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Using a 3-D Geological Model and Petroleum Data Analyses to Help Mitigate Environmental Impacts of Heavy Oil and Bitumen Production

Alberta Energy Regulator

AGS ALBERTA GEOLOGICAL SURVEY

Introduction

The Alberta Energy Regulator (AER) ensures the safe, efficient, orderly, and environmentally responsible development of hydrocarbon resources over their entire life cycle. This includes allocating and conserving water resources, managing public lands, and protecting the environment while providing economic benefits for all Albertans.

In January 2014, a panel of AER hearing commissioners conducted an inquiry into odours and emissions from heavy oil and bitumen operations in the Peace River area of Alberta, referred to in this report as the Peace River proceedings. On March 31, 2014, the panel released *Decision 2014 ABAER 005: Report of Recommendations on Odours and Emissions in the Peace River Area* (Alberta Energy Regulator, 2014).

One of the panel's findings was that there was insufficient data with respect to the geology and petroleum chemistry of the heavy oil and bitumen in this area, resulting in the following recommendation:

That the AER conduct or require operators in the Peace River area to submit a geochemical analysis of the volatile compounds from the heavy oil from the Gordondale-sourced bitumen at surface prior to processing.

In addition to identifying a need for new data, the panel put forward a hypothesis: increased odours in the Peace River Oil Sands (PROS) area could be directly related to "higher levels of sulphur and volatile components" (Alberta Energy Regulator, 2014) in the oils, likely related to the contribution of Gordondale-sourced hydrocarbons.

The present study was initiated to help determine how and where such geochemical analyses would take place. This includes determining what components to analyze for, the methodologies of the analytical tests, sample collection methodology, the number of samples to collect, and the location of the samples. The study also tests the panel's hypothesis. To accomplish this, we did the following:

- created a three-dimensional (3-D) geological model of the PROS area to delineate the subsurface geology and identify complex geological characteristics that might separate the oils in this area,
- designed and implemented a fluid petroleum sampling program to identify the source-rock contributions and the compounds which may contribute to the odours and emissions, and
- determined the geological extent of plays and heavy oil and bitumen deposit boundaries to aid regulatory response in the area.

For more information about the Peace River proceeding visit www.aer.ca/applications-and-notices/hearings/proceeding-1769924.

Location

Alberta is a province in Canada (Figure 1). The southern part of the province shares a border with the United States (Montana). The province covers an area of approximately 660 000 km² (~255 000 square miles). The oil sands deposits are located in the northern part of the province, and the administrative areas for oil sands deposits are shown in Figure 2. This study focuses on the PROS area, specifically the smaller recommendation areas defined by the hearing panel (Figure 3). The 3-D geological model area is shown on Figures 2 and 3.

