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Role of Groundwater Dynamics in the Genesis of the Athabasca Oil Sands

K. Udo Weyer and James C. Ellis
WDA Consultants Inc.(corresponding author: weyer@wda-consultants.com)

Summary

The regional groundwater dynamics caused by the “low fluid-potential drain” (Hitchon, 1969) is associated with flow through highly permeable karst. The amounts of winter discharge from the Paleozoic karst into the Athabasca River allows the general estimation of the rate of groundwater with oxygen annually penetrating the oil sands layer. The associated oxygen and biodegradation are assumed to be important agents for the transformation of oil into heavy oil and tar. The paper puts emphasis on the often-neglected impact of groundwater dynamics on geochemical processes.

Introduction

Regional flow systems have been the centre of attention within the Alberta basin since the work of Tóth (1962) and Freeze and Witherspoon (1967). Subsequently, Hitchon (1969) arranged head distributions at various depths in 2D horizontal slices along a series of vertical cross sections ranging from the Rocky Mountains to the edge of the Canadian Shield as shown in Figure 1. Figure 2 shows two of the 2D vertical cross-sections containing a low fluid-potential drain. Hitchon (1969, p.186) describes its function as follows:

“*The presence of a thick sequence of highly permeable Upper Devonian and Carboniferous carbonate rocks in the medium-depth portion of the Alberta basin has resulted in the development of a low fluid-potential drain, which essentially channels flow from most of the Alberta basin towards the Athabasca oil sands and has modified the theoretical relation between local and regional flow systems*.”

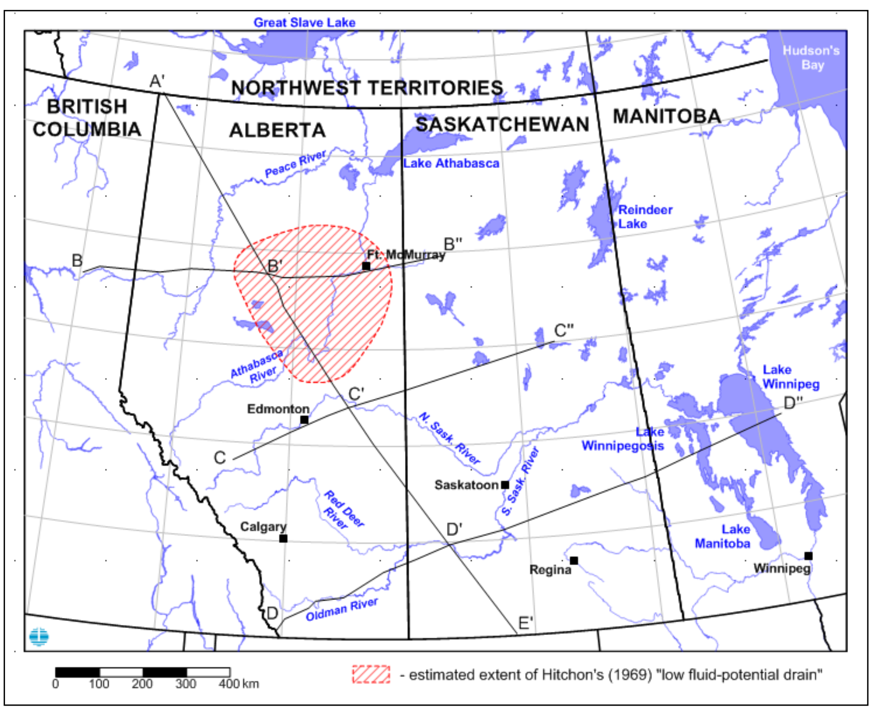


Figure 1: Location map of cross-sections (after Hitchon, 1969, Fig. 3). Red hatched area schematically depicts the estimated extent of Hitchon’s (1969) low fluid-potential drain based on positions marked in the cross-sections A’-E’ and B-B”.

