Regional groundwater flow, water production and waste water injection in the area of the Wabasca oil sands

by

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Basic features of regional groundwater dynamics (very abbreviated)

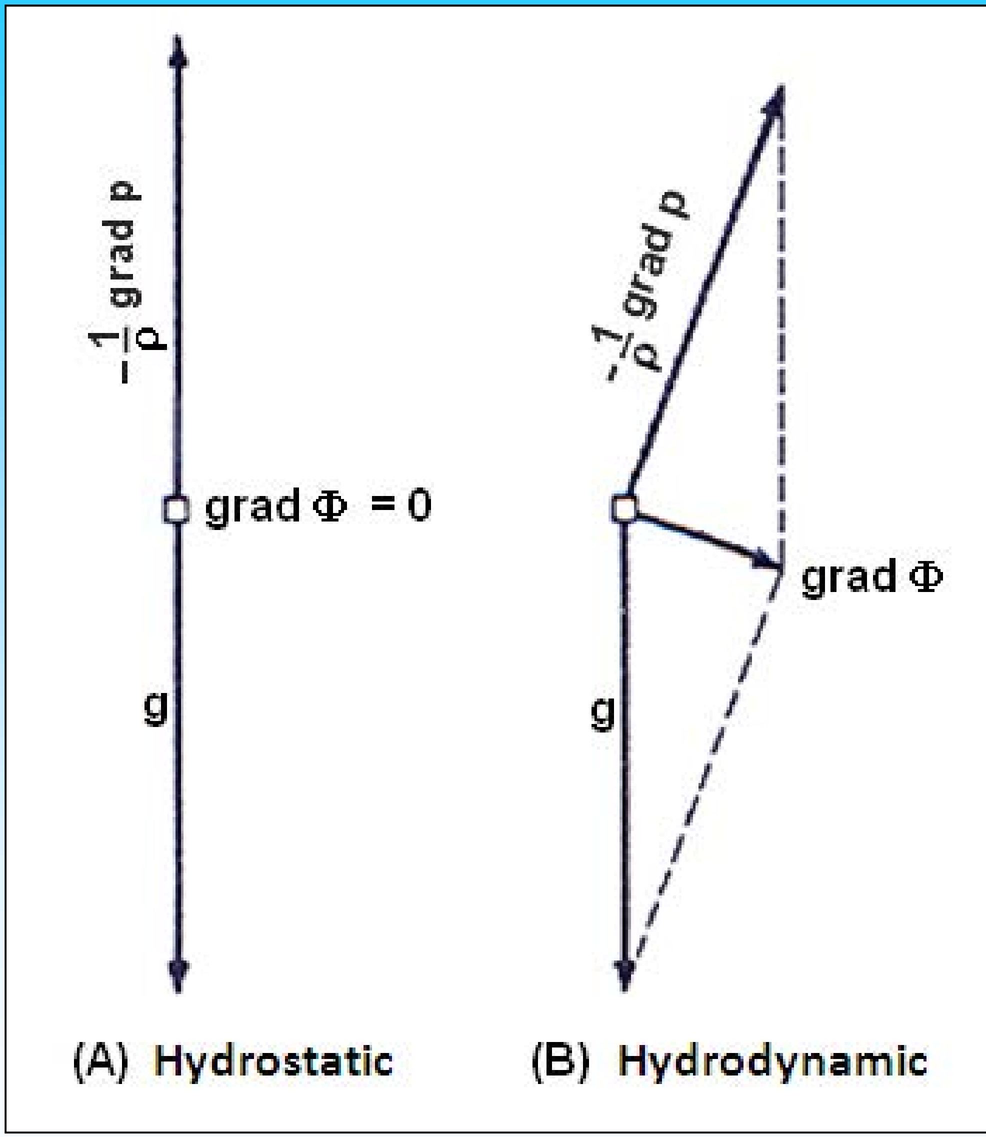
Those interested in details of physically based hydraulics should participate in the upcoming CSPG short course:

Dynamics of subsurface flow of water, hydrocarbons, and CO_2 **:**
Physics and field examples
Calgary, May 21/22, 2014,
www.cspg.org (select: Short Courses)

For the purpose of this talk let’s first debunk four concepts widely believed to dominate groundwater dynamics and commonly applied to groundwater flow in Alberta and in particular the Athabasca and Wabasca oil sands:

1. Buoyancy forces are directed vertically upwards or downwards under both hydrostatic and hydrodynamic conditions
2. The calculation of flow directions depends on two force fields; that of heads and that of buoyancy forces.
3. Groundwater flow takes the path of least resistance.
4. Recharge into deep aquifers occurs at the outcrop of aquifers in hills and discharge from these aquifers occurs at the downstream end of the same aquifer complexes.

The hydrodynamic work of the Alberta Research Council (ARC) has been dominated by these four assumptions since about 1990.

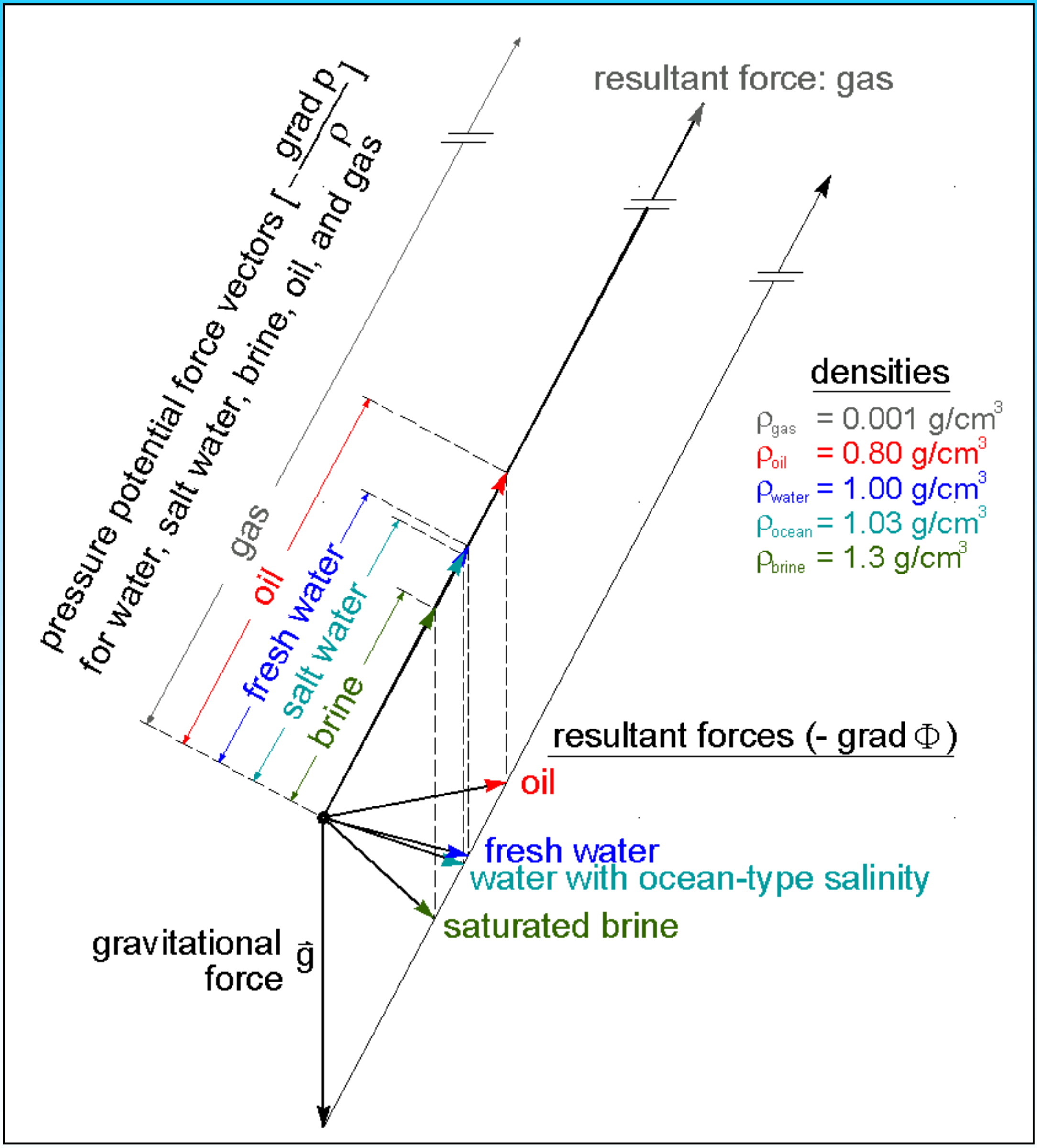


Hydraulic forces (grad Φ) under hydrostatic and hydrodynamic conditions

After Hubbert, M. King, 1953. Entrapment of petroleum under hydrodynamic conditions. AAPG Bulletin 37, no. 8, p. 1954-2026.

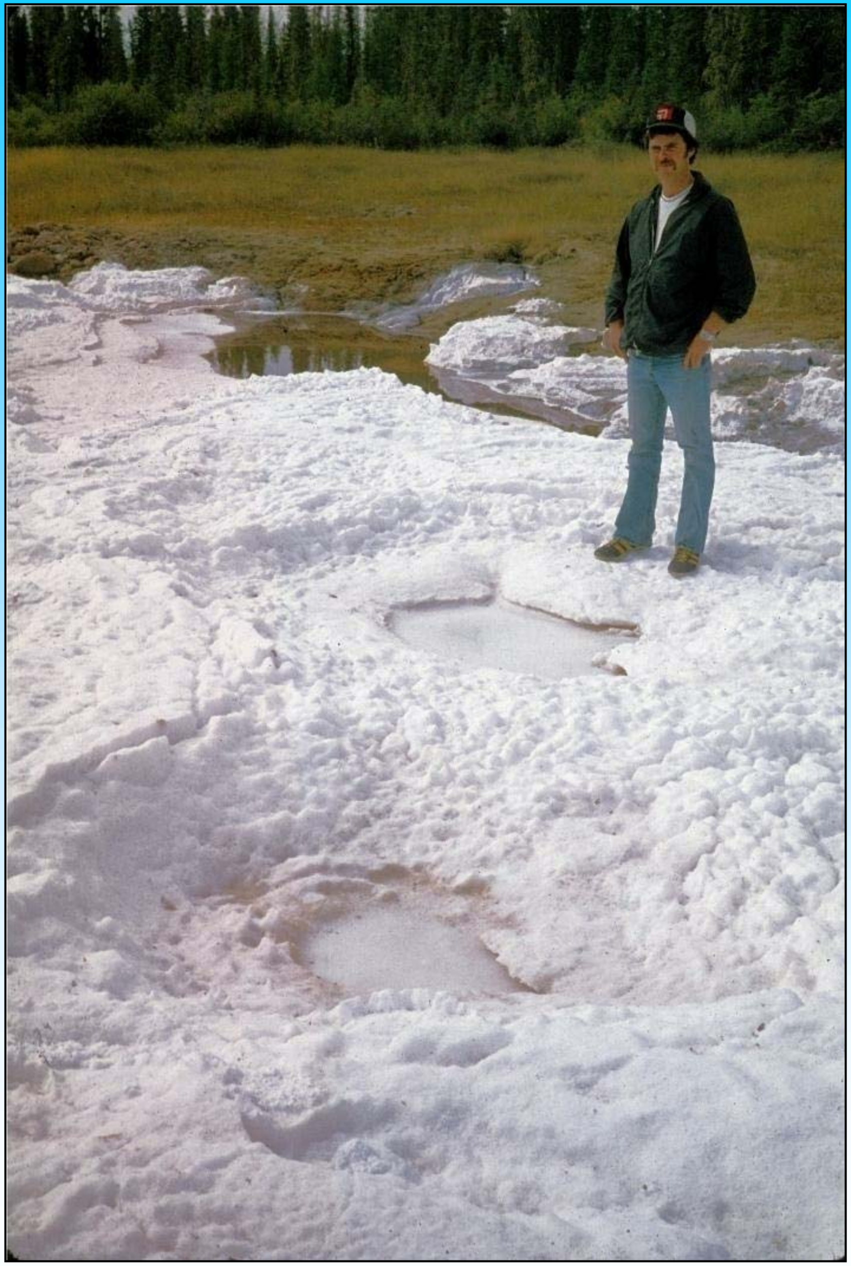
The fresh groundwater energy field of hydraulic potentials determines the state of energy for all fluids in the subsurface [Hubbert, 1953, p. 1960], for groundwater, salt water, oil, gas, and CO_2

Flow directions within fresh water force field



Schematics of differing flow directions for fresh water, salt water, brine, oil, and gas within the same fresh water force field based on density differences

Diagram modified after Hubbert, 1953: Entrapment of Petroleum Under Hydrodynamic Conditions



Upward discharge of saturated brine near Salt River, NWT, Canada

- Saturated [~350 g/l; density ~1.3 g/cm^3] brine discharging upwards beside a creek
- Salt deposit is caused by precipitation of salt not by evaporation of brine.

picture: K.U.Weyer, 1977

Bear (1972, section 10.7.6) assumes a counterplay of two driving forces namely, as put by Bachu et al. [1993, p.7], "*a potential force resulting from piezometric head differences, and a buoyancy force resulting from density differences (~~Hubbert, 1940~~, Bear, 1972, p.654)*"

Groundwater flow does not take the path of least resistance

instead

the multitude of pathways are arranged such that the energy consumption in the total flow field is minimized

Antiquated legacy concept of regional groundwater flow

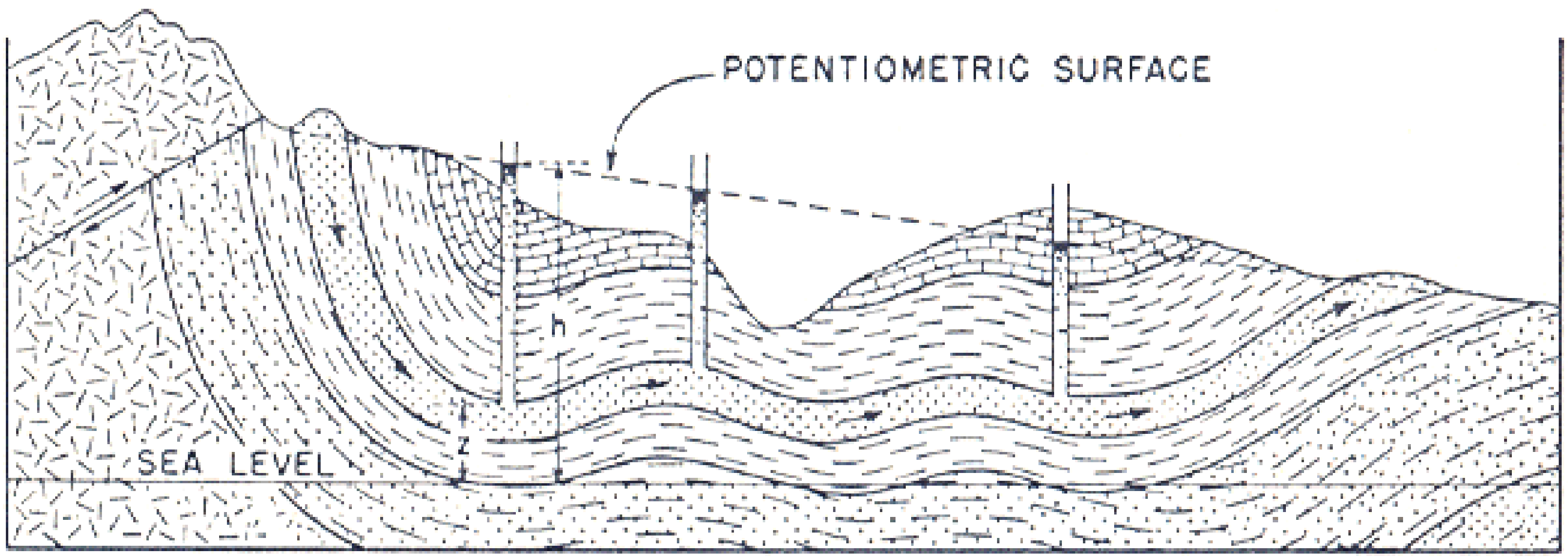
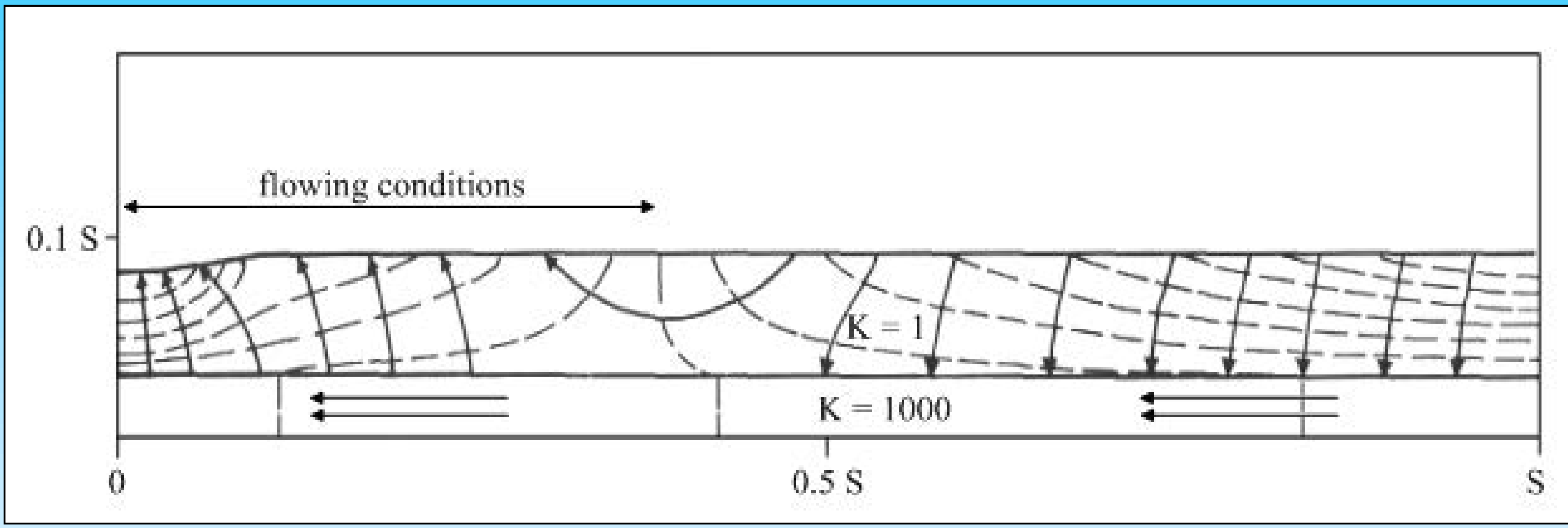


FIG. 11.—Regional flow of water through sand from higher to lower outcrop, showing continuous drop in potential.