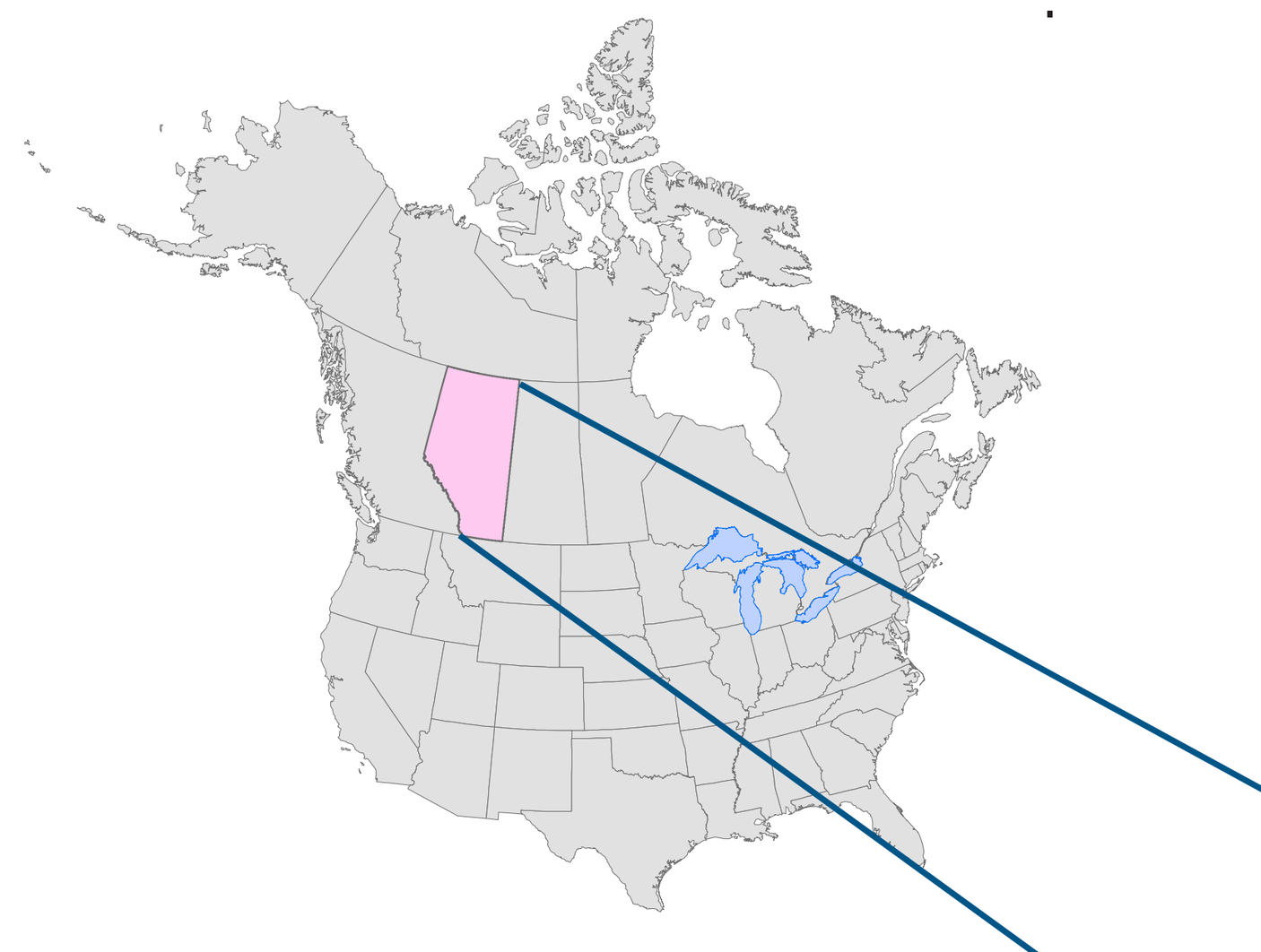

Figure 1. Location of the province of Alberta within Canada and the North American continent.