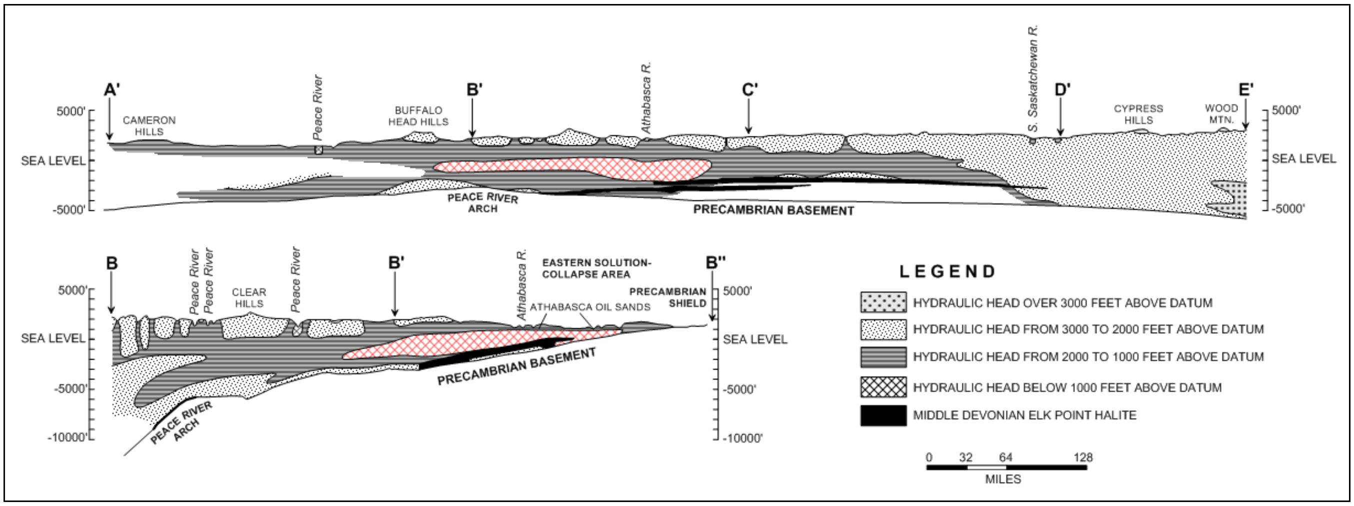
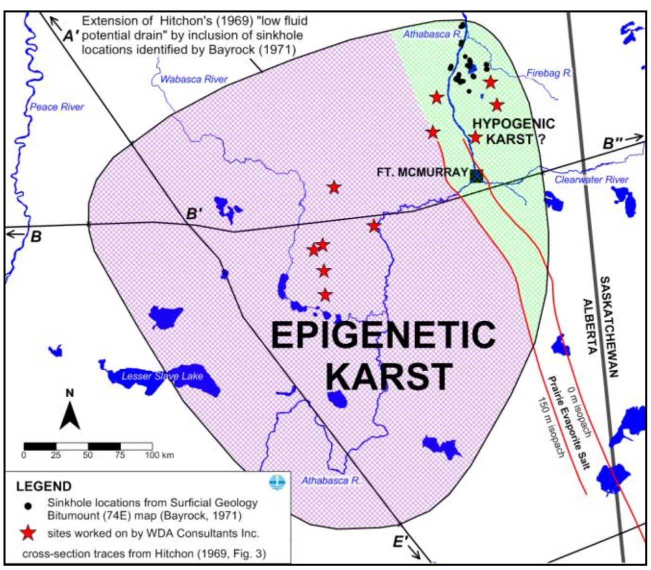


Figure 2: Hydraulic head distribution in cross-sections (modified after Hitchon, 1969, Fig. 8). The red hatched area represents Hitchon's (1969) low fluid-potential drain.

The cross-sections in his Figure 2 show that Alberta's major rivers draw up the deeper groundwater flow, as do some of the minor ones. The exception is the area of the low fluid-potential drain which captures deep and shallow groundwater flow and delivers it "*towards the Athabasca oil sands*" (Hitchon 1969, p. 186). In Figure 1 the cross-sections A'-E' and B-B" outline the approximate lateral extent of the low fluid-potential drain. Transferring those points onto our location map and connecting them schematically yields an estimate of the approximate outline of the 'low fluid-potential drain' (red hatched area in Figure 1). By including sinkhole locations identified by Bayrock (1971), the northeastern portion of the 'low fluid-potential drain' was modified as shown in Figure 3. Figure 4 shows the degree to which the low fluid-potential drain underlies much of the Athabasca oil sands. This implies that the Athabasca oil sands have been penetrated by recharged groundwater flowing downward into the Paleozoic karst whose position along the Cretaceous/Devonian unconformity is indicated in Figure 5.