Hubbert, 1953: Entrapment of Petroleum Under Hydrodynamic Conditions

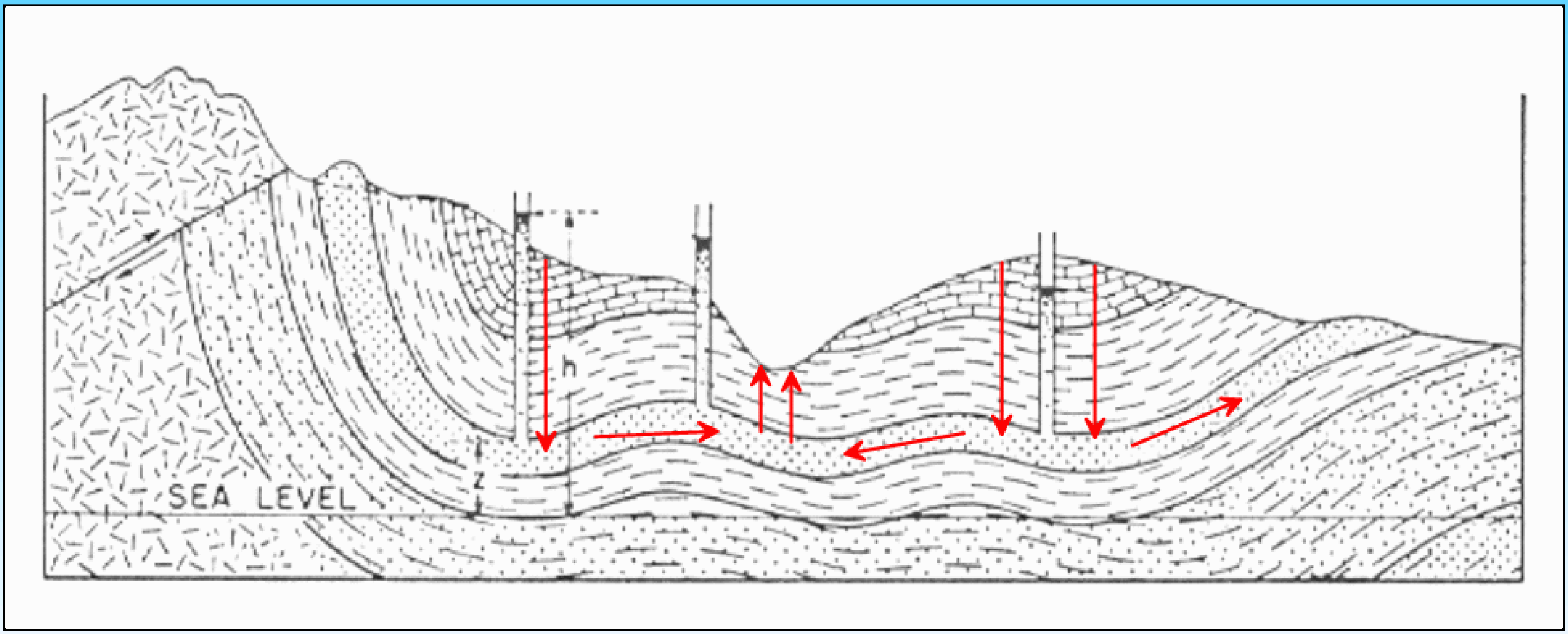
In this figure Hubbert restricted flow to the aquifer. Knowledge about groundwater flow systems penetrating aquitards only became available more than a decade later (Freeze and Witherspoon, 1966, 1967).



Freeze and Witherspoon, 1967, Figure 2C. Flow lines added.

Flow interaction between aquitard and underlying aquifer minimizing the total energy consumption. Under this geometrical configuration twice as much groundwater flows through the aquitard than in the aquifer

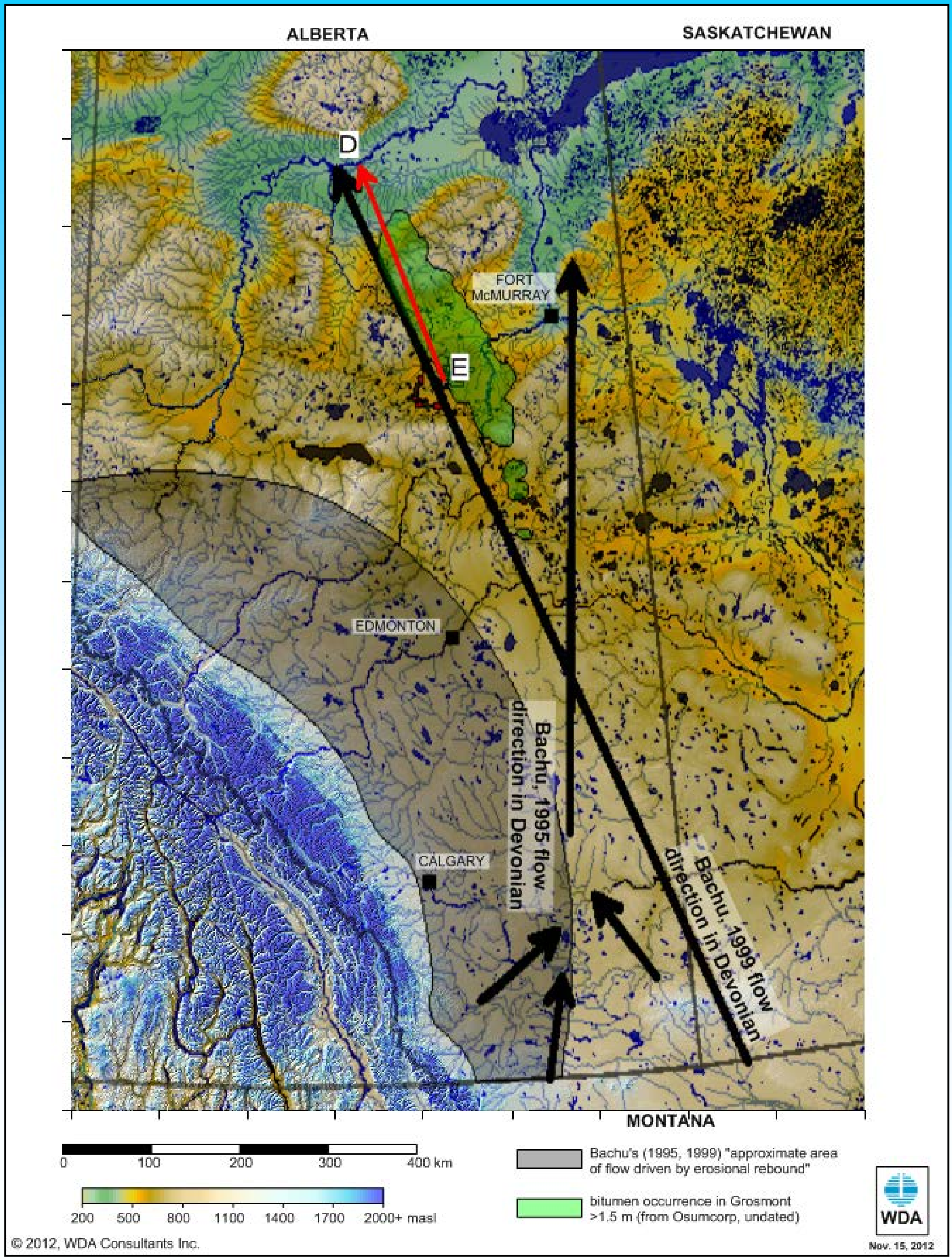
Revised concept of regional groundwater flow



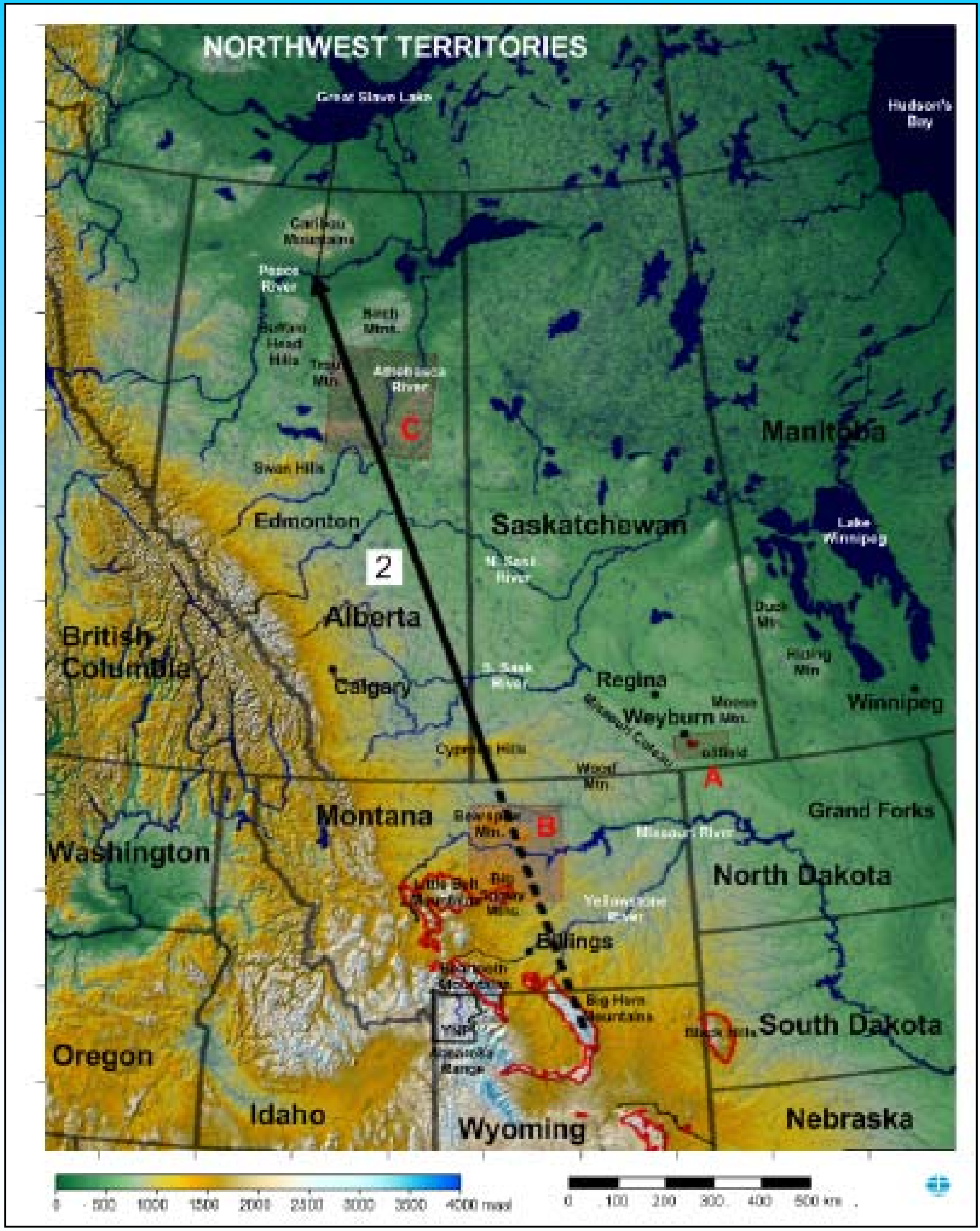
Schematic representation.

⊗

ARC's postulated groundwater 'pipelines'
Montana – Peace River

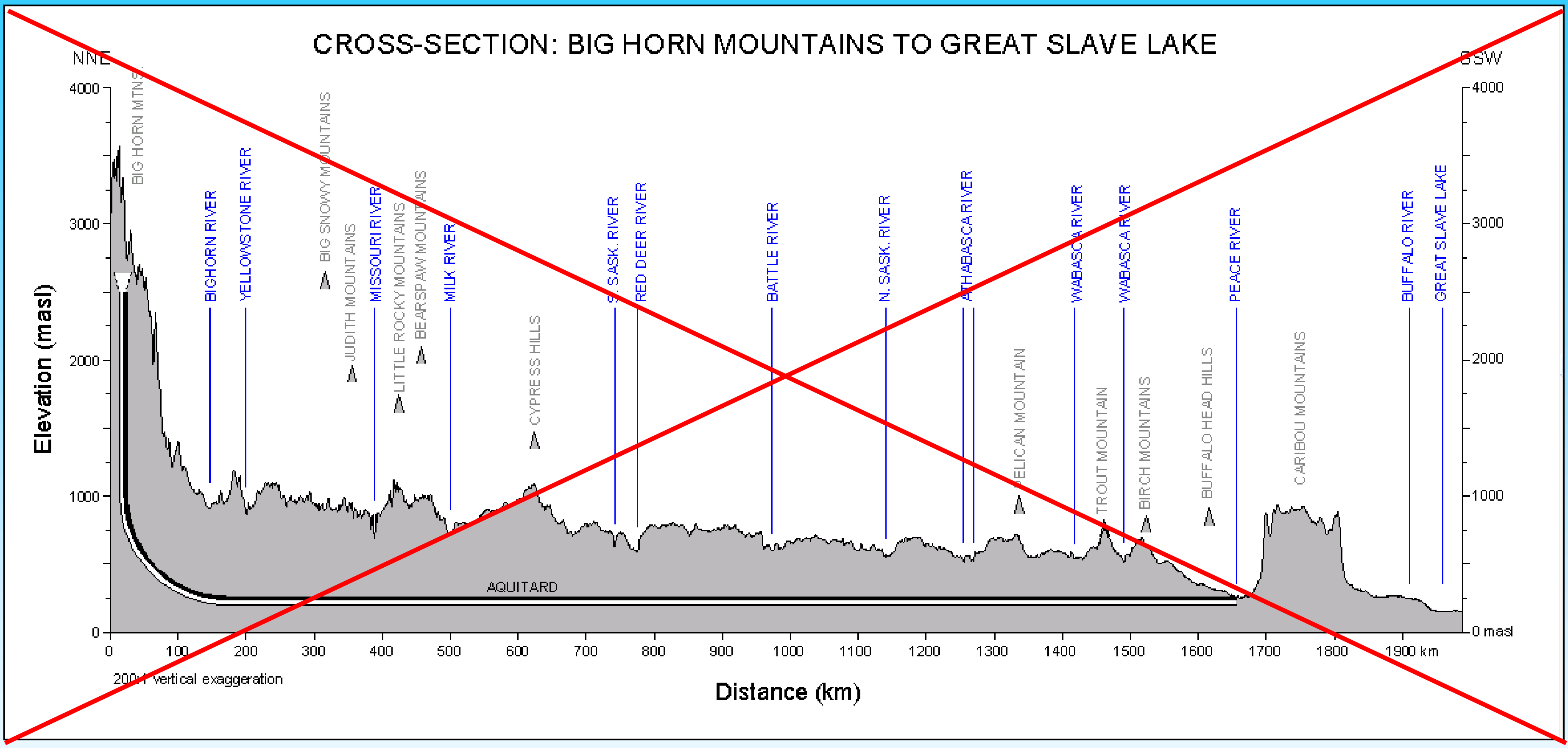


DEM showing the diverging directions and endpoints of topographically driven northward flow of formation waters proposed by Bachu (1995, 1999) as well as the area of assumed erosion rebound flow.



DEM showing the direction and endpoint of topographically driven long range groundwater flow of formation waters over approximately 1600 km from Montana's Big Horn Mountains to the Peace River postulated by Bachu (1999).

Dashed extension added by us.



Schematic representation of the long range flow system Montana to Peace River postulated by Bachu, 1999

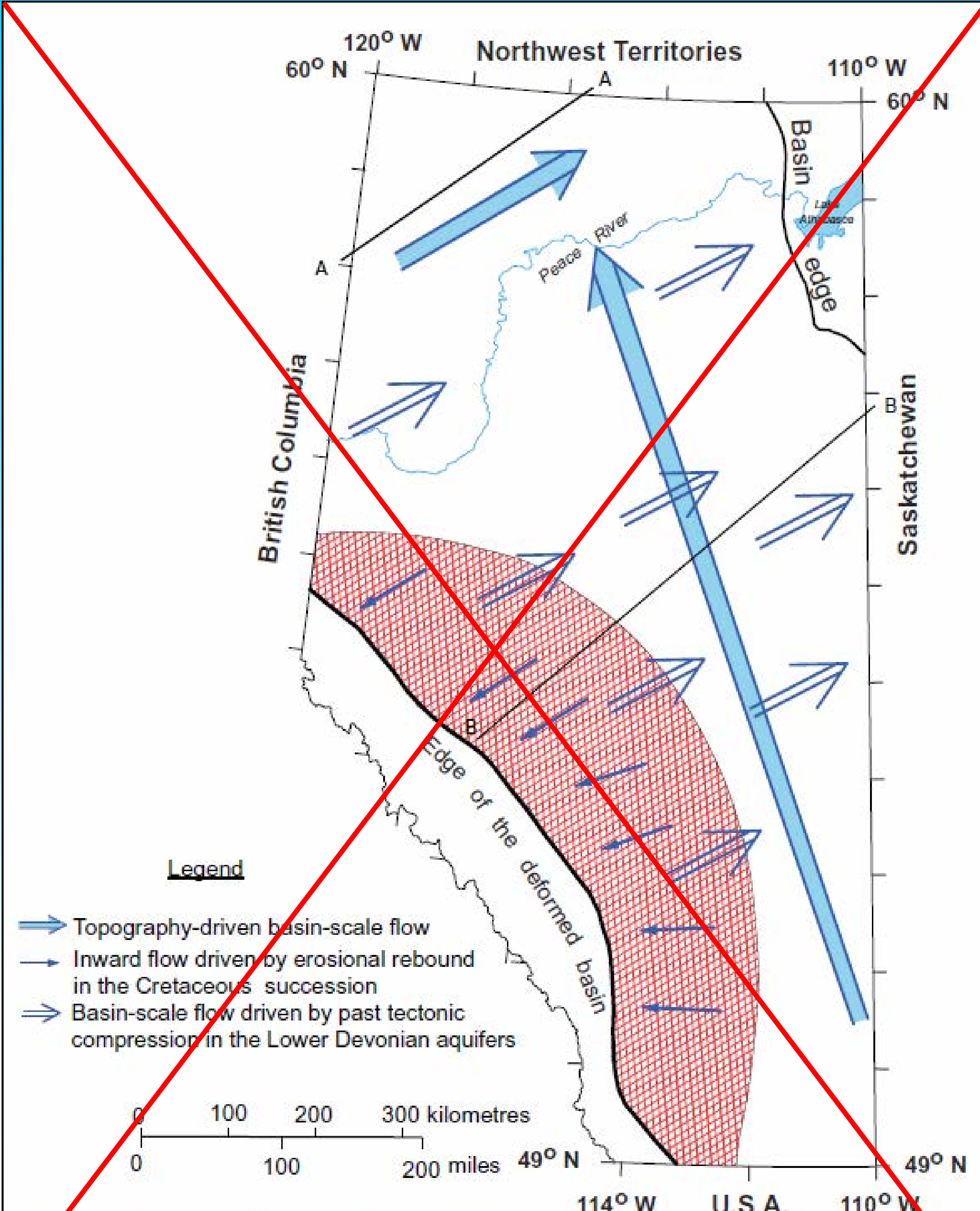
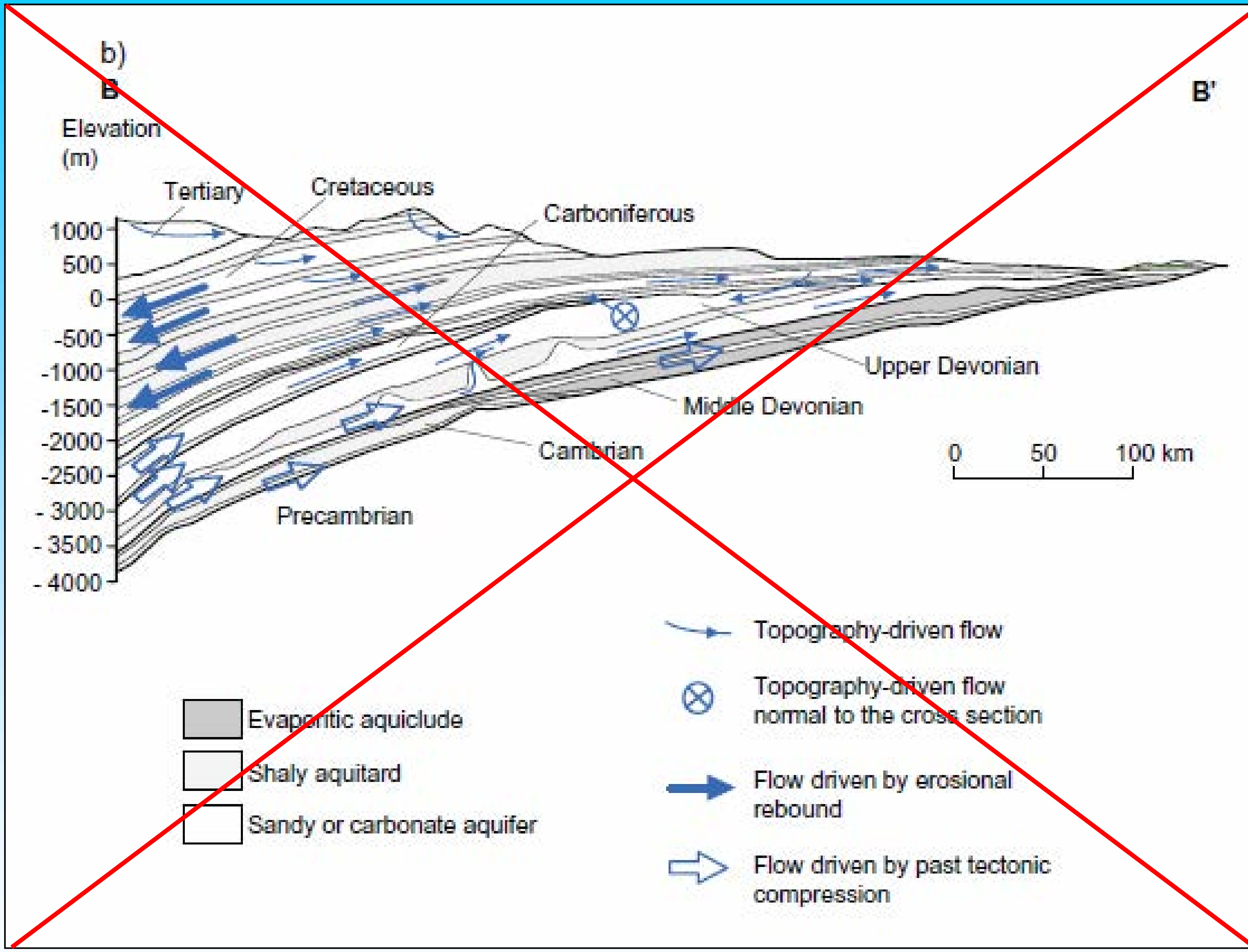