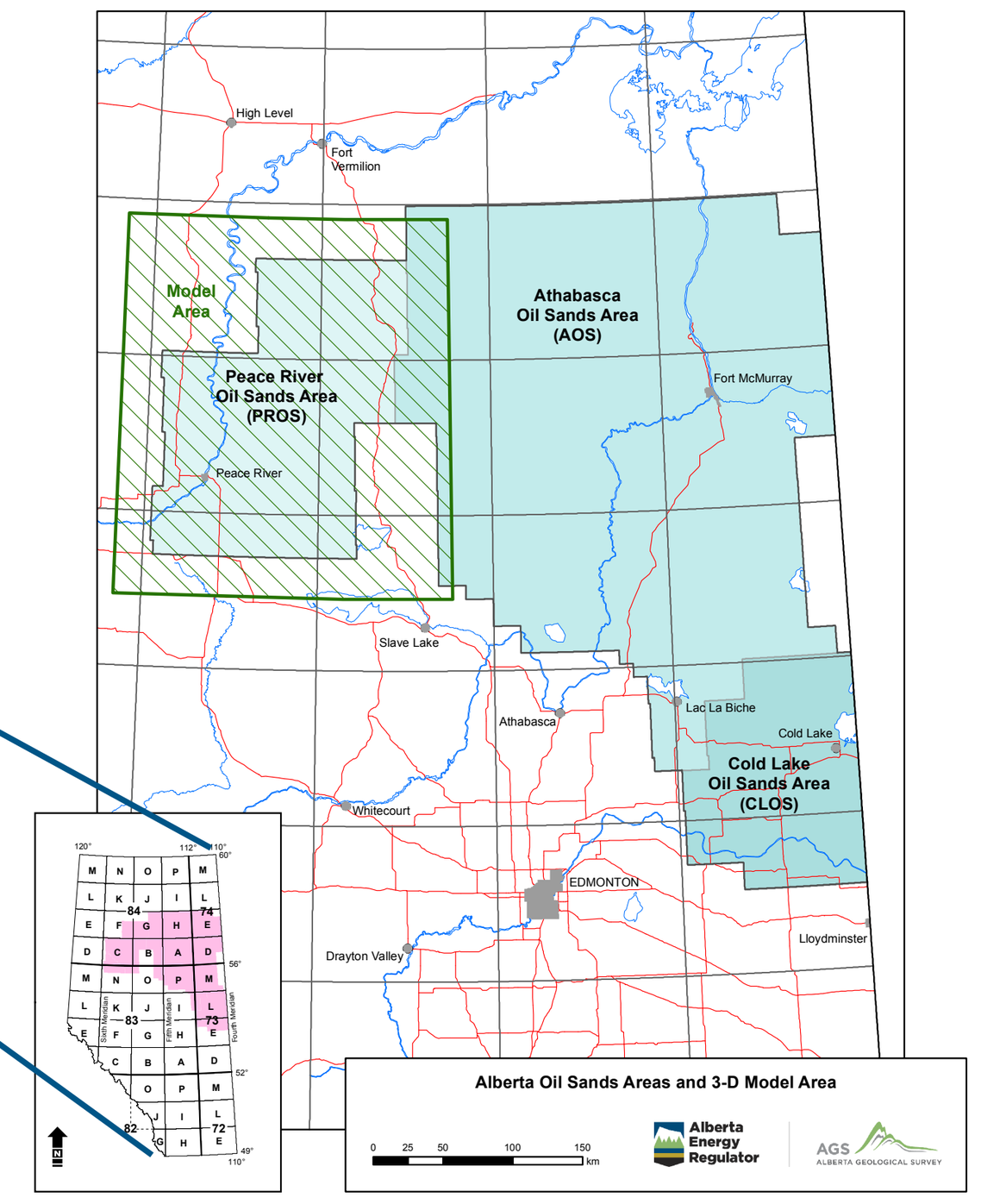

Figure 2. Map of the oil sands areas in Alberta and the 3-D model area. There are three oil sands areas (OSAs) defined by the AER: the Peace River Oil Sands (PROS) Area, the Athabasca Oil Sands (AOS) Area, and the Cold Lake Oil Sands (CLOS) Area. These defined areas are used to regulate and administrate heavy oil and bitumen deposits in the province. A 3-D geological model was used to visualize the complex arrangement of geological units and to analyze data in 3-D space in the PROS area. The model area was chosen based on the geographic extent of the PROS area with a buffer on each side