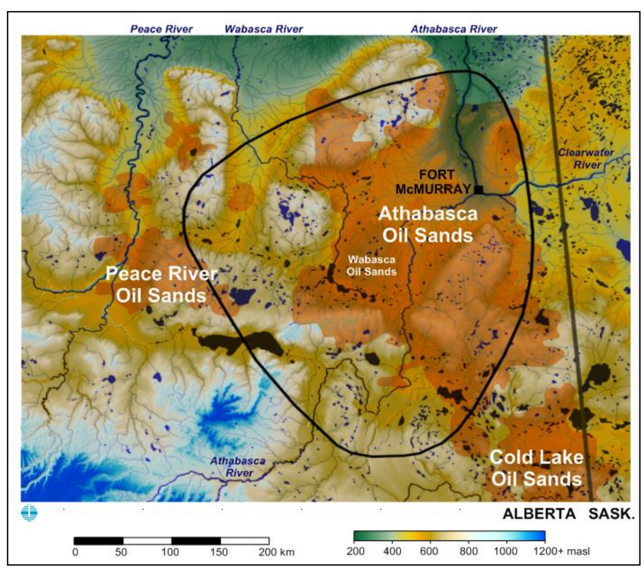


Figure 3 (left): Extension of Hitchon's (1969) "low fluid-potential drain" area by inclusion of sinkhole locations identified by Bayrock (1971).

Figure 4 (right): Schematically-estimated extent of Hitchon's (1969) "low fluid-potential drain" [including the Bayrock (1971) extension] in relation to the position of the Athabasca oil sands, including the sub-area of the Wabasca oil sands. Extent of oil sands indicated by an orange overlay.

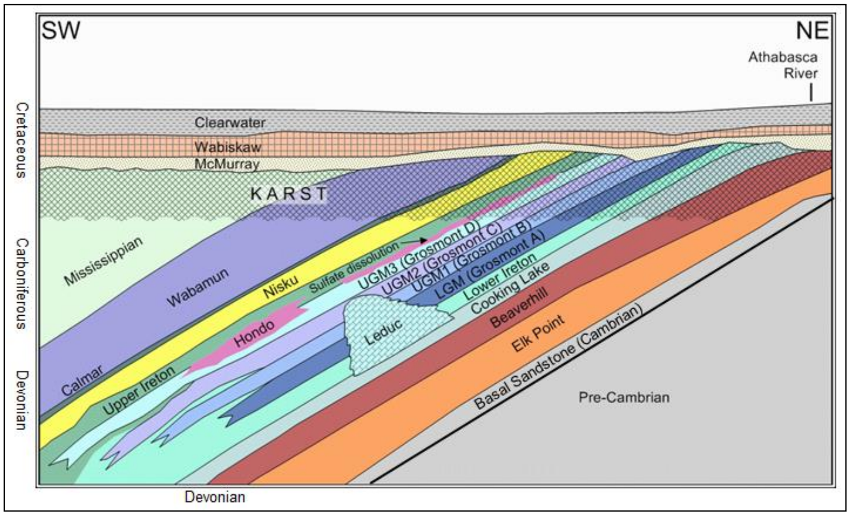
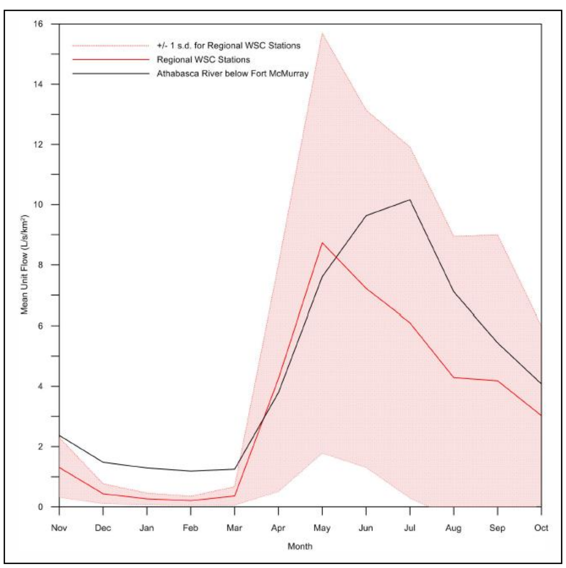


Figure 5: Schematic SW-NE stratigraphic section in the region of the Wabasca oil sands (modified from Machel et al., 2012, Fig. 5). The figure is highly exaggerated vertically. The actual SW-dip of the layers is about 1°.

Flow rate of groundwater and associated transport of oxygen through the oil sands

Due to the hilly topography and its incised major river valleys, all of the area of the Athabasca oil sands is dominated by groundwater recharge and associated downward flow with high gradients except for the incised valleys which are discharge areas with high upward directed gradients. These flow systems have been modelled and reported by Weyer (2006) and Weyer et al. (2012), based on measured lateral equipotential lines reported by DCEL (2005). Thus it appears that a constant stream of oxygen has been delivered into and through the oil layers of the Athabasca oil sands for as long as such gravitational groundwater flow systems have been operative.