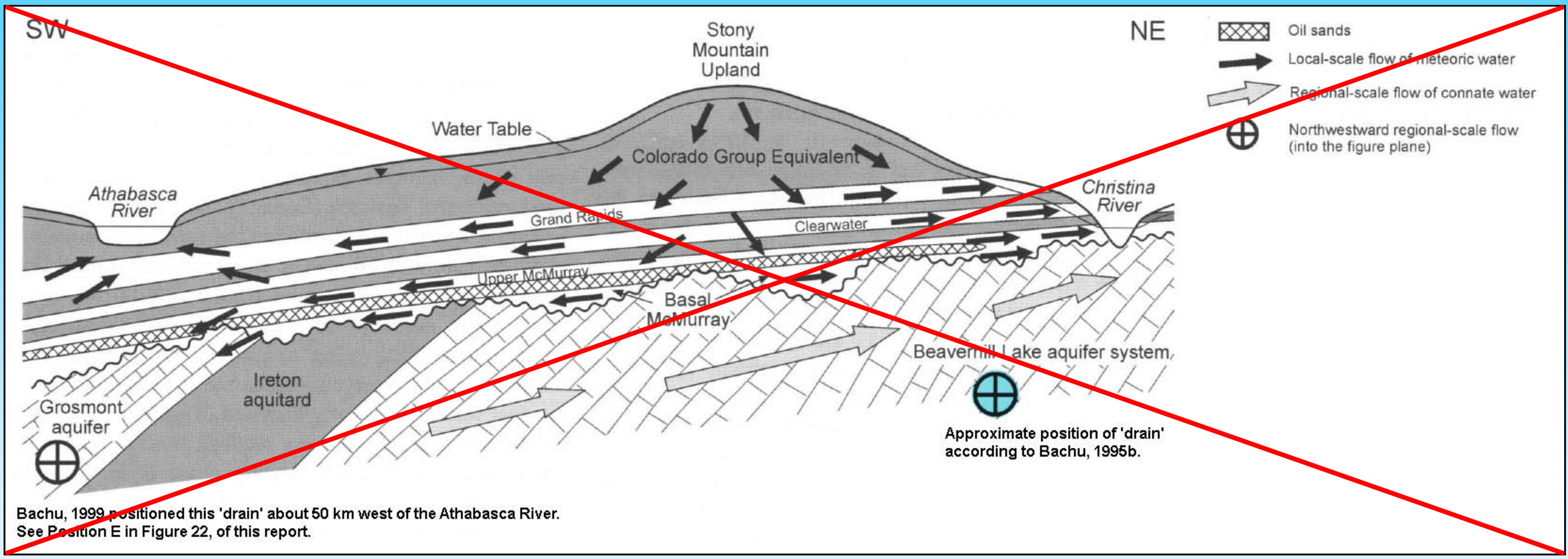
Figure 28: Plan-view diagrammatic representation of the flow systems and pattern in Alberta's subsurface. Lines of cross sections refer to Figure 29.

"*Plan-view diagrammatic representation of the flow systems and pattern in the Alberta basin*" postulated by Bachu et al. [2000, Figure 28].

Cross section B-B is shown in the next slide.

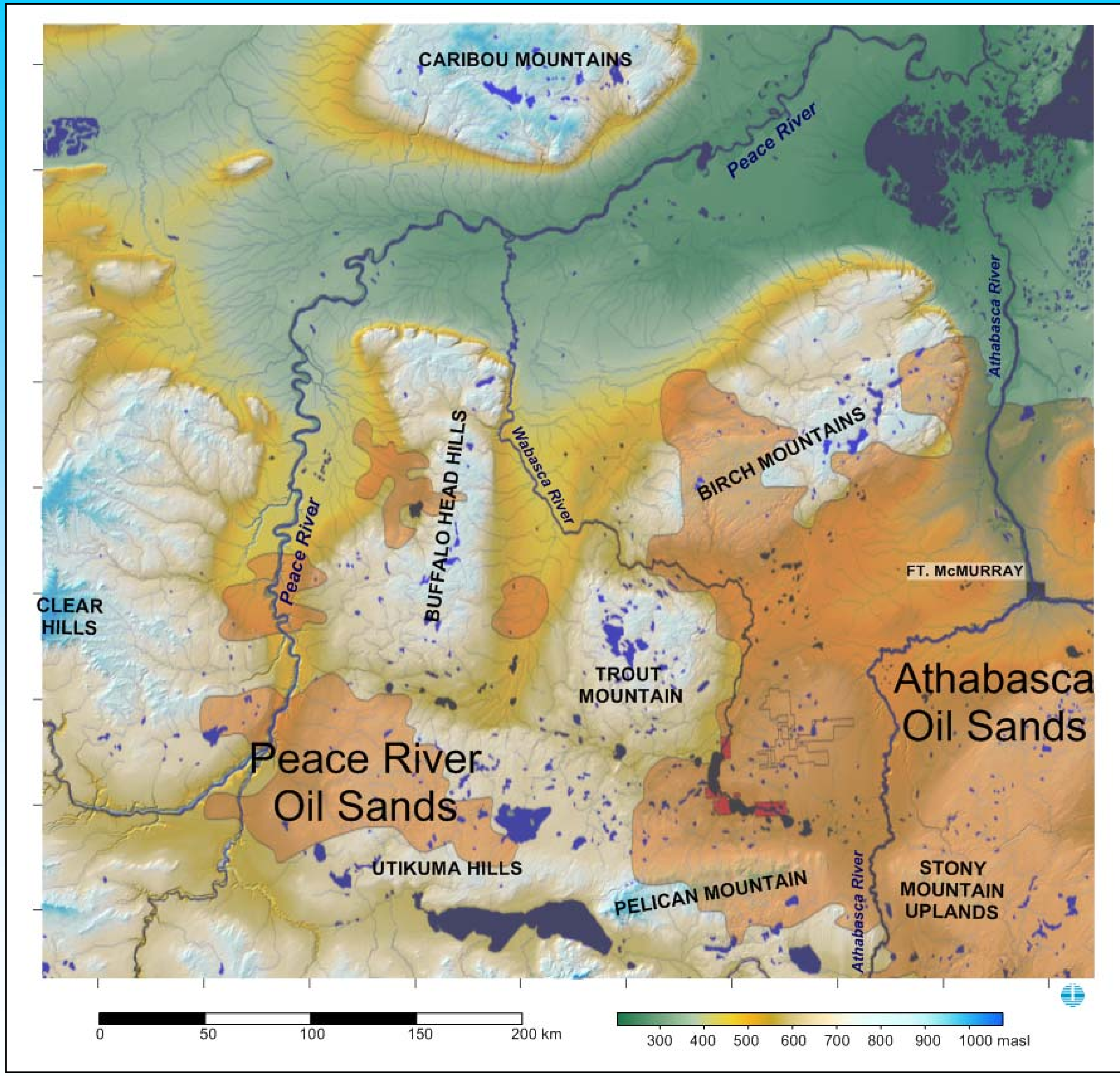


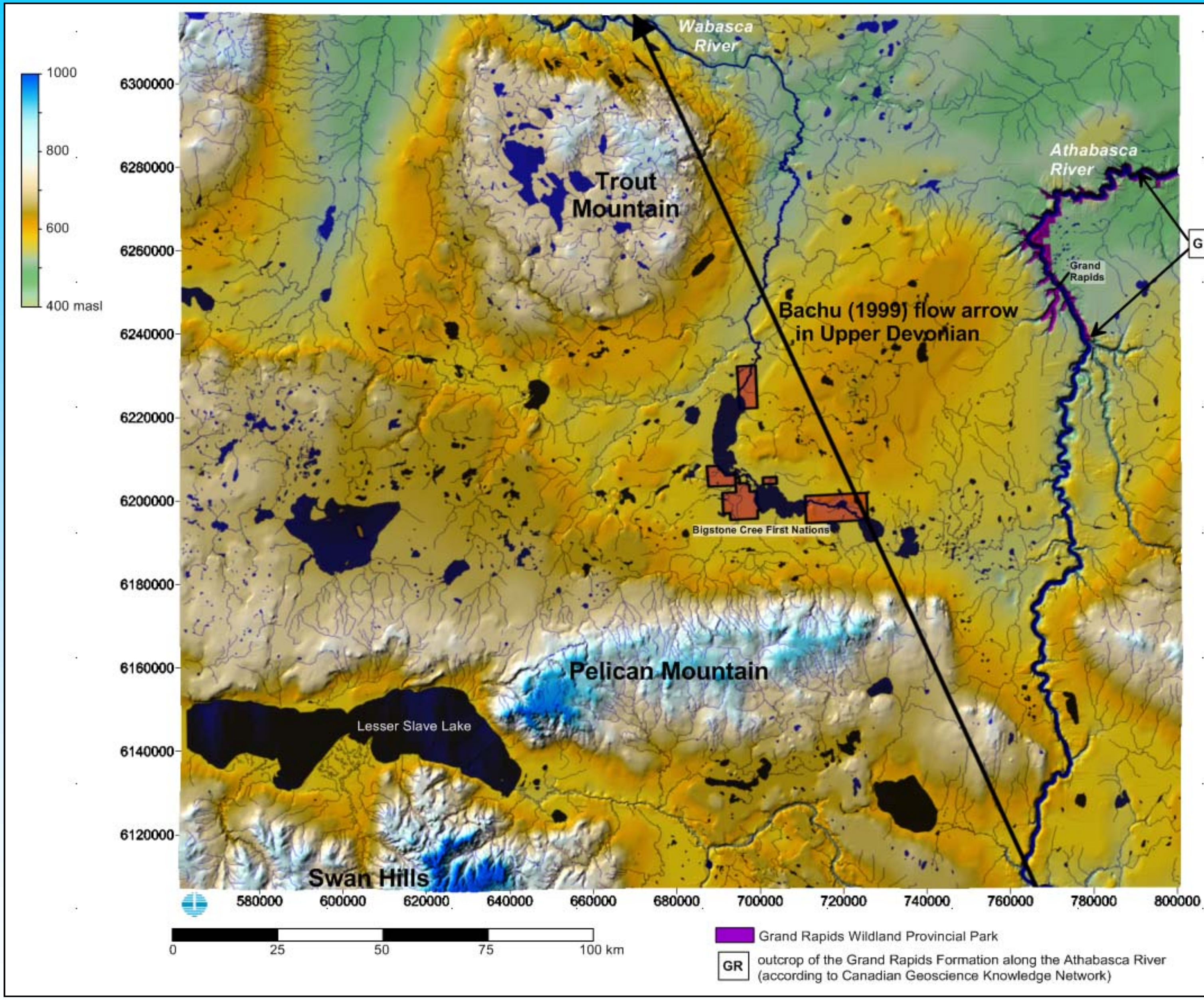
The location of the cross section (from Bachu et al, 2000, Fig 29B) is shown in the previous slide



Diagrammatic representation of groundwater flow under the Stony Mountain Uplands between Athabasca River and Christina River (modified after Barson, Bachu, and Esslinger, 2001, Fig. 6).

Wabasca oil sands


CARIBOU MOUNTAINS
Peace River
Athabasca River
BIRCH MOUNTAINS
Wabasca River
BUFFALO HEAD HILLS
Peace River
FT. McMURRAY
CLEAR HILLS
TROUT MOUNTAIN
Athabasca Oil Sands
Peace River Oil Sands
UTIKUMA HILLS
PELICAN MOUNTAIN
Athabasca River
STONY MOUNTAIN UPLANDS
0 50 100 150 200 km
300 400 500 600 700 800 900 1000 masl



1000
800
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6300000
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6180000
6160000
6140000
6120000
580000
600000
620000
640000
660000
680000
700000
720000
740000
760000
780000
800000
Wabasca River
Trout Mountain
Athabasca River
GR
Grand Rapids
Bachu (1999) flow arrow in Upper Devonian
Bigstone Cree First Nations
Pelican Mountain
Lesser Slave Lake
Swan Hills
0
25
50
75
100 km
Grand Rapids Wildland Provincial Park
GR
outcrop of the Grand Rapids Formation along the Athabasca River (according to Canadian Geoscience Knowledge Network)

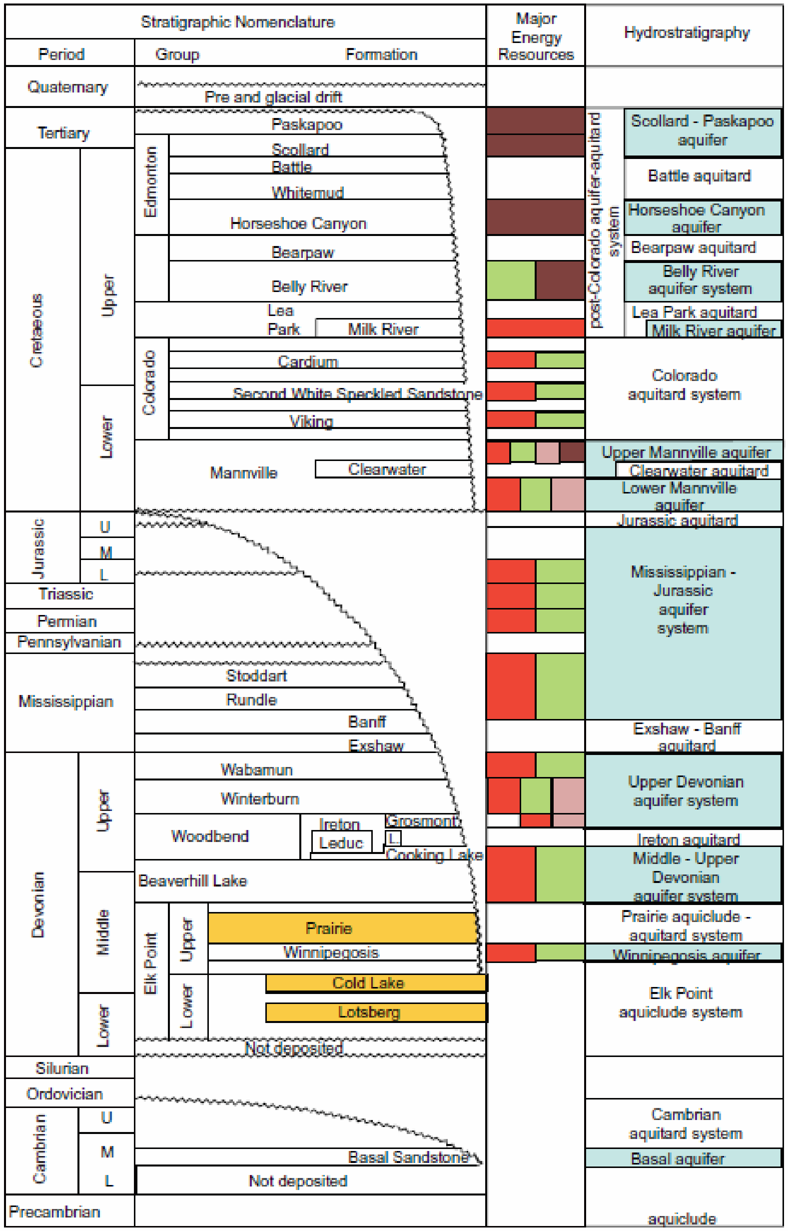
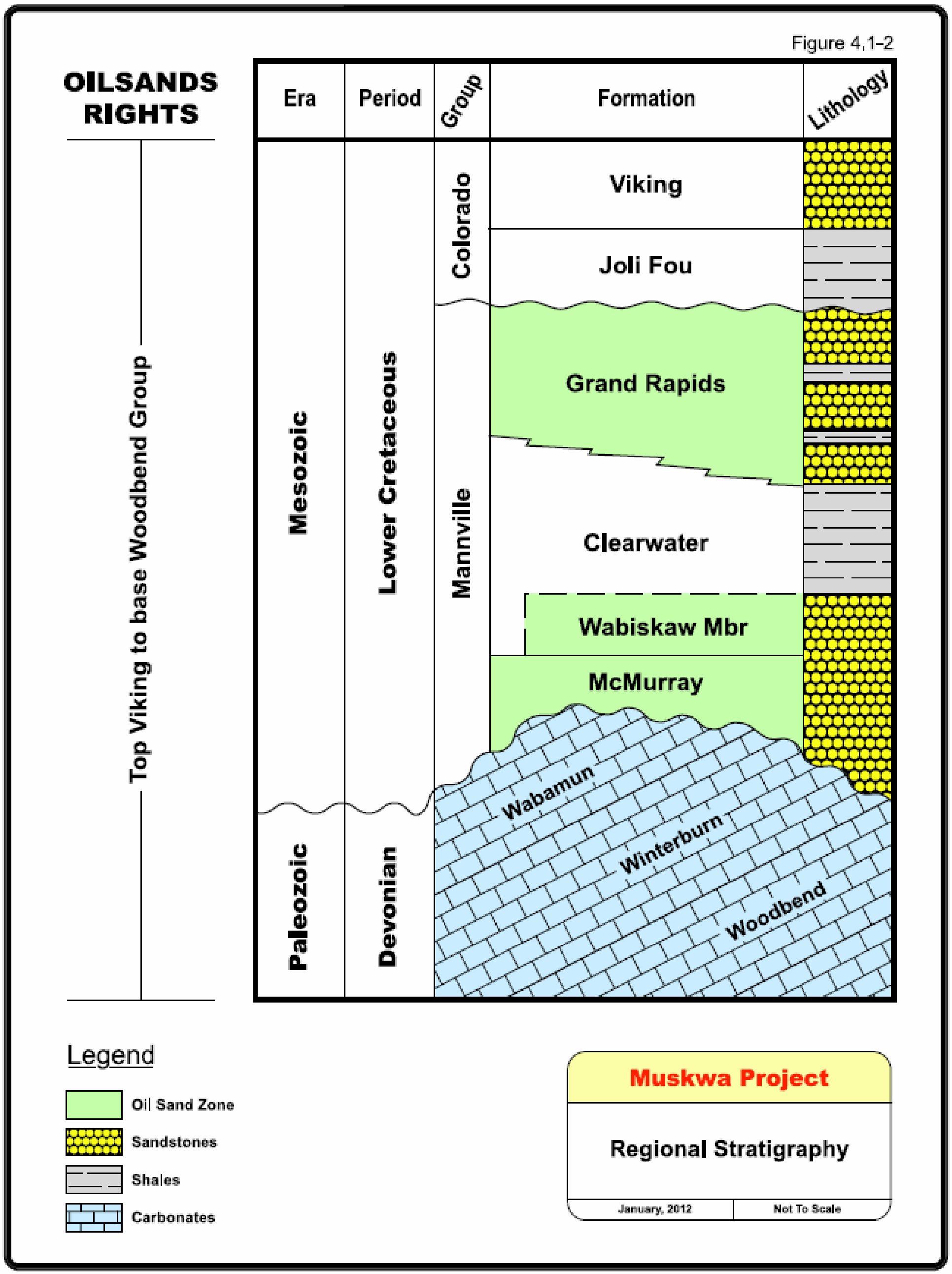


Figure 5: Relevant basin-scale stratigraphic and hydrostratigraphic delineation and nomenclature in the southern and central parts of the Alberta basin (Legend: gas; oil; heavy oil and oil sands; coal; salt; aquifer).