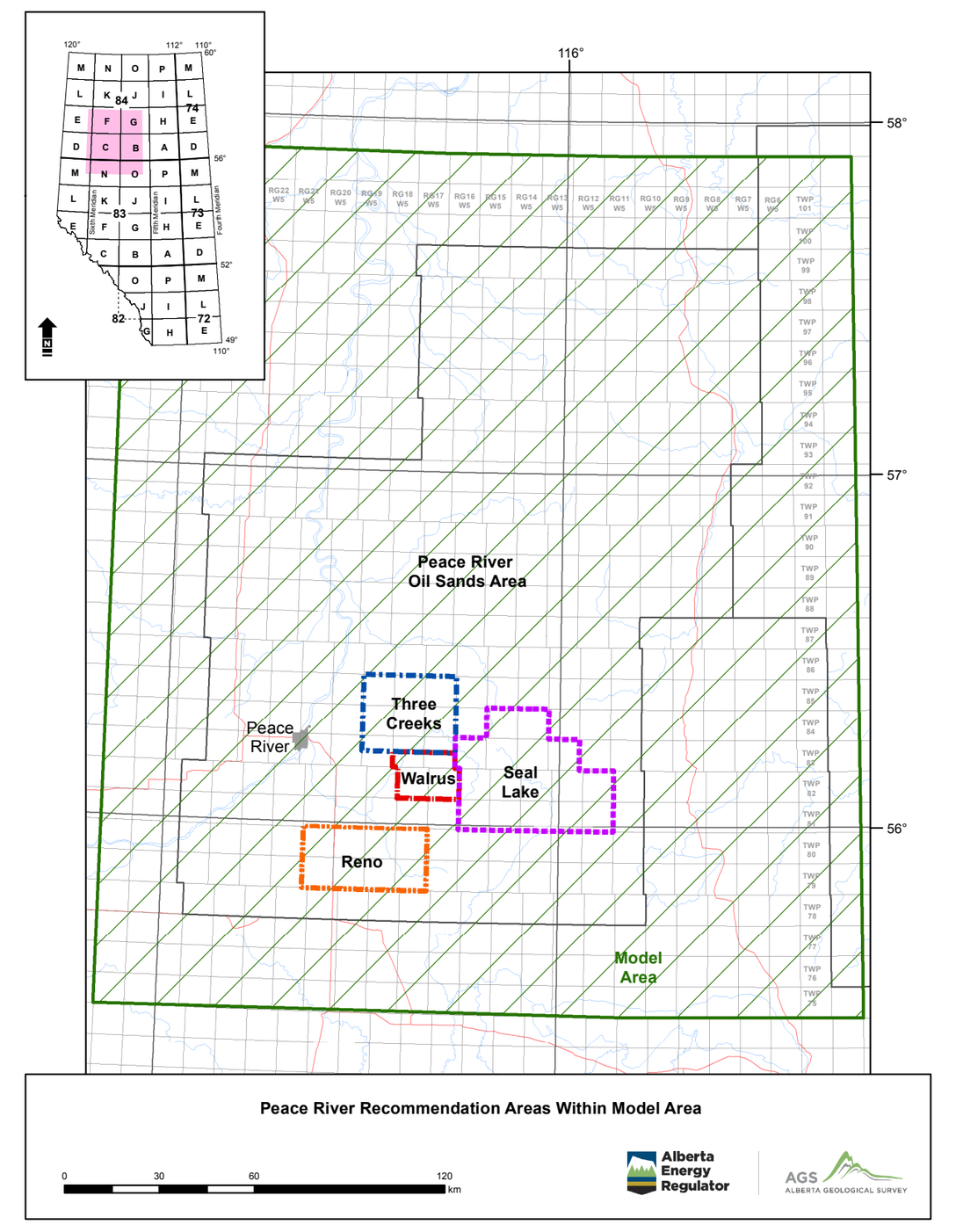

Figure 3. Map of the recommendation areas within the 3-D model area. The Peace River proceedings introduced four smaller recommendation areas defined within the PROS area: Three Creeks, Walrus, Seal Lake, and Reno.

Terminology

Geological Play

A set of known or postulated oil or gas accumulations (pools and deposits) within a petroleum system sharing similar geochemical, geological, geographic, and temporal properties. These properties can include reservoir lithology and facies and trapping mechanisms. Geological plays occur below the ground surface and can be represented at the surface by geographic boundaries, which represent the lateral extent of the geological elements that define it in the subsurface. In this study, the geological plays are approximately equivalent to the geological formation.

Heavy Oil and Bitumen Deposit

The area within a play where known or postulated heavy oil and bitumen accumulations have similar characteristics and have the potential to be an economic resource now or in the near future. Heavy oil and bitumen deposits are determined using log analysis based on current technology and can therefore change over time.

Heavy Oil and Bitumen Scientific Definitions

- Natural bitumen have densities >1000 kg/m³ (<10 API gravity) and viscosities >10 000 cP (Kashirtsev and Hein, 2012).
- Heavy oils and extra-heavy oils have densities >934 kg/m³ (<20 API gravity) and viscosities between 1000 and 10 000 cP (Kashirtsev and Hein, 2012).

Heavy Oil and Bitumen Regulatory Definitions

- Crude oil with a density greater than or equal to 900 kilograms per cubic metre (kg/m³) is classified as "heavy."
- Crude bitumen is extra-heavy oil that will not flow to a well in its natural state.
- Any heavy oil or crude bitumen found within designated oil sands geological formations and within the oil sands areas is designated as "oil sands" for administrative purposes.