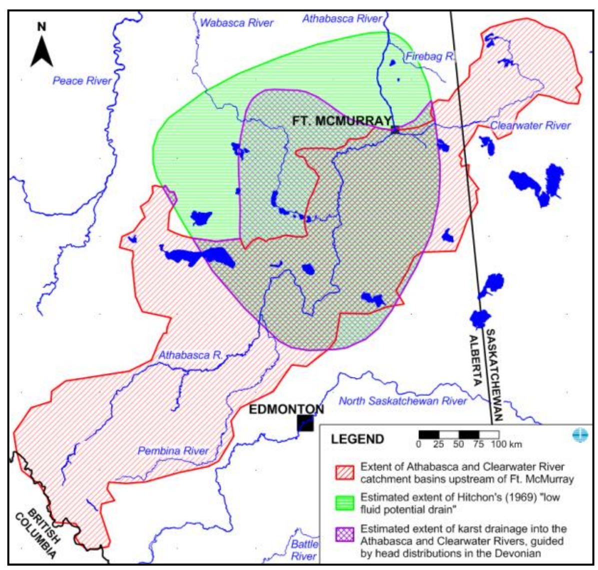


Figure 6 (left): Recorded Regional Mean Monthly River Flows in the Athabasca River (black line), as compared to other river stations in the area (red line). The Athabasca River winter flow suggests substantial groundwater discharge from the karst. One l/sec/km^2 is equivalent to 32 mm annual precipitation. Data obtained from Water Survey of Canada (WSC) gaging station 07DA001, Athabasca River below Ft. McMurray. Gross drainage area: 132,585 km^2. Figure modified from Osum (2013, Fig 6.5-4).

Figure 7 (right): Comparison of the overlap of the catchment basins (red hatching) of the Athabasca and Clearwater Rivers upstream of the Water Survey of Canada gaging station 07DA001, with the karstic low fluid-potential drain (green hatching) described by Hitchon (1969) including the Bayrock (1971) extension. The northern bulge to the catchment basin (purple hatching) was for comparison purposes as a karst contributor to the Athabasca River based upon equal head lines published by Bachu et al. (1993).

We will now turn our attention towards hydrograph data measured by the Water Survey of Canada (WSC) for the Athabasca and Clearwater River just below their confluence downstream of Fort McMurray and for a collection of river flow hydrographs typical to the region outside of these two catchment basins (Figure 6). The winter discharge of the Athabasca River has a much higher flow [appr. 1.3 l/km^2 s] than rivers not affected by water discharging from the “low fluid-potential drain” [appr. 0.3 l/km^2 s]. The winter low flows have been compared in Figures 6 and 7 with the procedures and results consolidated in Table 1. The estimated rates of groundwater recharge flowing downwards through the oil sands with associated oxygen migration have been estimated in Table 1 to be between 50-100 mm/year during the winter season. The annual flow rate may be considerably higher when taking summer conditions with its active recharge into account. It appears that the estimated rates of groundwater flow downwards through the oil sands with associated oxygen migration are sufficient to induce weathering processes and biodegradation, causing heavy oil and tar to develop.

	catchment area	area	January normalized discharge	January river flow		recharge
		km^2	l/s km^2	l/s	m^3/s	mm/a
	A	B	C	D		E
	measured normalized flow: (from hydrographs)					
1	Regional WSC stations (red hydrograph)	--	0.3	--	--	10
2	Athabasca/Clearwater basin (black hydrograph)	132,000	1.3	171,600	171.6 [1]	42
3	Non-karstic part within A/C basin	86,900	0.3	26,100	26.1 [2]	10
	calculated flow from karst:			145,500	145.5 [3]	
4	Total LFPD - Hitchon drain (Paleozoic karst)	102,000	1.4 [4]	--	--	46
5	Karst within the A/C basin	45,100	3.2 [5]	--	--	103
6	Karst within A/C basin + assumed subsurface drain	67,900	2.1 [6]	--	--	69

Notes:
- 1 l/s km^2 is equivalent to approximately 32 mm/a of precipitation
- LFPD = Low Fluid Potential Drain (Hitchon, 1969)
- [1] B2 x C2 [2] B3 x C3 [3] D2 - D3 [4] D5 / B4 [5] D5 / B5 [6] D5/B6

Table 1. Estimation of recharge through the Athabasca oil sands into the Paleozoic karst, based on winter low-flow measurements in the Athabasca River at WSC gaging station 07DA001.

Conclusions

The regional groundwater dynamics caused by the “low fluid-potential drain” (Hitchon, 1969) is associated with flow through highly permeable karst. The amounts of winter discharge from the Paleozoic karst into the Athabasca River allows the estimation of the rate of groundwater with oxygen annually penetrating the oil sands layer. The associated oxygen and biodegradation are assumed to be important agents for the transformation of oil into heavy oil and tar. The paper puts emphasis on the often-neglected impact of groundwater dynamics on geochemical processes.

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