Regional stratigraphy column with hydrocarbon occurrence and hydrostratigraphy from Bachu et al. (2000).

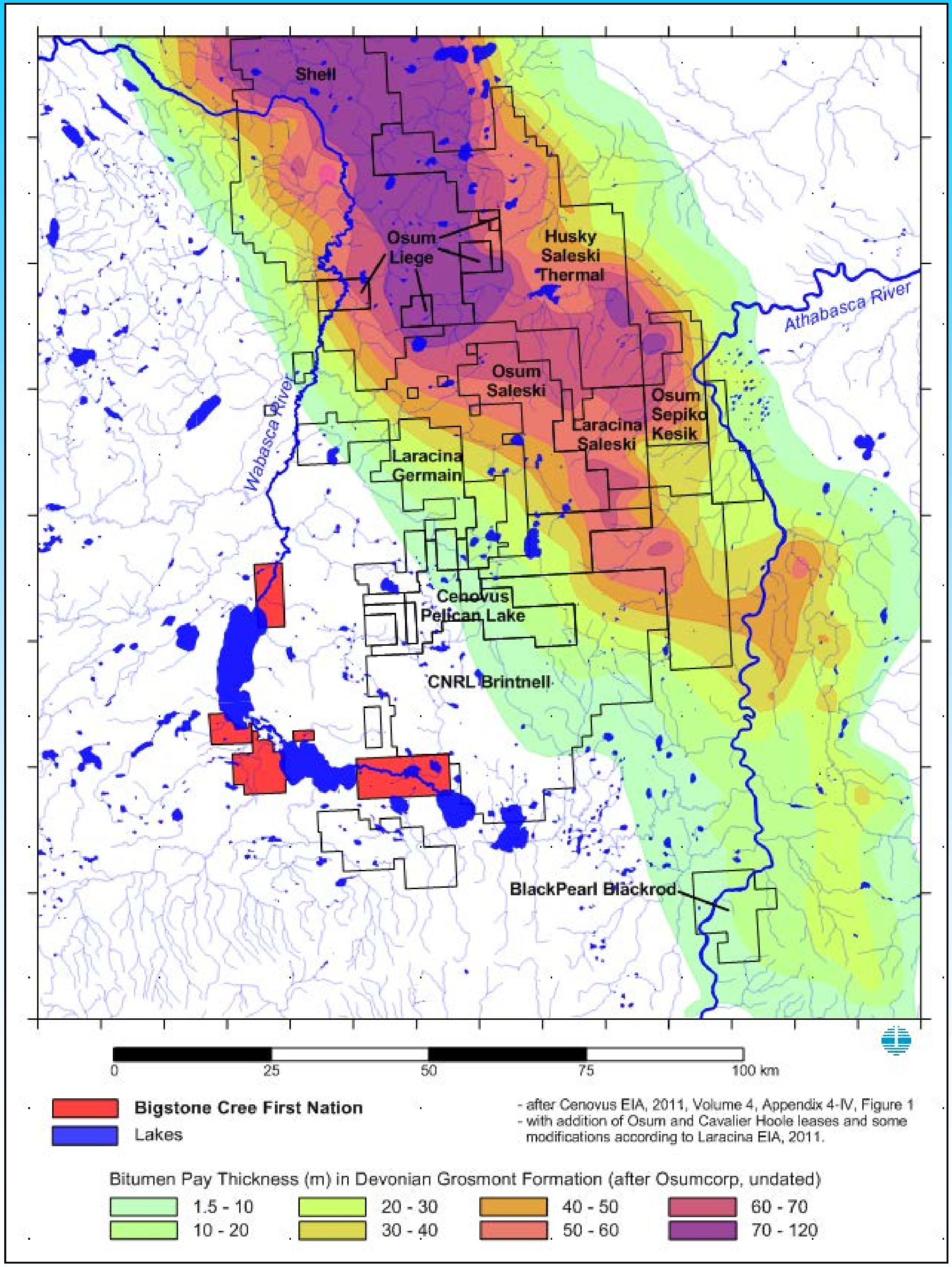
** bitumen

* bitumen



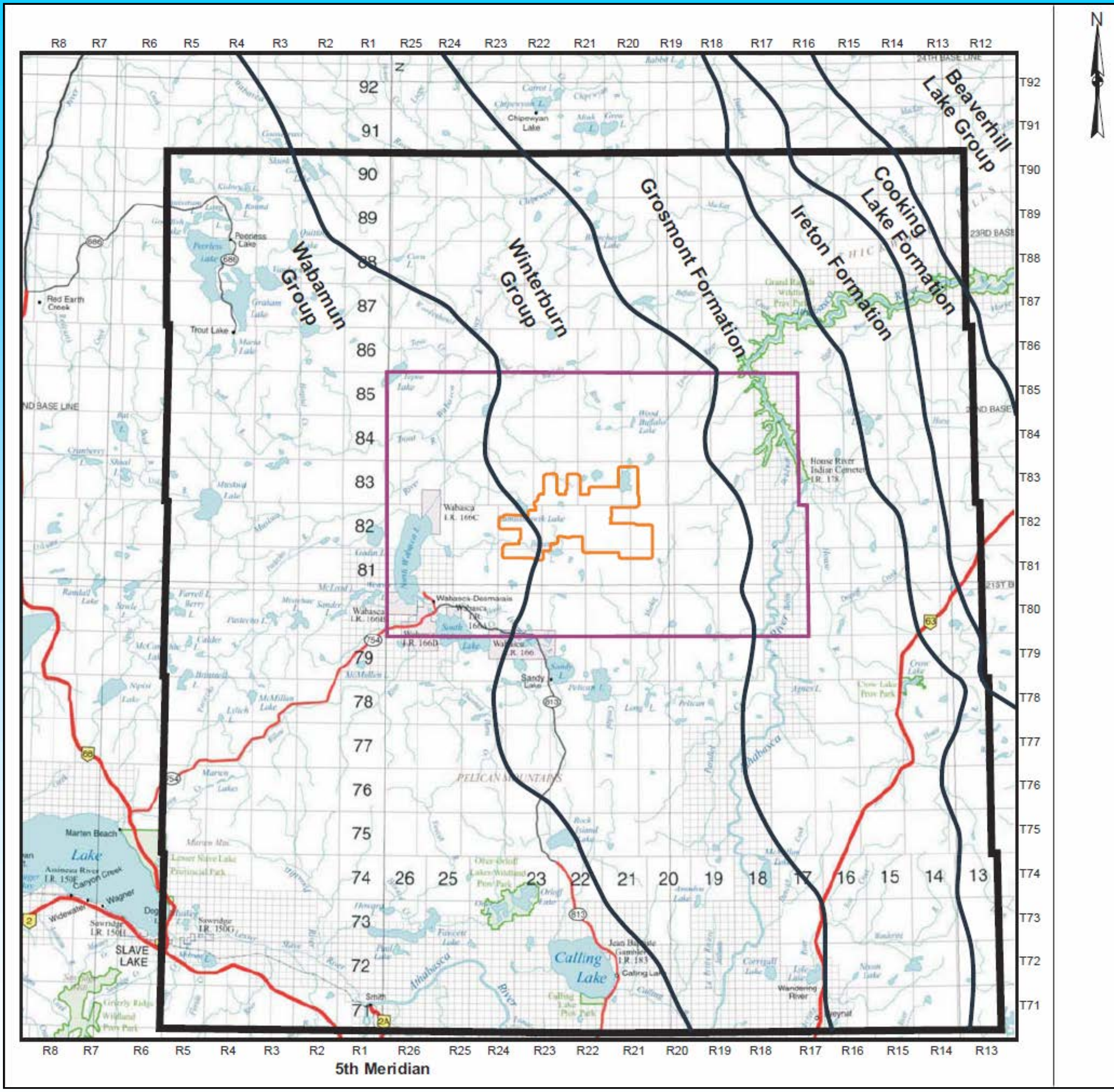
Regional stratigraphy

From Koch Exploration Canada LP, 2012, Fig. 4.1-2



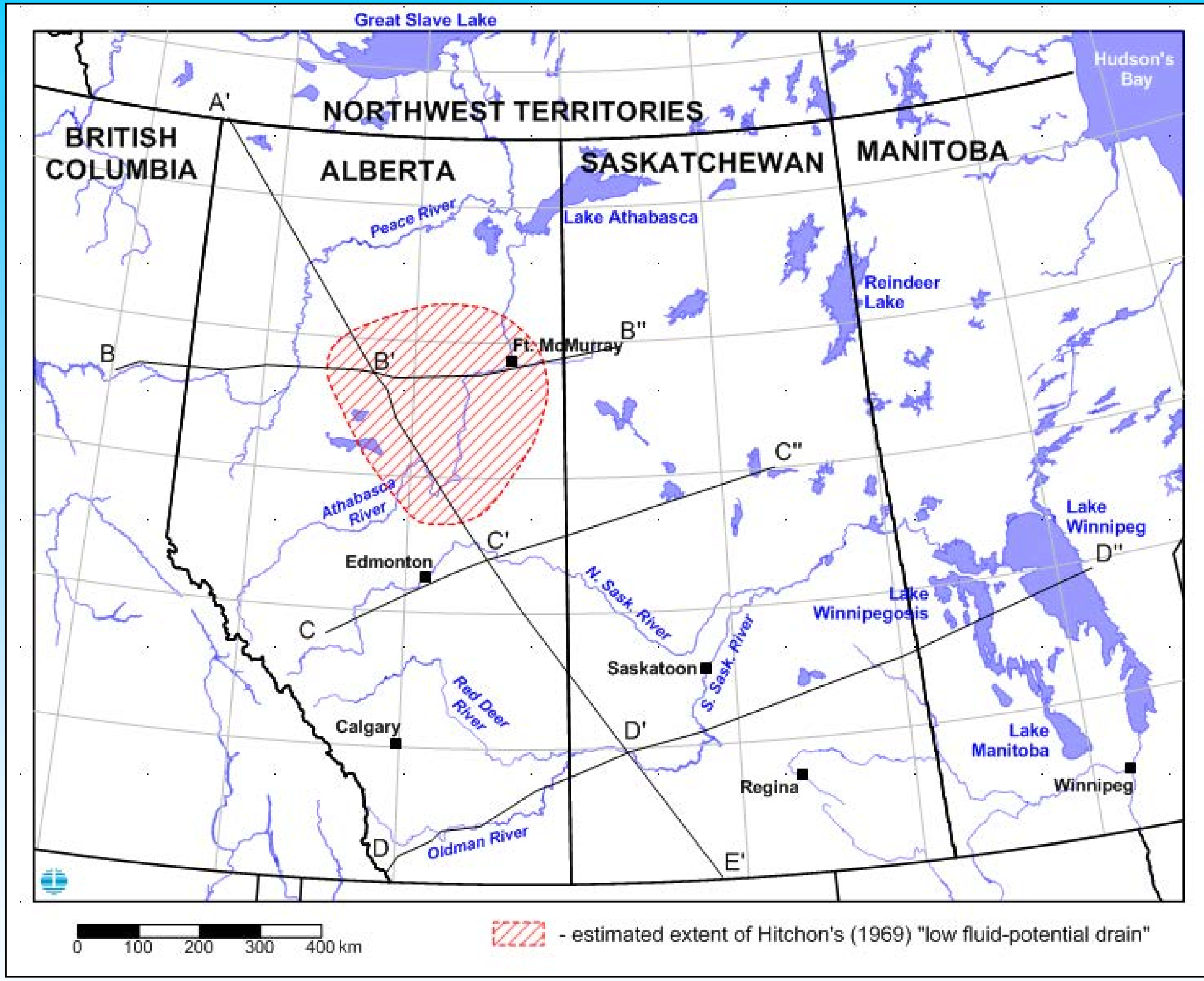
Occurrence of bitumen with a pay thickness exceeding 1.5 m within the Devonian Grosmont Platform (after Osum, undated).

The bitumen reservoir has been found to be highly permeable when drilled (Arseniuk et al. 2009).

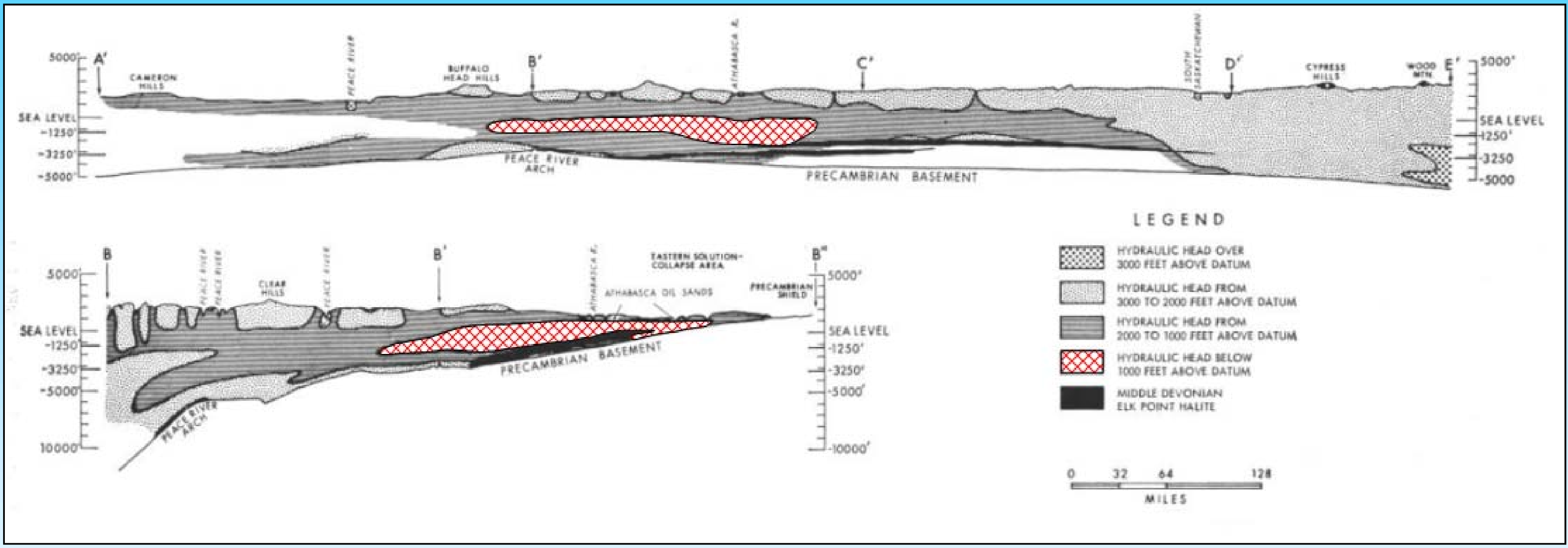


Devonian subcrop map (from Cenovus, 2011).

