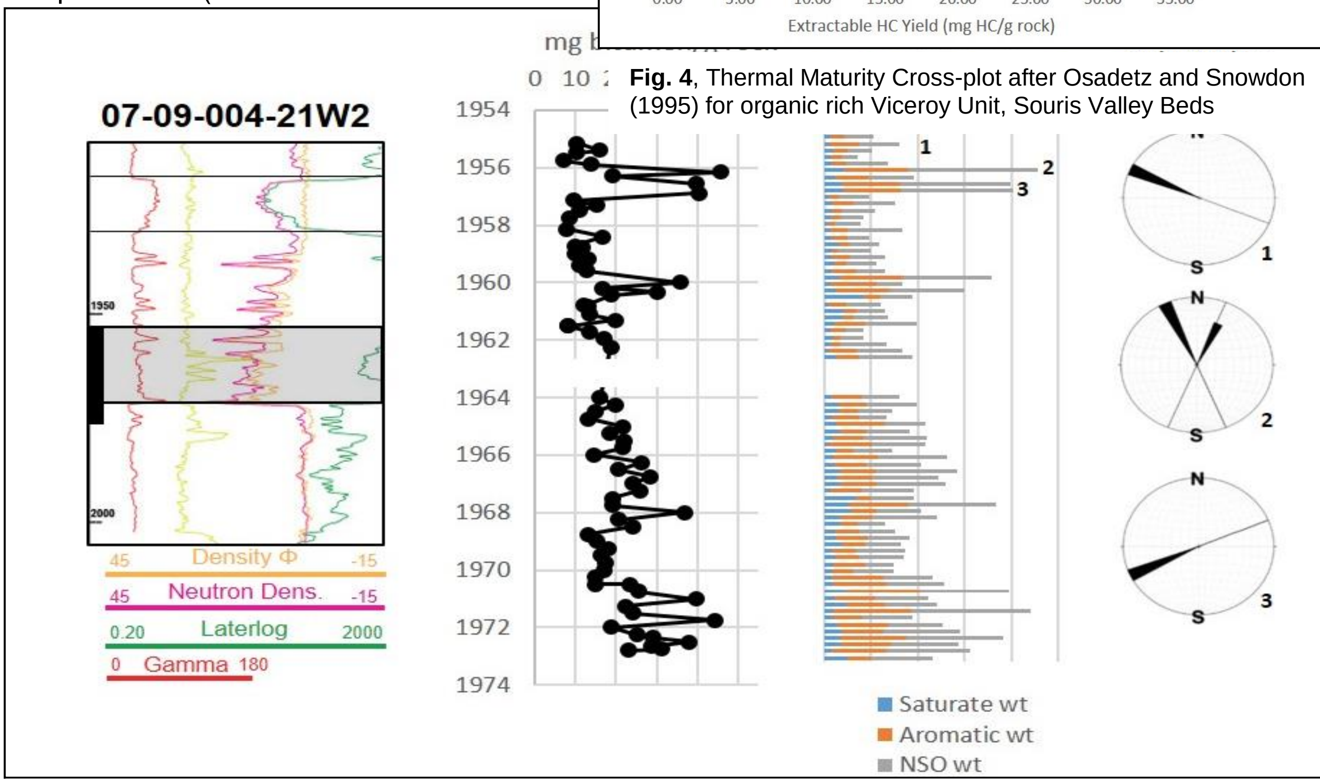


Fig. 3, Example of bitumen yield and bitumen composition depth profile for 07-09-004-21W2. Geochemistry sampling interval shaded in grey on petrophysical wireline log. Note temporal variability in log response, total extract yield in mg bitumen/g rock (black), and bitumen extract composition (saturate hydrocarbons (blue), aromatic hydrocarbons (orange), and NSO non-hydrocarbons). Three rose diagrams located at 1955.80 m, 1956.00 m, and 1956.35 m show no prevalent fracture orientation (Fracture analysis from Johnson 2015).

hydrocarbons, aromatic hydrocarbons, and N- S- O- non-hydrocarbon molecules) are also variable temporally and geographically, an example of bitumen extract and fractional analysis is shown in **Figure 3**. The extracted bitumen consists of 3 to 33 mg hydrocarbon/g of sample. The fractional analysis of the bitumen extracted from samples obtained from core (e.g., 07-09-004-21W2 and 02-03-001-13W2) yielded hydrocarbon contents that ranged from 35 to 67% and 33 to 86% respectively of the total extract, with average yields of 47% and 61% hydrocarbon respectively. By comparison, the Upper Bakken Shale Member bitumen yielded only 13% hydrocarbon on average at the 07-09-004-21W2 location. The bitumen and hydrocarbon yield varies due to differences in thermal maturity and the sedimentalogical characteristics of the host rock. The Osadetz and Snowdon (1995) *Maturity Cross-plot* (percent hydrocarbon *versus* total extractable hydrocarbon yield) shows the Viceroy Unit to be marginal to thermally mature (**Figure 4**). All 150 samples taken within the Viceroy Unit plot above the above immature zone, indicating many sampled intervals are within the main hydrocarbon generating phase (e.g. samples from 02-03-001-13W2). Thermal maturation caused by burial depth can be observed through the comparison of cored locations 07-09-004-21W2 (1955 – 1974 m) and 02-03-001-13W2 (2240

– 2255 m). The 07-09-004-21W2 location had an average extract yield of 20 mg bitumen/g of sample, where 45% of the bitumen was composed of hydrocarbon. The 02-03-001-13W2 cored location had an average extract yield of 28 mg bitumen/g of sample, and 61% of that bitumen was composed of hydrocarbon. This is evidence of maturation of kerogen, and thermal cracking of bitumen to hydrocarbon with increasing depth.

Detailed natural fracture analysis has already documented that that the SVB has one of the highest natural fracture density recorded in core (Johnson, 2015). These fractures do not display a preferred fracture orientation and are the result of localized increase in pore pressure due to the generation of (Johnson 2015) and the presence of *low differential stress* combined with a *heterogeneous and brittle rock* has led to the formation of an *intense and complex, natural, sub-vertical to parallel and cross cutting macro- to micro-fracture system due to brittle/extensional failure*.

Significant petroleum has generated within SVB in Saskatchewan. Analysed intervals from 07-09-004-21W2 core yields between 7 to 49 kg hydrocarbon/m^3 of rock, and preliminary estimations using our data yields 650 million bbl of *in situ* hydrocarbon within the Viceroy Unit of the SVB.

Conclusions

The “Marker Bed” unit of the SVB horizons both internally and across the Williston Basin are not correlatable, therefore this study herein proposes a change in nomenclature proposing the term Viceroy Unit. Within the Souris Valley Beds thermally mature organic rich horizons up to 30 meters thick are generating petroleum within Saskatchewan. Bitumen composition in the three cored locations are quite variable but show an increase in hydrocarbon yield with increasing depth; for example in the deeper buried and more mature samples (02-03-001-13W2 location, 2250 m burial) the associated bitumen contains up to 75% hydrocarbon. *In situ* generation, coupled with a brittle lithology and low differential stress has generated a very high natural fracture network.

This study establishes preliminary evidence that the organic rich Viceroy Unit in the Souris Valley Beds are petroleum generating, possess a high density of natural fractures displaying brittle failure and represents a potential self-sourcing unconventional resource, in addition to functioning as a petroleum source rock. The proposed sub-facies could be used for unconventional completion targets.

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