Heavy Oil and Bitumen Definitions for This Study

- "Heavy oils" have densities between 900 and 950 km/m³.
- "Oil sands designated heavy oil and bitumen" have densities ≥950 kg/m³ and viscosities ≥1000 cP.

Odour

A compound in a gaseous concentration strong enough to be detected by olfactory receptors lining the nose. Odours are often expelled from solids or liquids through sublimation, evaporation, or boiling.

Odour Threshold

The concentration at which a compound may be detected by olfactory receptors and become odorous. Odour thresholds can be determined by different methods, resulting in a broad range of thresholds (Ruth, 1986). For consistency, this study uses mostly the threshold values listed in Nagata (2003) (Table 1).

Observations About Odourous Compounds

Observations about the potential for a sample to be more odorous are based on the number of times the measured compounds exceeded the odour threshold. It is assumed here that the more times the compound concentration was over the threshold, the more likely it was to remain odorous when diluted in air. Odour thresholds are not available for all compounds tested.

Table 1. Odour thresholds (Nagata, 2003) for compounds analyzed in this study. Compounds without measured thresholds or that are odourless are not included in the table. RSC is reduced sulphur compound. VOC is volatile organic compound. (* Odour thresholds are for single-bonded (alkane) hydrocarbons only)

Compound	Odour Threshold	Unit of Measure	Compound Group
1-Butene	0.36	ppmv	C1-C4
Propylene	13	ppmv	C1-C4
n-Butane	1200	ppmv	C1-C4
n-Propane	1500	ppmv	C1-C4
iC5	0.000	frac	C1-C7+*
C5	0.000	frac	C1-C7+*
C6	0.000	frac	C1-C7+*
C2	0.001	frac	C1-C7+*
C4	0.001	frac	C1-C7+*
C3	0.002	frac	C1-C7+*
Butyl mercaptan	0.003	ppbv	RSC
Isopropyl mercaptan	0.006	ppbv	RSC
Ethyl mercaptan	0.009	ppbv	RSC
Propyl mercaptan	0.013	ppbv	RSC
tert-Butyl mercaptan	0.029	ppbv	RSC
Methyl mercaptan	0.07	ppbv	RSC
Hydrogen sulphide	0.41	ppbv	RSC
Thiophene	0.56	ppbv	RSC
Dimethyl disulphide	2.2	ppbv	RSC
Dimethyl sulphide	3	ppbv	RSC
Carbonyl sulphide	55	ppbv	RSC
Carbon disulphide	210	ppbv	RSC
N-butyl Mercaptan	0.003	ppbv	TSA
Isopropyl mercaptan	0.006	ppbv	TSA
Isobutyl mercaptan	0.007	ppbv	TSA
Ethyl mercaptan	0.009	ppbv	TSA
n-Propylmercaptan	0.013	ppbv	TSA
tert-Butyl mercaptan	0.029	ppbv	TSA
Diethyl sulphide	0.033	ppbv	TSA
Methyl mercaptan	0.07	ppbv	TSA
Hydrogen sulphide	0.41	ppbv	TSA
Thiophene	0.56	ppbv	TSA
Diethyl disulphide	2	ppbv	TSA
Dimethyl disulphide	2.2	ppbv	TSA
Dimethyl sulphide	3	ppbv	TSA
Carbonyl sulphide	55	ppbv	TSA
p-Diethylbenzene	0.39	ppbv	VOC
Acrolein	3.6	ppbv	VOC
n-Propylbenzene	3.8	ppbv	VOC
p-Ethyltoluene	8.3	ppbv	VOC
Isopropylbenzene	8.4	ppbv	VOC
m-Ethyltoluene	18	ppbv	VOC
Methyl butyl ketone	24	ppbv	VOC
Styrene	35	ppbv	VOC
Isoprene	48	ppbv	VOC
m-Diethylbenzene	70	ppbv	VOC
o-Ethyltoluene	74	ppbv	VOC
1-Pentene	100	ppbv	VOC
2-Methylheptane	110	ppbv	VOC
n-Dodecane	110	ppbv	VOC
1,2,4-Trimethylbenzene	120	ppbv	VOC
1-Hexene	140	ppbv	VOC
Methylcyclohexane	150	ppbv	VOC
1,3,5-Trimethylbenzene	170	ppbv	VOC
Ethylbenzene	170	ppbv	VOC
Methyl isobutyl ketone	170	ppbv	VOC
Carbon disulfide	210	ppbv	VOC
Methyl methacrylate	210	ppbv	VOC
1,3-Butadiene	230	ppbv	VOC
Toluene	330	ppbv	VOC
1-Butene	360	ppbv	VOC
o-Xylene	380	ppbv	VOC
2,3-Dimethylbutane	420	ppbv	VOC
2-Methylhexane	420	ppbv	VOC
Methyl ethyl ketone	440	ppbv	VOC
Ethanol	520	ppbv	VOC
n-Decane	620	ppbv	VOC
2,2,4-Trimethylpentane	670	ppbv	VOC
n-Heptane	670	ppbv	VOC
Tetrachloroethylene	770	ppbv	VOC
3-Methylhexane	840	ppbv	VOC
Ethyl acetate	870	ppbv	VOC
n-Undecane	870	ppbv	VOC
2,4-Dimethylpentane	940	ppbv	VOC
Isopentane	1300	ppbv	VOC
n-Pentane	1400	ppbv	VOC
3-Methylheptane	1500	ppbv	VOC
n-Hexane	1500	ppbv	VOC
Methylcyclopentane	1700	ppbv	VOC
n-Octane	1700	ppbv	VOC
n-Nonane	2200	ppbv	VOC
Cyclohexane	2500	ppbv	VOC
Benzene	2700	ppbv	VOC
Chloroform	3800	ppbv	VOC
Trichloroethylene	3900	ppbv	VOC
2,3-Dimethylpentane	4500	ppbv	VOC
Carbon tetrachloride	4600	ppbv	VOC
2-Methylpentane	7000	ppbv	VOC
3-Methylpentane	8900	ppbv	VOC
2,2-Dimethylbutane	20000	ppbv	VOC
Isopropyl alcohol	26000	ppbv	VOC
Acetone	42000	ppbv	VOC
n-Butane	1200000	ppbv	VOC