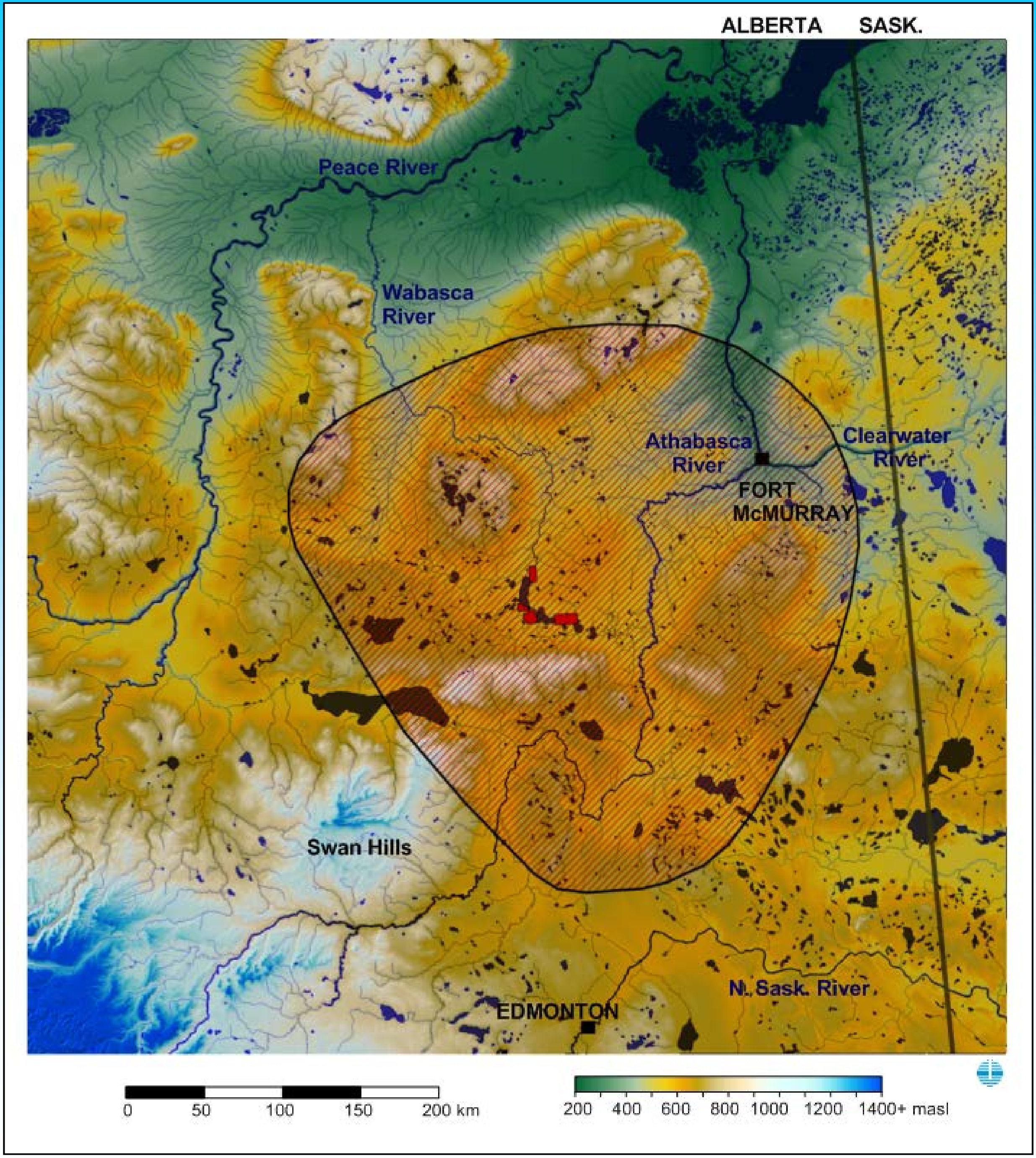
Regional groundwater flow towards the oil sands



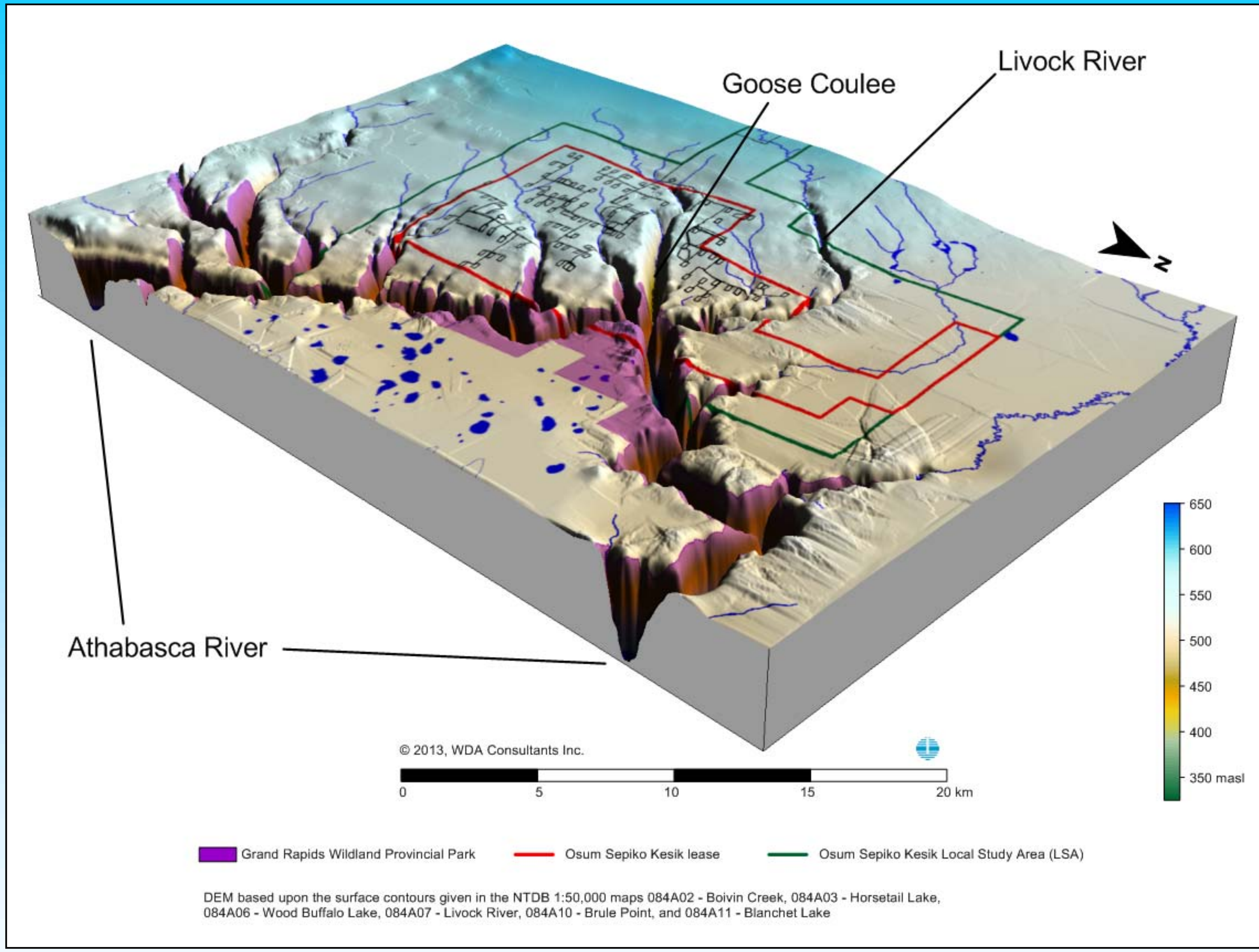
Location map of cross-sections (after Hitchon, 1969, Fig. 3). Red hatched area schematically depicts the estimated extent of Hitchon's (1969) low fluid-potential drain based on positions marked in the cross-sections A'-E' and B-B".



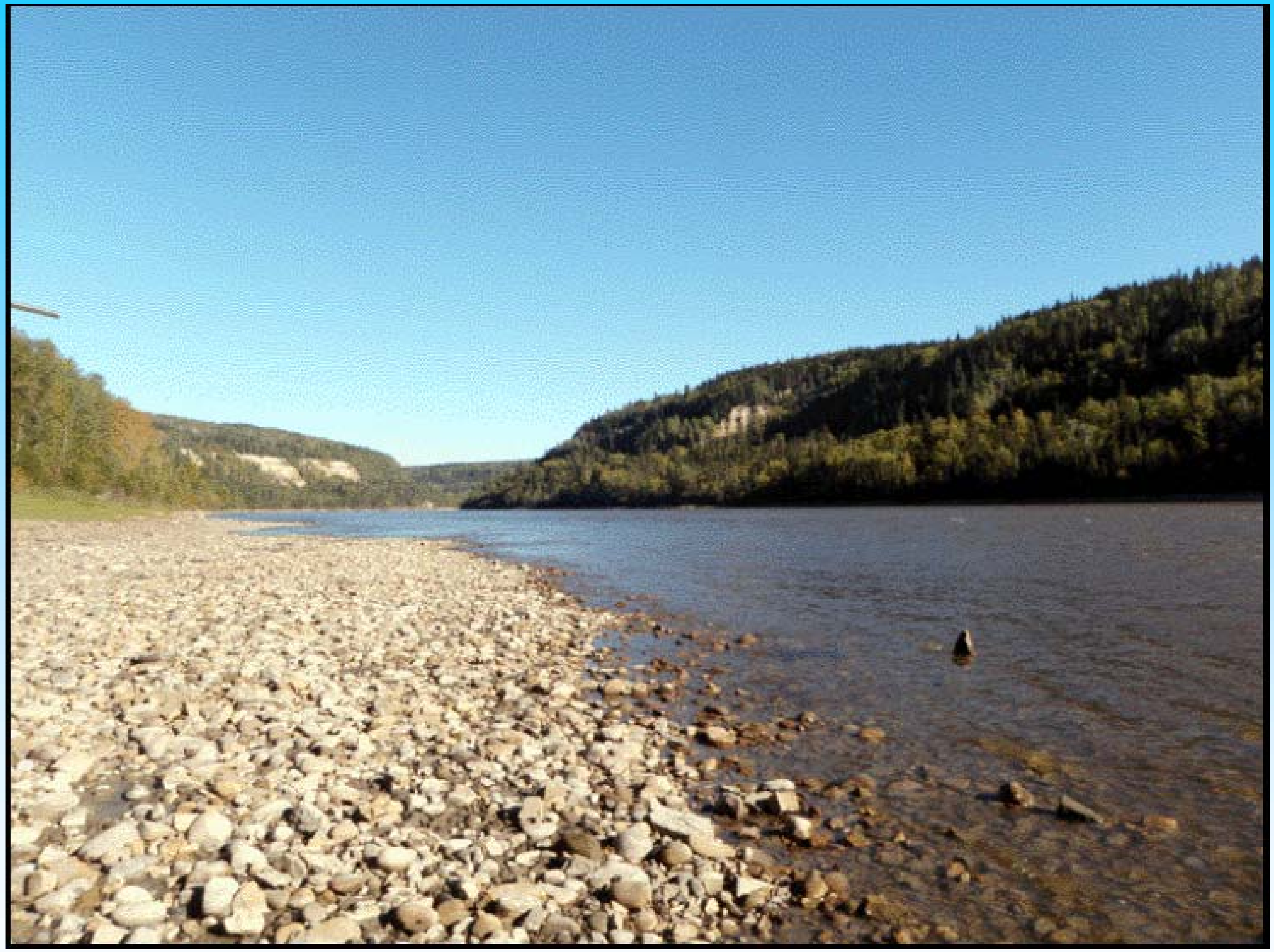
Hydraulic head distribution in cross-sections (modified after Hitchon, 1969, Fig. 8). The red hatched area represents Hitchon's (1969) low fluid-potential drain.



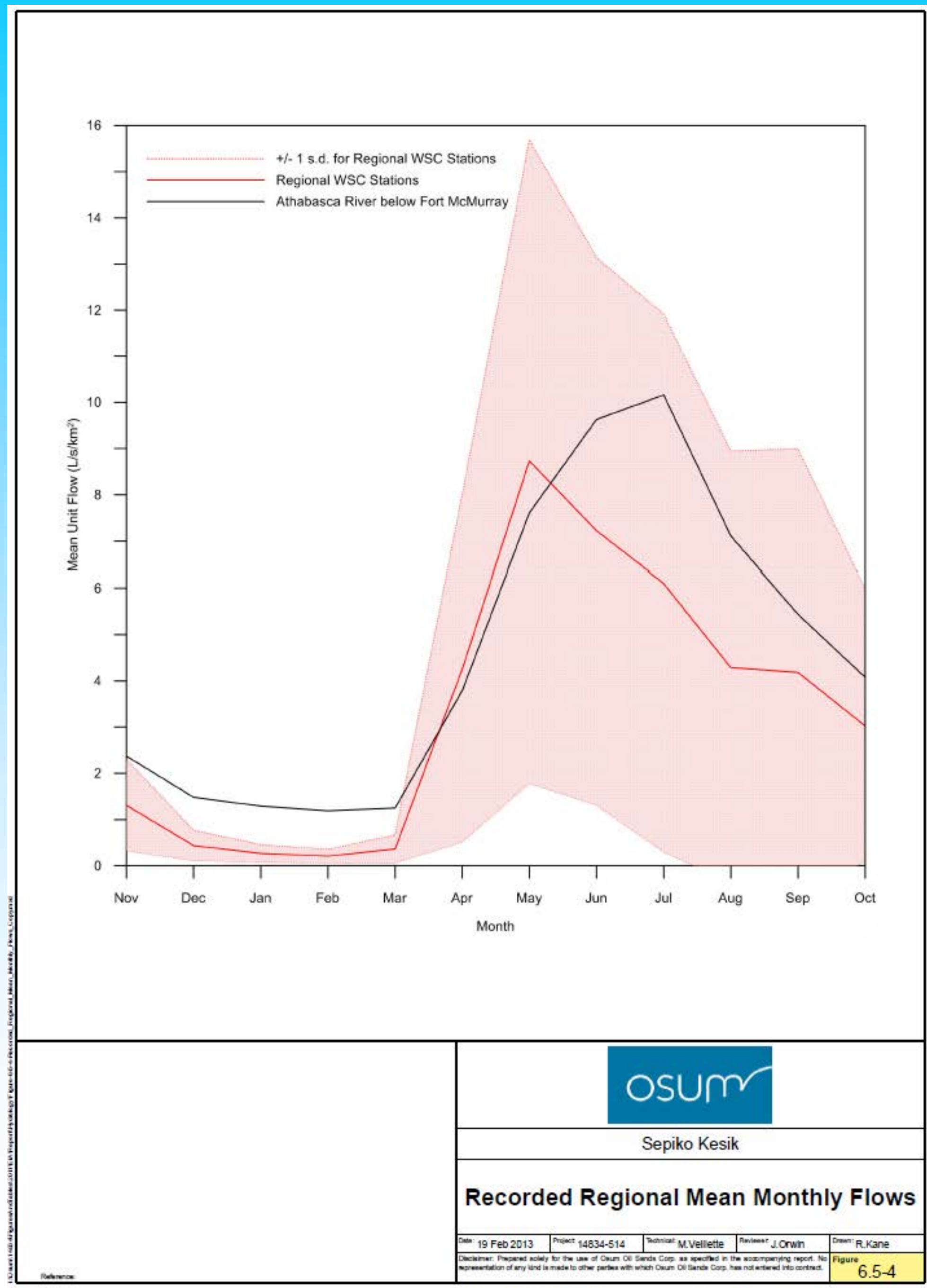
Schematically-estimated extent of Hitchon's (1969) "low fluid potential drain"



DEM of the Sepiko Kesik lease site (site plan taken from Osum, 2013) with the incised Athabasca River canyon.



Canyon of the Athabasca River viewing downstream. Picture from Osum, 2013, Fig. 8.5-9.

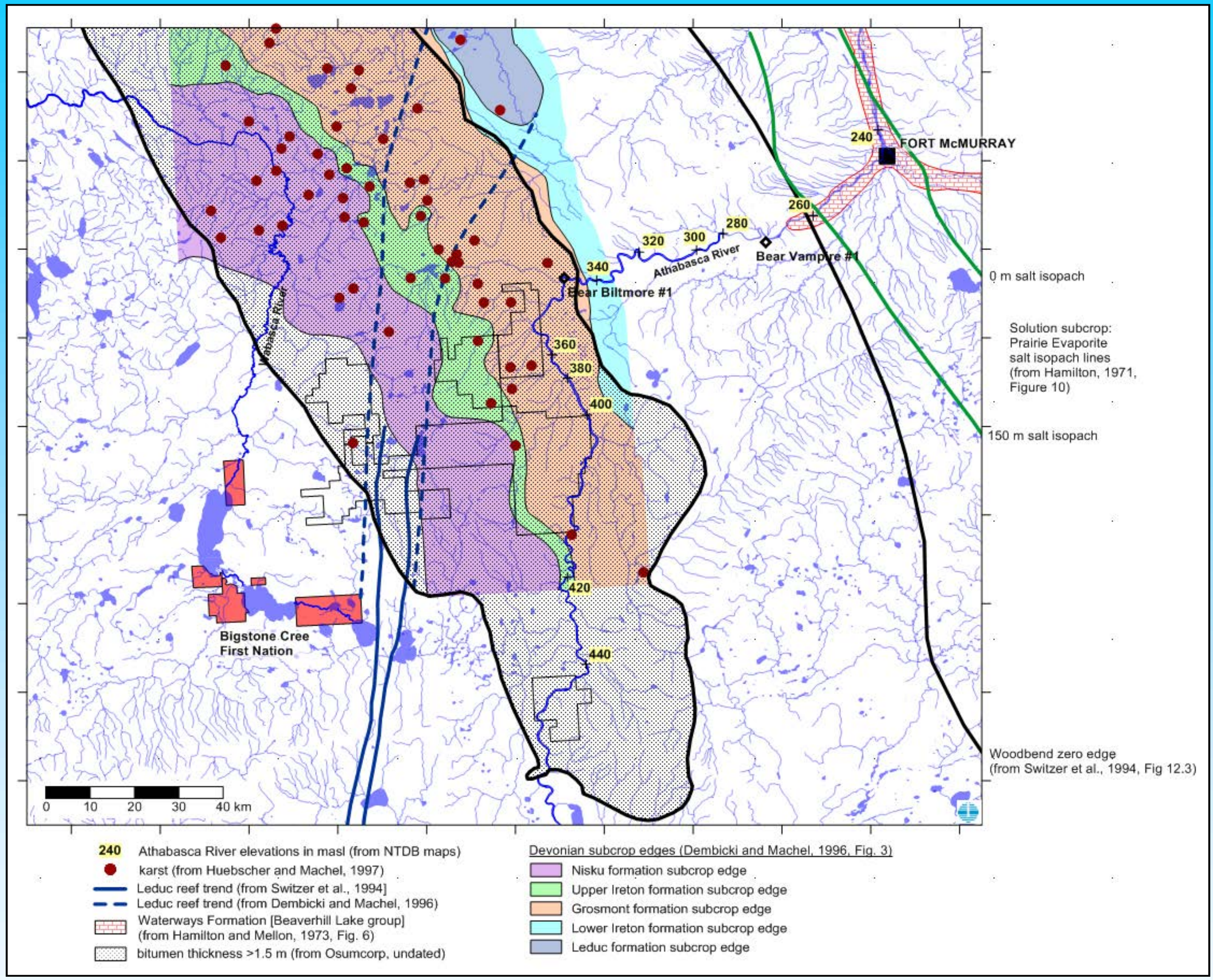


Recorded Regional Mean Monthly Flows. From Osum, 2013, Fig 6.5-4.

The relatively high winter flow of the Athabasca River may indicate substantial groundwater discharge from the Upper Devonian karst into the Athabasca River. One l/sec km^2 is equivalent to 32 mm annual precipitation.

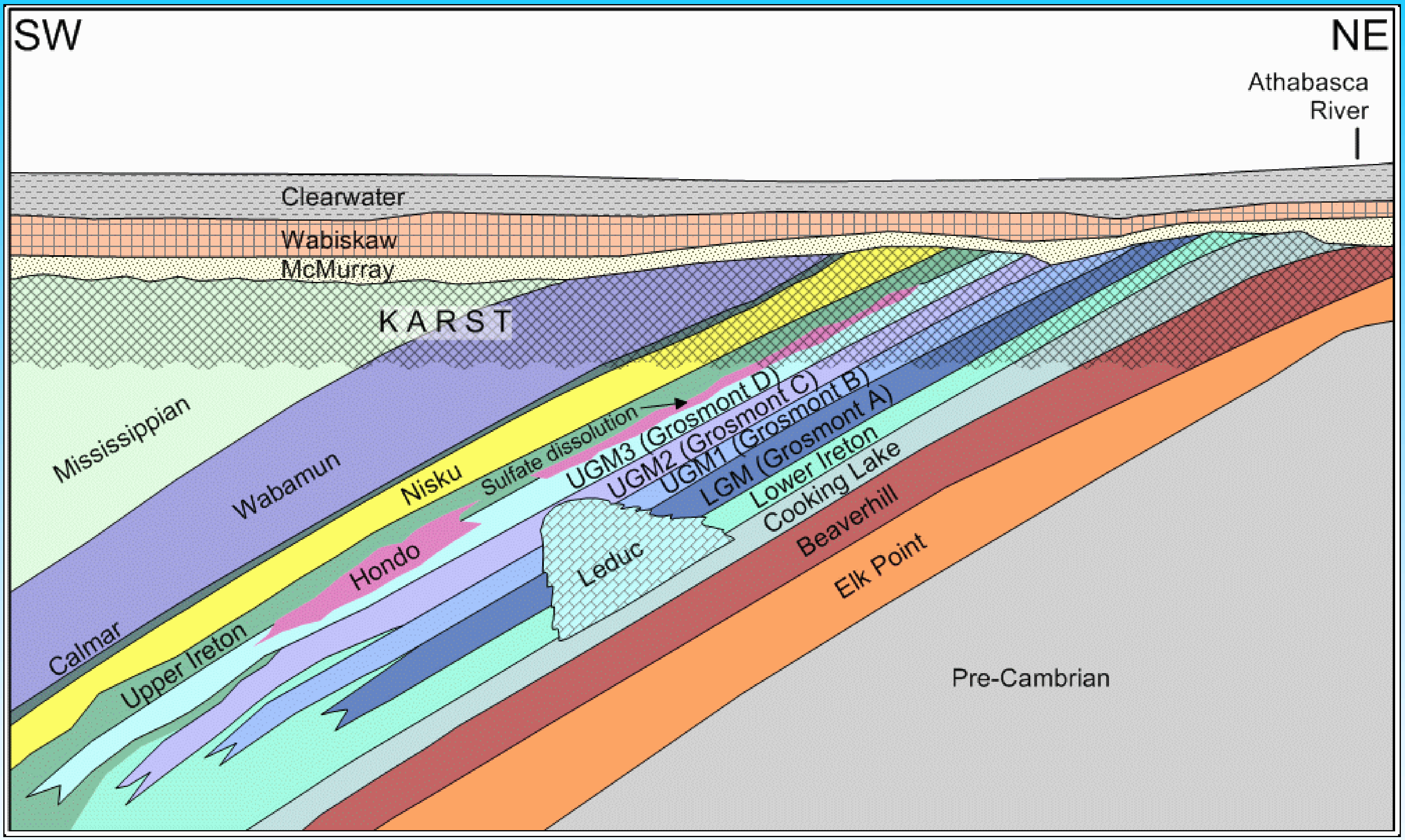
Athabasca River below Ft. McMurray
gaging station 07DA001
Gross drainage area: 132,585 km^2

Karst !!

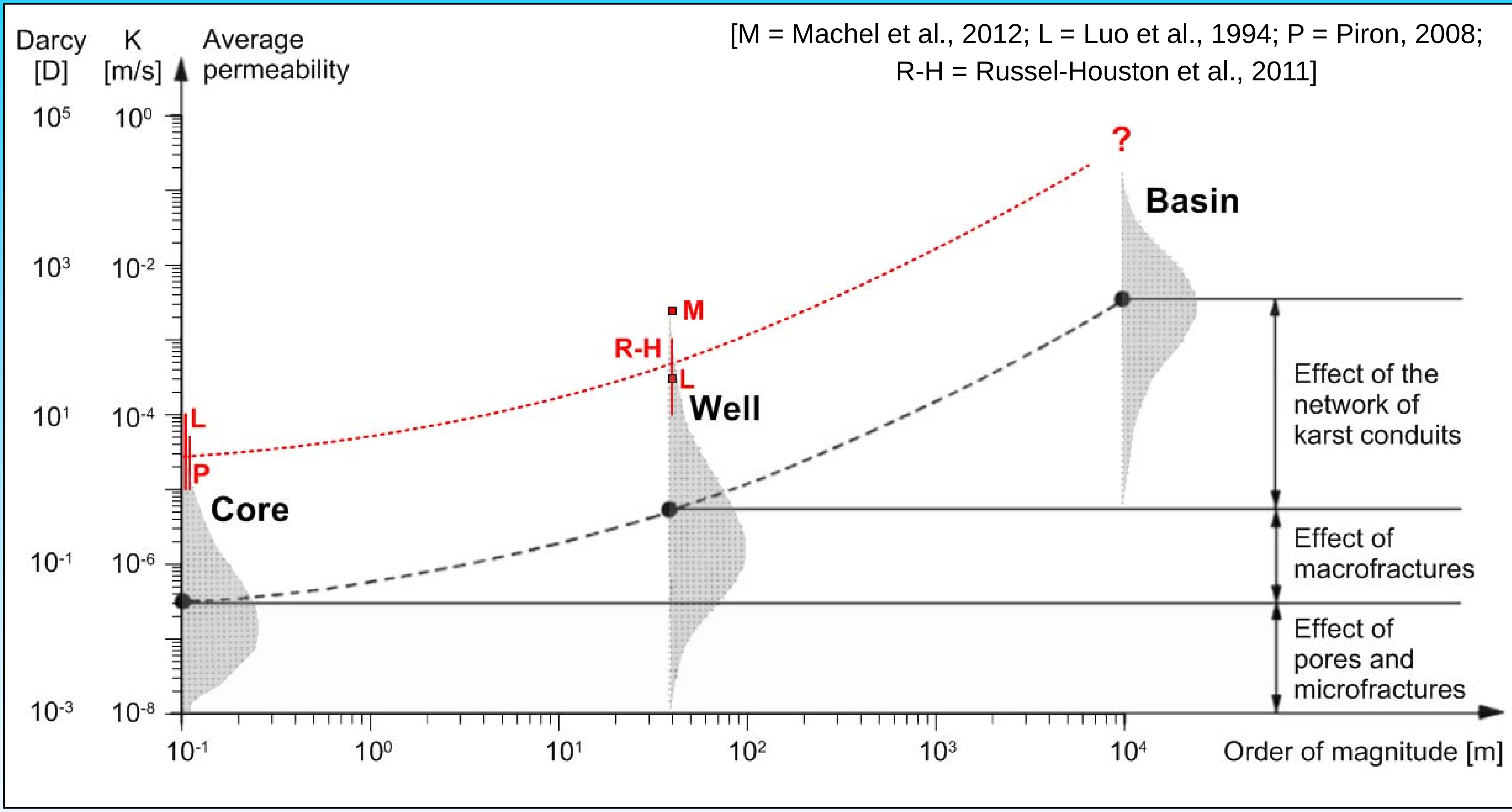


Bitumen in the Grosmont platform, karst in boreholes within the Grosmont Formation, and river water elevations in the Athabasca Canyon the regional discharge area

[From Weyer et al., 2013, Figure 11]

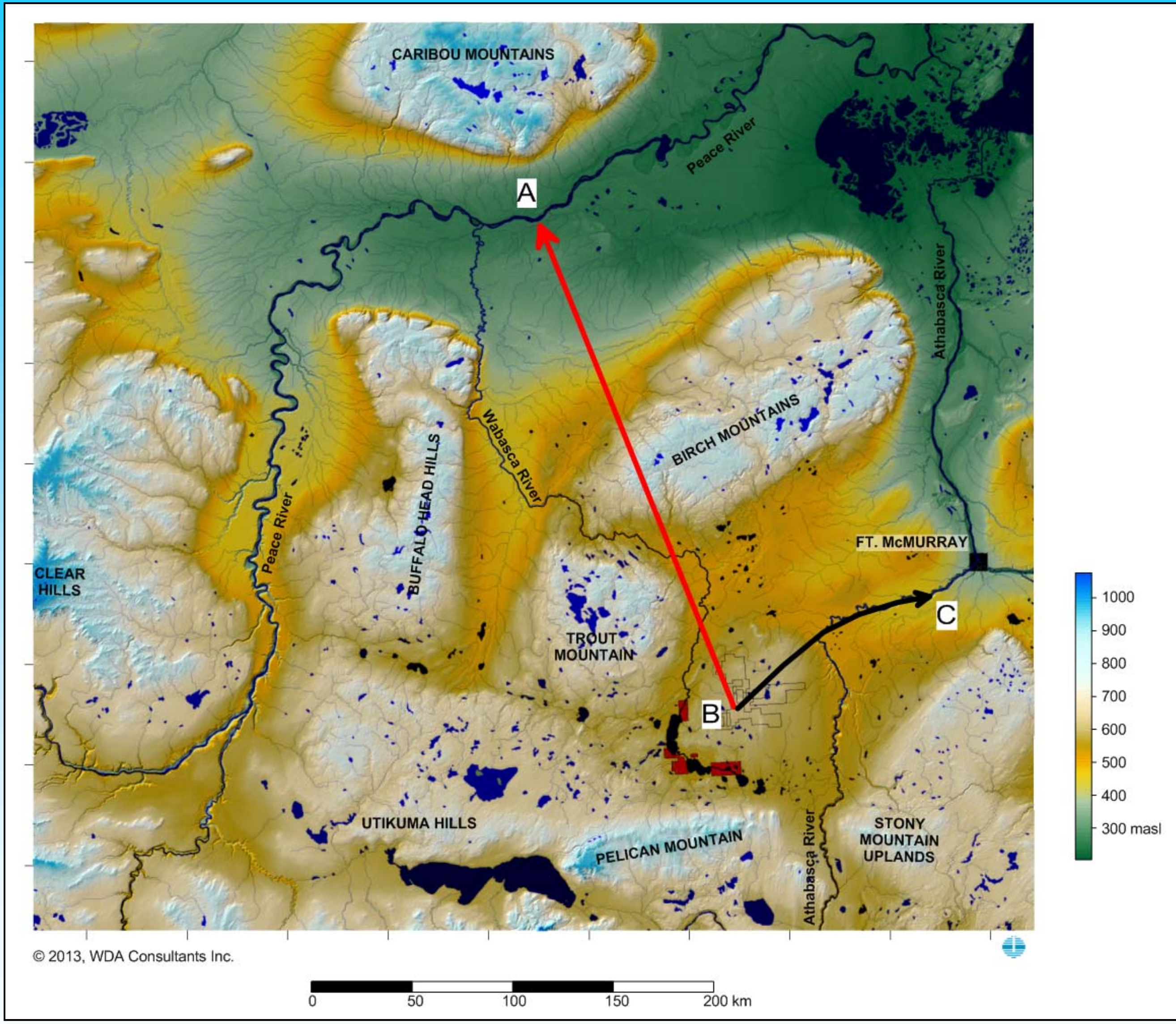


Schematic SW-NE stratigraphic section in the region of the Wabasca oil sands (Weyer et al., 2013, Fig. 15). The figure is highly exaggerated vertically. The actual SW-dip of the layers is about 1°. The Grosmont has been subdivided into A, B, C, D from the bottom up.

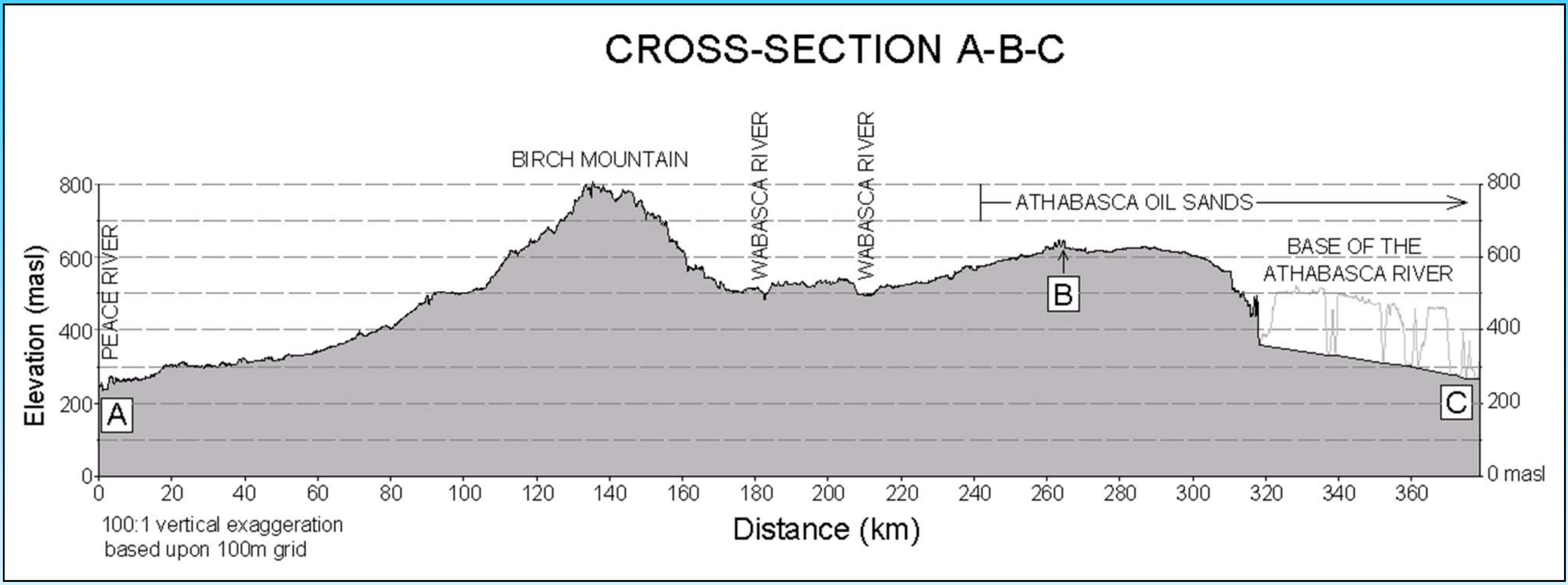


Schematic representation of the effect of scale on permeability in karst (modified after Kiraly, 1975, Fig. 19). Reported literature data for the Grosmont reservoir have been added indicating, together with the upwards-shifted trend curve by Kiraly, possible karst permeabilities in the hundreds of Darcies at the well scale. Extrapolating the Grosmont data speculatively to larger scales yields thousands of Darcies for a basin-scale network of karst conduits. Figure taken from Weyer et al., 2013, Figure 17

Wabasca oil sands: Regional groundwater flow



Regional Topography (groundwater table) and its reflection within cross-section A-B-C (next slide).



B-A: Part of Bachu's (1999) postulated long range groundwater flow system (compare previous slide); B-C topographical cross-section for schematic groundwater flow within the Grosmont from point B into the canyon of the Athabasca River.

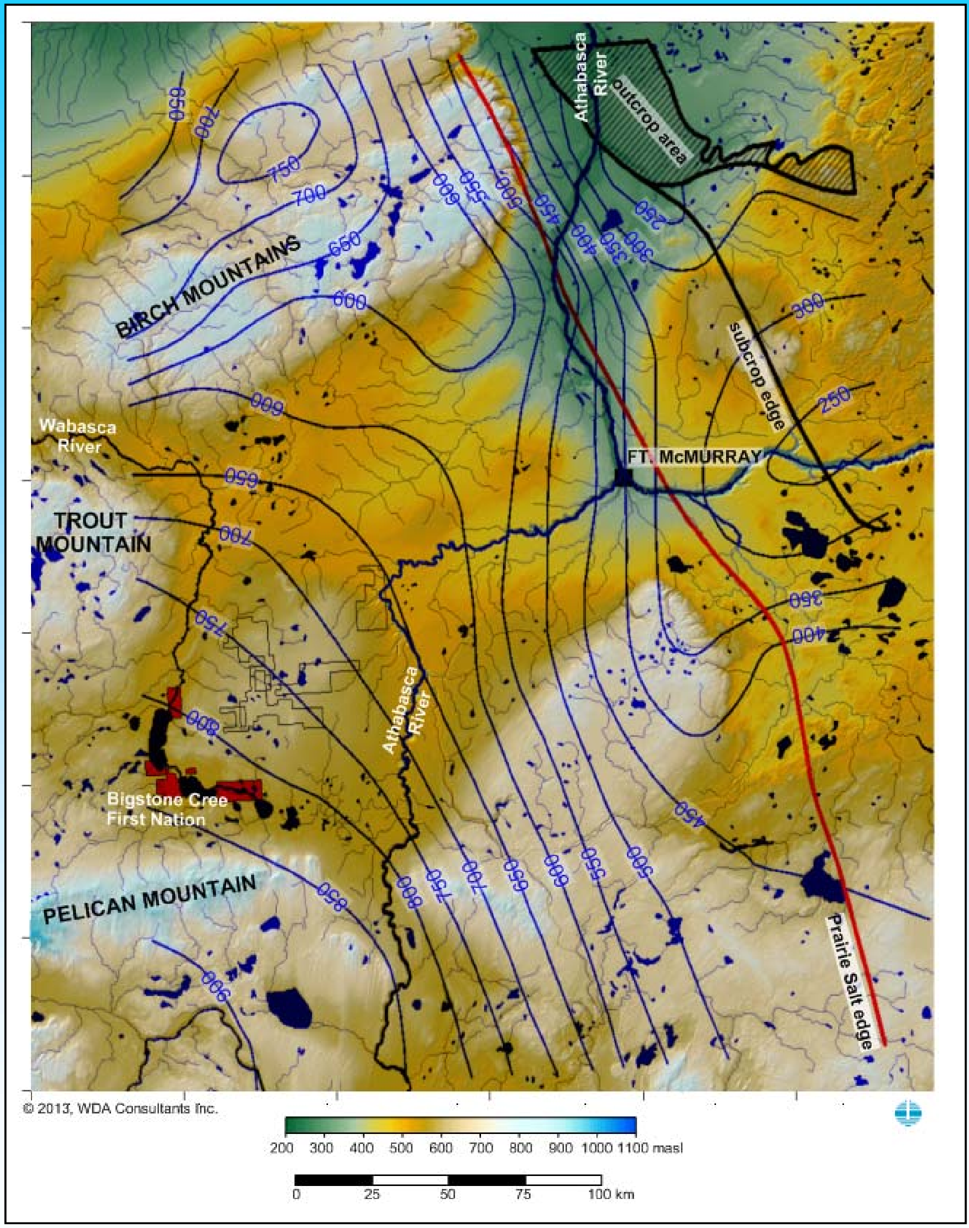
Eon	Era	Period		Group	Formation	Unit	System
				Stratigraphy		**Hydrostratigraphy**	
Phanerozoic	Ceno-zoic	Quaternary Tertiary			Pleistocene deposits	aquifer	
	Mesozoic	Cretaceous	Upper	Colorado	Colorado shale	aquitard	Colorado aquitard system
					2nd White Specks		
					Base of Fish Scales	aquitard	
			Lower		Viking	aquifer	
					Joli Fou	aquitard	
				Mannville	Grand Rapids	aquifer	Grand Rapids
					Clearwater	aquitard	Clearwater
						aquitard	McMurray - Wabiskaw aquifer/aquitard system
					McMurray	aquifer	
		Jurassic					
		Triassic					
	Paleozoic	Permian					
		Carboniferous			Sub-Cretaceous Unconformity		
		Devonian	Upper		Wabamun	aquifer	Winterburn - Wabamun aquifer system
					Winterburn	aquifer	
				Woodbend	Upper Ireton	aquitard	Upper Ireton
					Grosmont	aquifer	Grosmont
					Lower Ireton	aquitard	Lower Ireton
					Cooking Lake	aquifer	Beaverhill Lake - Cooking Lake aquifer system
				Beaverhill Lake	Waterways	aquifer - aquitard	
					Slave River	aquifer	
					Fort Vermillion	aquiclude	Prairie - Watt Mountain aquiclude system
			Middle	Elk Point — Upper	Watt Mountain	aquitard	
					Prairie	aquiclude	
					Winnipegosis (Keg River)	aquifer	Contact Rapids - Winnipegosis aquifer system
				Elk Point — Lower	Contact Rapids	aquifer - aquitard	
			Lower		Cold Lake	aquiclude	Lower Elk Point aquifer - aquiclude system
					Ernestina Lake	aquifer - aquitard	
					Upper Lotsberg	aquiclude	
					Lower Lotsberg	aquiclude	
					Basal Red Beds	aquifer - aquitard	Basal aquifer
		Silurian					
		Ordovician					
		Cambrian					
Pre-Cambrian						aquiclude	

Generalized stratigraphic and hydrostratigraphic units in Northeast Alberta (modified from Bachu and Underschultz, 1993 and Gue, 2012).