Geology

The reservoirs containing designated oil sands deposits (designated by the AER) in the PROS area centre around and are controlled by the paleotopography of the sub-Cretaceous angular unconformity (Sub-K). This unconformity separates the lower, but older, passive margin succession from the upper, but younger, foreland basin succession in the Western Canada Sedimentary Basin (WCSB). An important feature to the oil sands designated heavy oil and bitumen in the PROS area is the Red Earth Highlands (Figure 4). This feature was a paleotopographic high during early Cretaceous sedimentation, discussed in Hubbard et al. (1999). The tectonostratigraphic history of the WCSB, as it applies to the oil and gas deposits in the PROS area, is summarized by Berbesi et al. (2012).

Summary of Relevant Geological Units and Surfaces

Upper Devonian to Lower Mississippian Exshaw Formation – a source rock that has contributed hydrocarbons to the oil sands deposits in the PROS area. It consists primarily of black shale deposited in a deep marine environment. The Exshaw Formation subcrop area is located on the northeastern edge of the Red Earth Highlands (Figure 4).

Mississippian Pekisko and Debolt Formations – secondary hosts of oil sands deposits in the PROS area. In this area, both formations are primarily composed of marine limestone that has undergone intensive dolomitization near the Sub-K, resulting in vuggy carbonate reservoirs. The Debolt Formation can be subdivided into an upper, middle, and lower unit. The upper Debolt is composed of limestone and dolostone overlying a regional anhydrite bed that pinches out to the northeast (Figure 5). The middle and lower Debolt are composed of argillaceous and clean carbonates, respectively. The Pekisko and Debolt formations both have subcrop areas within the Red Earth Highlands area, where they come into contact with the Bluesky and Gething formations (Figures 4 and 5).

Permian Belloy Formation – secondary host of the oil sands deposits in the PROS area, primarily composed of sandstone deposited in a shallow marine environment. The Belloy subcrop area is located at the southwestern edge of the Red Earth Highlands, putting it in direct contact with the Bluesky and Gething formations (Figures 4 and 5).