* head map

* head map

* head map

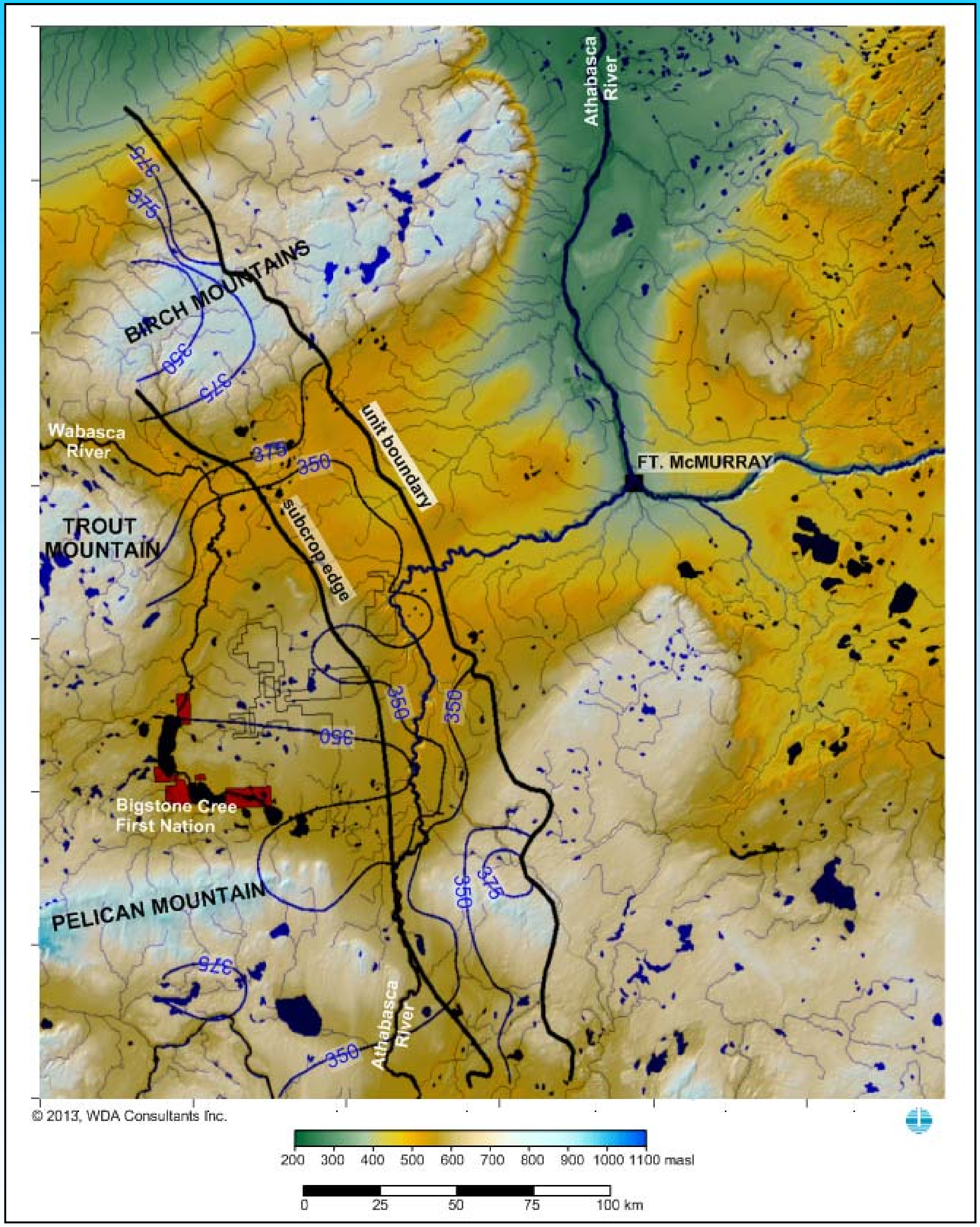


Pre-industrial hydraulic heads in the Contact Rapids/Winnipegosis aquifer system.

From Bachu et al. (1993, Figure 17b) with topography added indicating the elevation of the groundwater table.

Pre-industrial hydraulic heads in the Beaverhill Lake/Cooking Lake aquifer system.

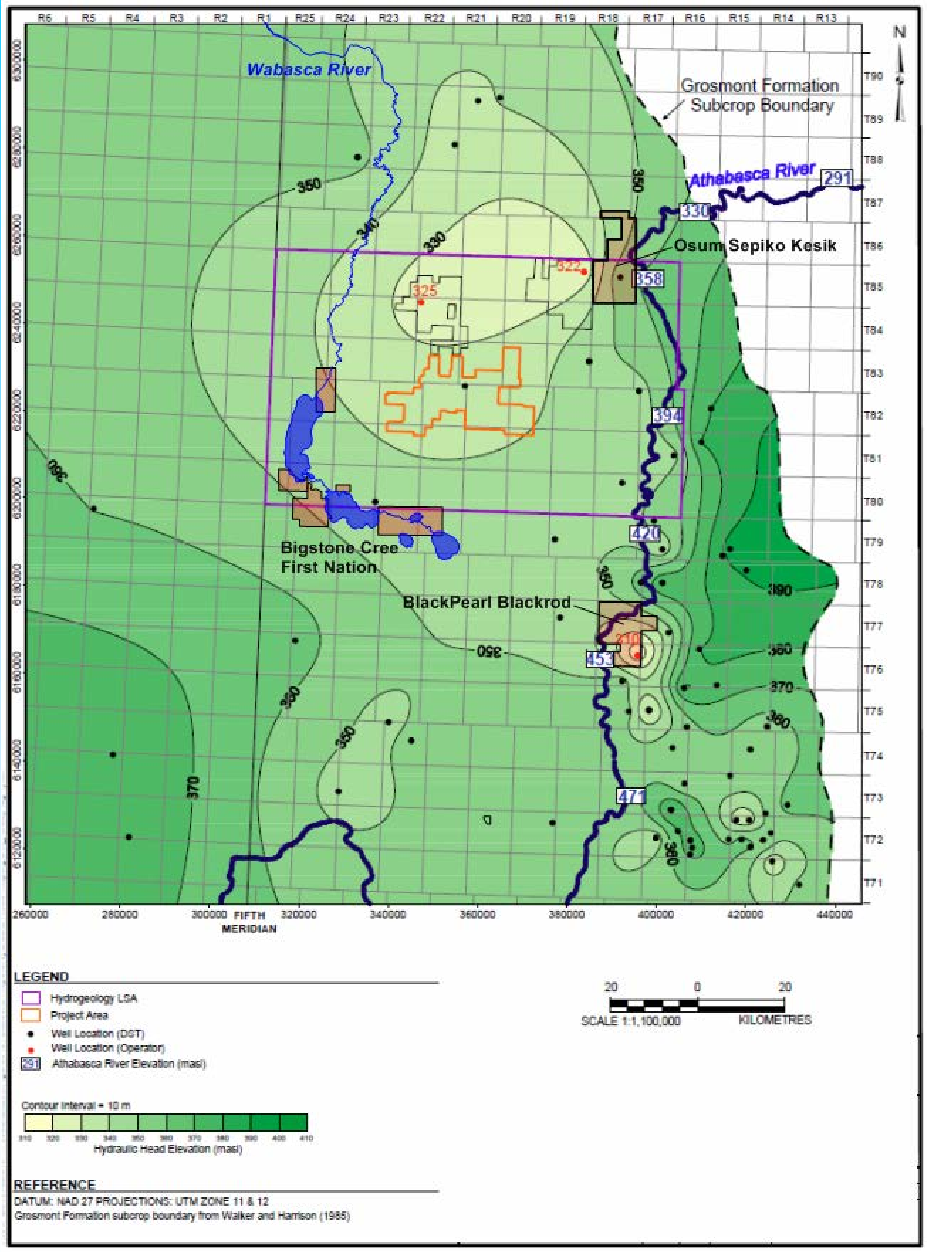
From Bachu et al. (1993, Figure 18b) with topography added indicating the elevation of the groundwater table.



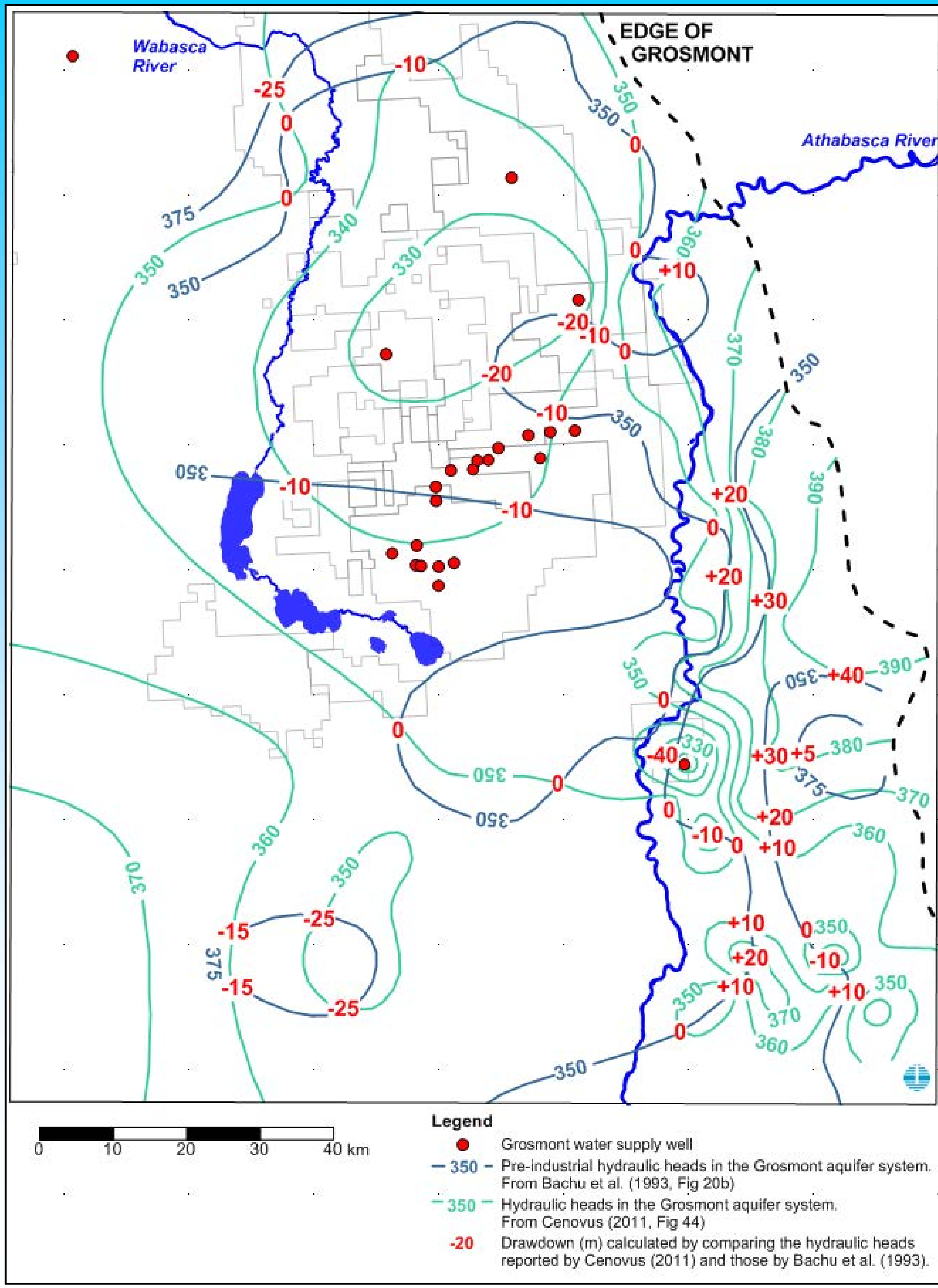
Pre-industrial hydraulic heads in the Grosmont aquifer system.

From Bachu et al. (1993, Figure 20b) with topography added indicating the elevation of the groundwater table.

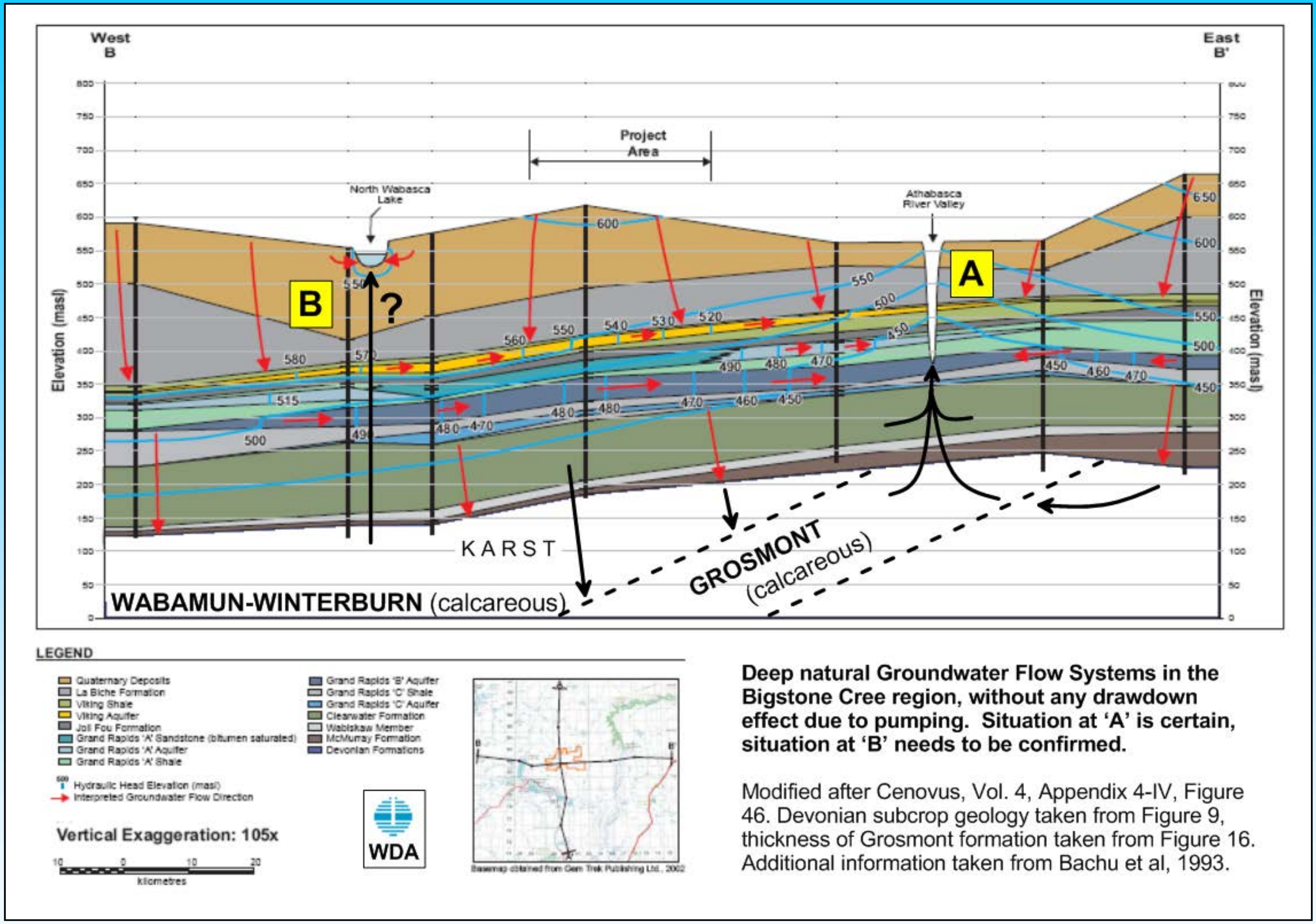
Effect of industrial activities



Hydraulic head distribution in the undifferentiated Grosmont formation. Modified from Cenovus (2011, Figure 44).



Head drawdown and rise (in m, red numbers) calculated by comparing the hydraulic heads from Cenovus (2011, Figure 44) and those by Bachu et al. (1993, Fig 20b).



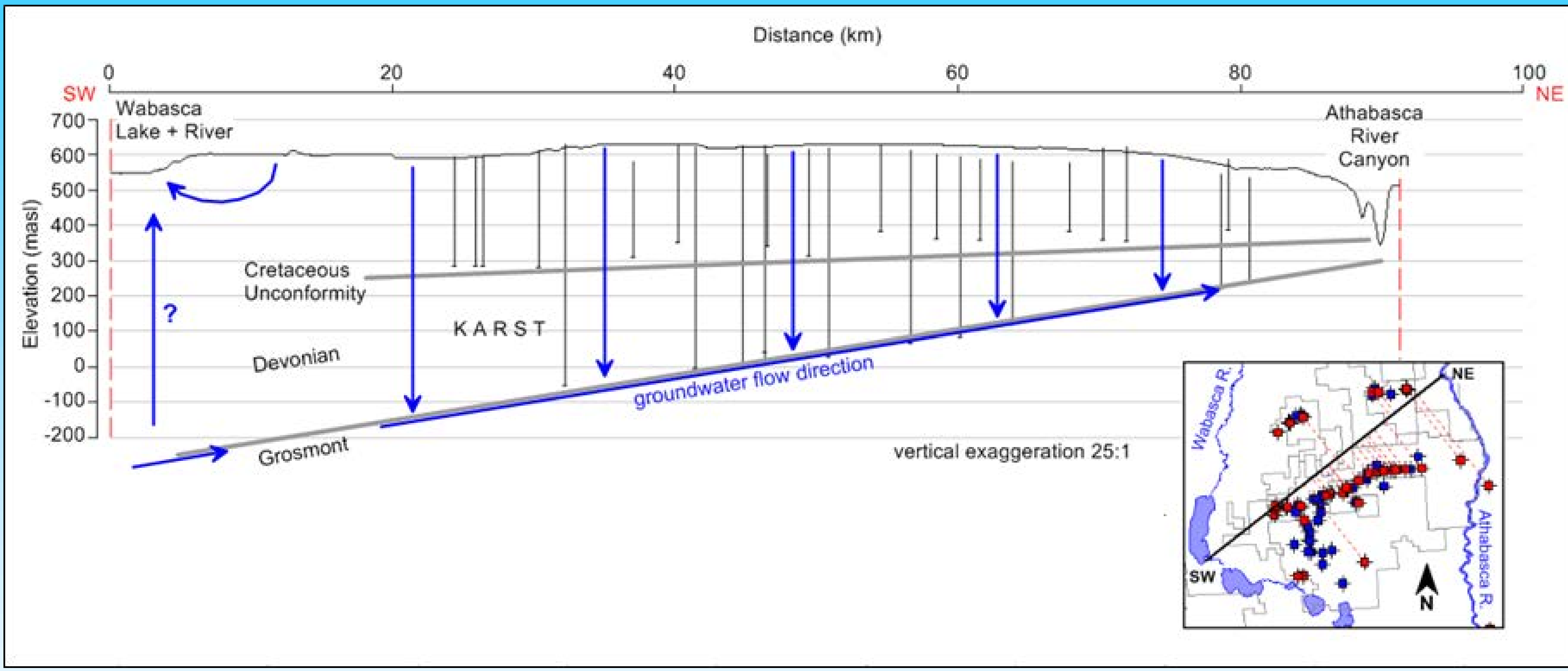
Pattern of regional groundwater flow systems in the area of the Wabasca oil sands. The cross-section has been adopted from Cenovus [2011] and shows the downward flow (red arrows) from the surface into the Devonian layers. The black arrows have been added to schematically show regional groundwater flow through the Devonian layers toward the Athabasca River and potentially to the Wabasca River.

REMINDER

Groundwater flow does not take the path of least resistance

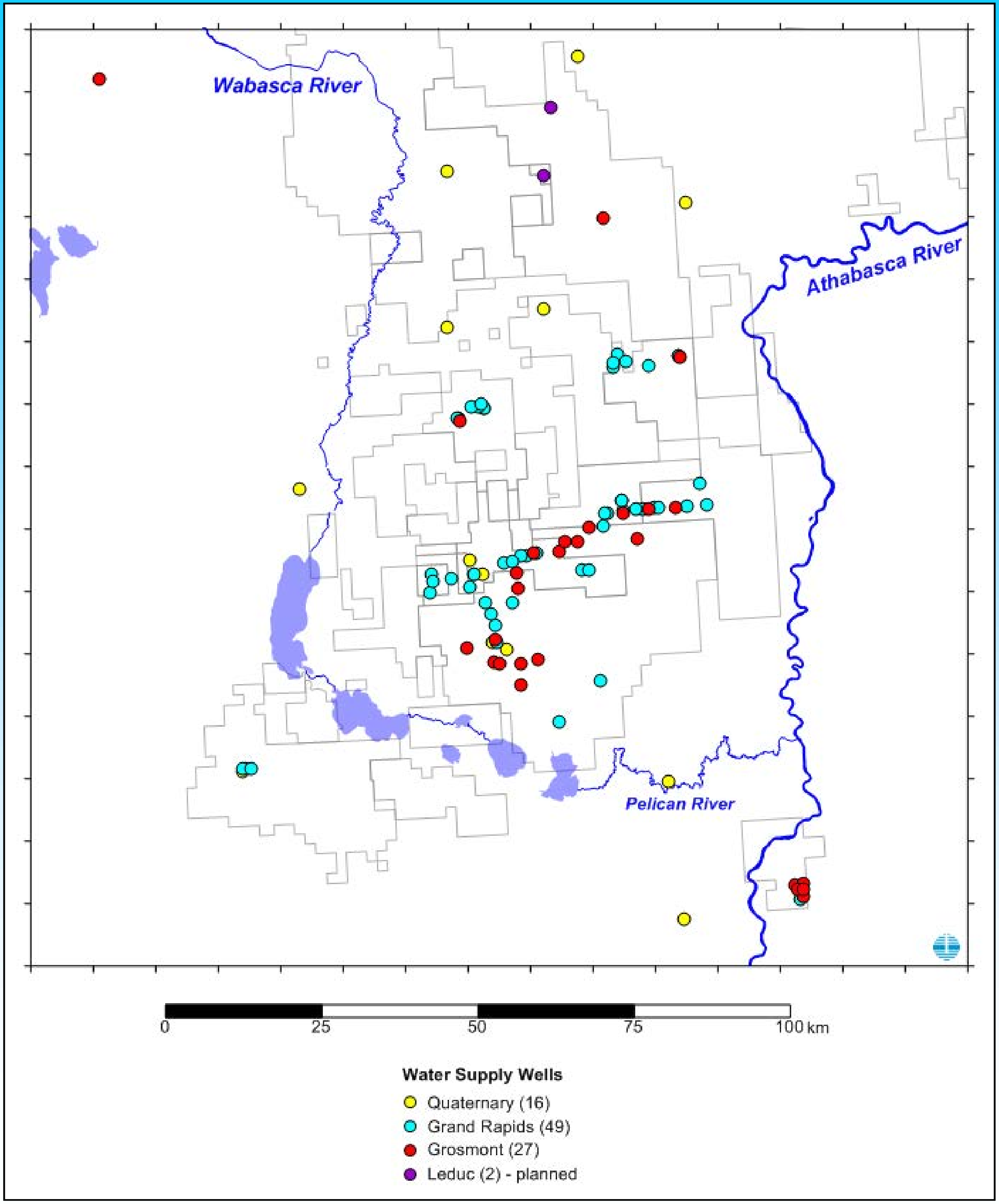
instead

the multitude of pathways are arranged such that the energy consumption in the total flow field is minimized

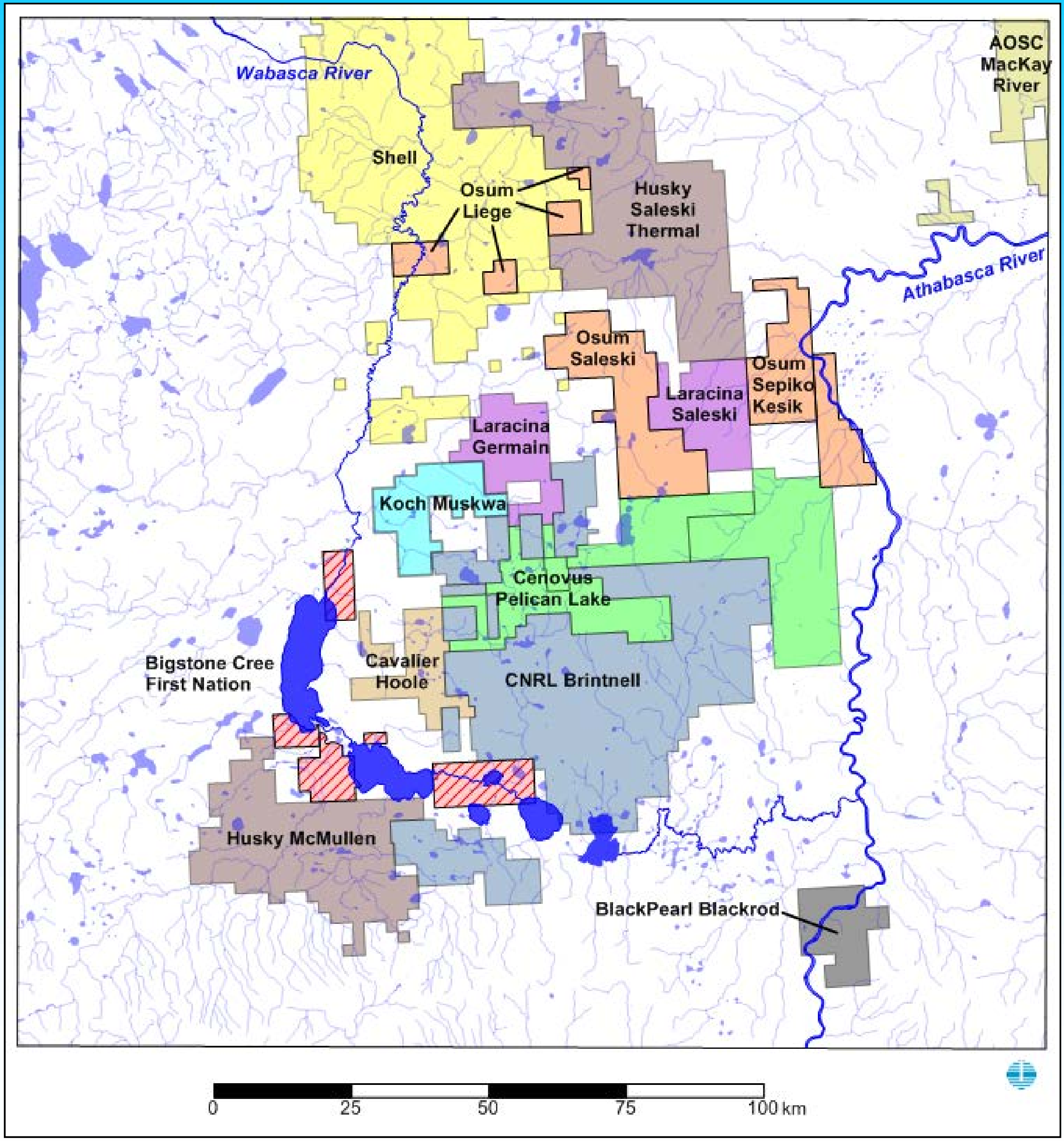


Schematic SW-NE cross-section from the town of Wabasca-Desmarais (SW) to the east bend of the Athabasca Canyon (NE) with deduced pre-industrial groundwater flow directions.

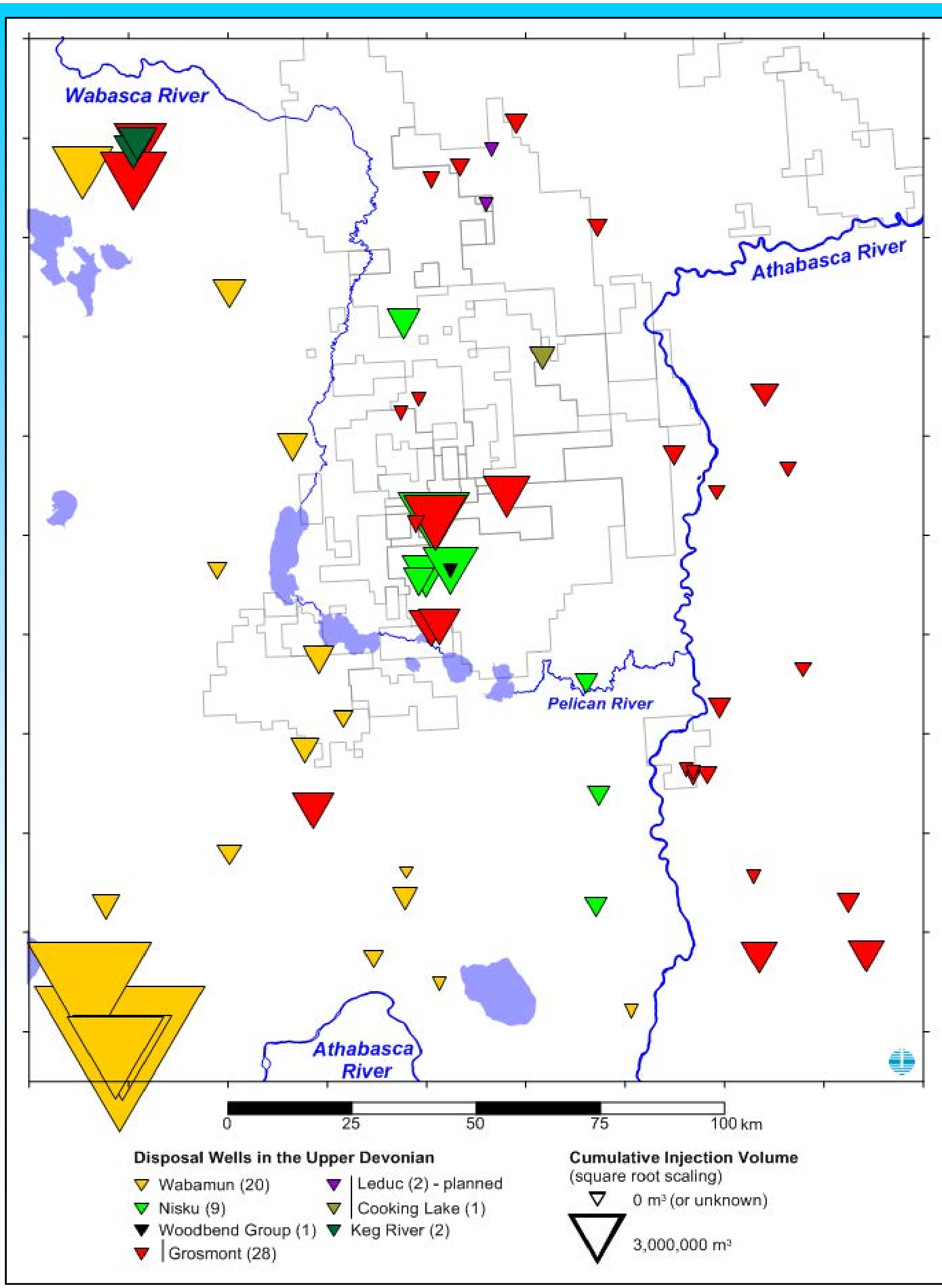
Water production and water injection



Map showing location of water production wells in the area of the Wabasca oil sands and surroundings

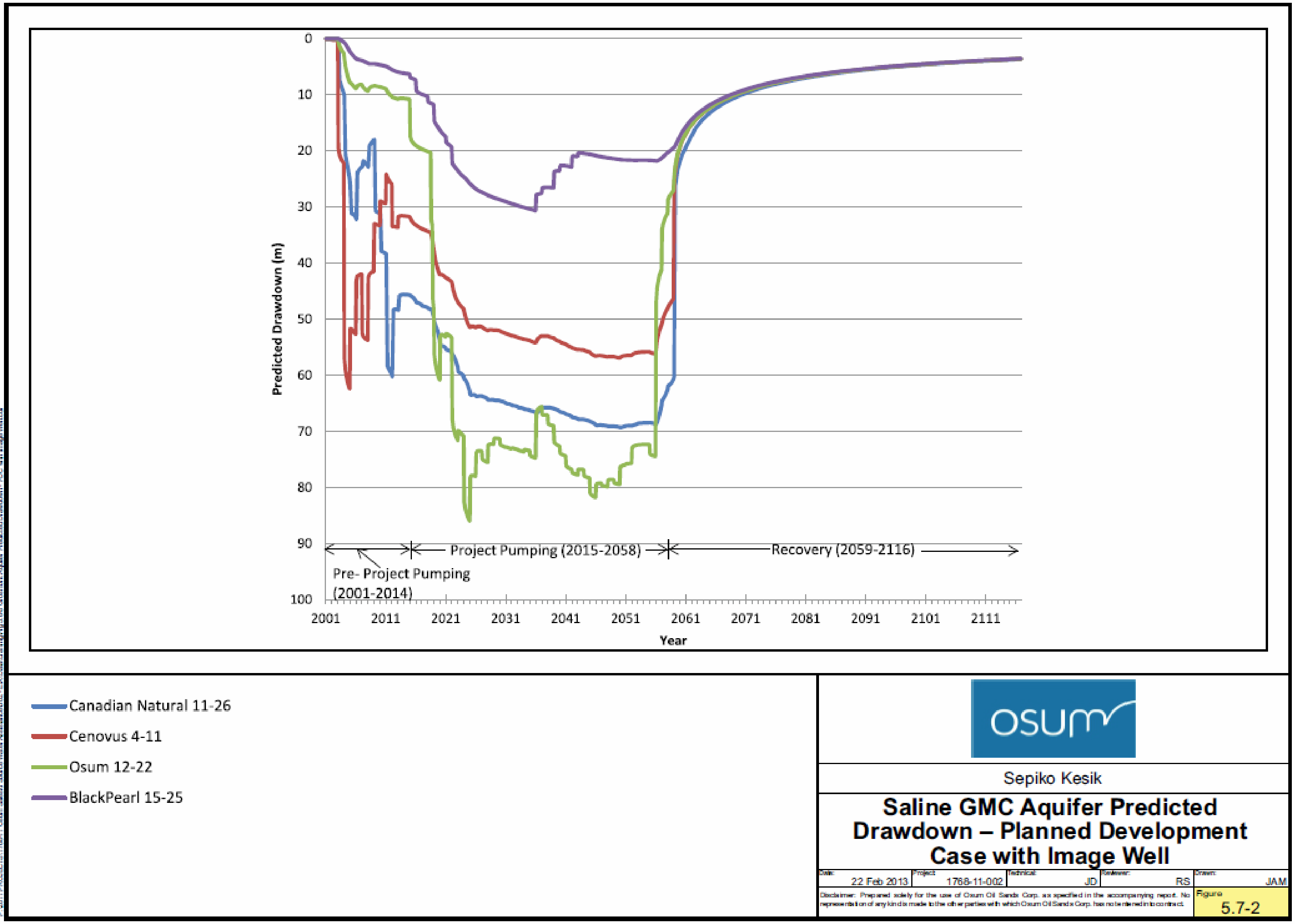


Oil leases in the Wabasca oil sands and vicinity



Location of injection wells targeting the Upper Devonian in the area of the Wabasca oil sands and surroundings

Between 1966 and 2011, approximately 86 million m^3 (approaching 0.1 km^3) of waste water have been injected into the area of the Wabasca oil sands and the nearby Upper Devonian aquifer system.



Drawdown predicted in the Grosmont C aquifer. From Osum, 2013, Fig 5.7-2

Increase of water production and waste water injection

While freshwater is regulated and has been recycled in the 80-95% range (Alberta Government, 2014), salt water has so far not been regulated although it is part of regional groundwater flow systems.

The EIAs [2010-2013] evaluated by us indicate that between 1966 and 2011, a cumulative injected waste water volume for the area of the Wabasca oil sands and the nearby Upper Devonian aquifer system of 86 million m^3 (approaching 0.1 km^3), most of it since the early 1980s.

According to NEB (2006, p.38), recycling in SAGD operations reuses 90 to 95 % of the water (using some fresh mixed with saline groundwater), but for every cubic metre of bitumen produced, about 0.2 cubic metres of additional groundwater must still be used. In the wake of the new SAGD developments, the amount of injection may increase significantly, as will the amount of water production.

Summary

1. Bear’s 1972 method of adding gravitationally driven flow and hydrostatic vertical buoyancy forces leads to misleading results.
2. ARC’s postulated groundwater ‘pipeline’ from Montana to Peace River does not exist.
3. Waste water injected within the Wabasca oil sands will not flow towards the Peace River, but towards the Athabasca River instead
4. Within the Wabasca oil sands area, recharged groundwater flows vertically downwards through the Quaternary, Tertiary, and Cretaceous layers into the karstic Devonian layers and from there through the highly permeable karstic Grosmont Formation towards the Athabasca canyon and into the Athabasca River.
5. Within the Birch Mountains, recharged groundwater penetrates as deep as the Contact Rapids Formation below the Prairie Evaporites. Part of the deep groundwater flow system discharges into the Athabasca River downstream of Fort McMurray.
6. In all likelihood groundwater discharge into the Wabasca River has already been affected by rearrangement of fluid potentials due to groundwater production and possibly also by injection. That effect may become more prominent with the expected significant increase in water production.

Moving Forward

- More attention needs to be directed towards the cumulative effect side of our work in the Wabasca oil sands
- The appropriate government agency should reinterpret the data generated for ARC's head distribution maps and add the location of the wells onto these maps.
- Dr. Hitchon to be contracted expediently to oversee a detailed determination of the extent of the low fluid potential drain in NE Alberta.
- In order to shed light onto the matter of horizontal flow in Cretaceous aquifers above the Grosmont, a suitable 2D vertical model to be calculated for flow lines stretching from beyond the town of Wabasca-Desmarais to the east bend of the Athabasca River Canyon and beyond.
- Groundwater-surface water interaction along the relevant parts of the Wabasca and Athabasca Rivers should be investigated.
- All data for water production and injection should be centrally collected and interpreted for fresh, brackish and saline groundwater.
- An encompassing numerical 3D-model should be developed for the Wabasca oil sands and the Grosmont, suited to determine cumulative effects and to adequately manage water production and injection by the various energy companies.

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