Jurassic Gordondale Member (Historically the Nordegg Member Shale) of the Fernie Formation – a source rock that has contributed hydrocarbons to the PROS area, including the oil sands deposits (Creaney and Allan, 1992). It consists of variously phosphatic limestones, including calcitic mudstone, calcilutite, and calcarenite, deposited in a marine environment (Asgar-Deen et al., 2004). The Gordondale Member is partially overlain by the other shales of the Fernie Formation and by the Gething Formation fluvial deposits in the PROS area. The Gordondale Member subcrops at the Sub-K in the Reno area and the southwest corner of the Three Creeks area (Figure 4).

Together, the Gordondale Member and Exshaw Formation are considered to be the main source rocks for the oil sands deposits in the PROS area. The contribution of both of these strata to the oil sands deposits has been in debate for many years. Complications with determining source-rock contribution stem from the influence of biodegradation on the geochemical signature of heavy oil and bitumen.

Sub-Cretaceous Unconformity (Sub-K) – divides Cretaceous rocks from older rocks, as mentioned above. Due to the angular nature of this unconformity, a number of underlying formations are in contact with Cretaceous units at this unconformity surface (Figure 5).

Lower Cretaceous Gething Formation – secondary host of oil sands deposits in the PROS area. It consists of sandstone and mudstone deposited in a fluvial environment. The Gething Formation is overlain by Wilrich Member shale of the Spirit River Formation where the overlying Bluesky Formation is absent. The Gething is underlain in some areas by the Cadomin Formation or is in direct contact with the Sub-K, where it overlies several older geological units. Gething Formation deposition was controlled by the Red Earth Highlands.

Lower Cretaceous Bluesky Formation – the primary host of the oil sands designated heavy oil and bitumen in the PROS area. It consists of sandstone and mudstone deposited in a shoreline to shallow shelf environment, with the main reservoir sands deposited in a wave-dominated estuarine environment. The Bluesky is overlain by Wilrich Member shale of the Spirit River Formation (within the Fort St. John Group) and underlain by Gething Formation fluvial deposits. Deposition of the Bluesky was controlled by the Red Earth Highlands, separating deposition in the northeast from the southwest (Figure 5). Oil sands production is currently occurring mainly in the southwest, with only minor exploration occurring in the northeast.

Bluesky-Gething – Oil sands deposits contained in the Bluesky and Gething formations are often referred to together in literature as the Bluesky-Gething deposits, and this is the terminology used in this report. A gross isopach map of the Bluesky-Gething shows thinning to complete absence of the unit in the area of the Red Earth Highlands, highlighting the influence of this paleotopographic feature on deposition (Figure 6). A net pay map displays the thickness of bitumen-saturated sands using a ≥6% mass bitumen cut-off (Figure 7). The sands range in character from relatively clean and homogeneous to finely laminated. Homogeneous sands may also be separated by several metres of shale.

References

Alberta Energy Regulator (2014): Decision 2014 ABAER 005: report of recommendations on odours and emissions in the Peace River area; Alberta Energy Regulator, 74 p., URL <http://www.aer.ca/documents/decisions/2014/2014-ABAER-005.pdf> [February 2015].

Asgar-Deen, M., Riediger, C. and Hall, R. (2004): The Gordondale Member: designation of a new member in the Fernie Formation to replace the informal "Nordegg Member" nomenclature of the subsurface of west-central Alberta; Bulletin of Canadian Petroleum Geology, v. 52, no. 2, p. 201–214.

Berbesi, L.A., di Primio, R., Anka, Z., Horsfield, B. and Higley, D.K. (2012): Source rock contributions to the Lower Cretaceous heavy oil accumulations in Alberta: a basin modeling study; American Association of Petroleum Geologists Bulletin, v. 96, no. 7, p. 1211–1234.

Creaney, S. and Allan, J. (1992): Petroleum systems in the Foreland Basin of western Canada; *in* Foreland basins and fold belts, R.W. Macqueen and D.A. Leckie (ed.), American Association of Petroleum Geologists, Memoir 55, p. 279–307.

Hubbard, S.M., Pemberton, S.G. and Howard, A.E. (1999): Regional geology and sedimentology of the basal Cretaceous Peace River Oil Sands deposit, north-central Alberta; Bulletin of Canadian Petroleum Geology, v. 47, no. 3, p. 270–297.

Kashirtsev, V.A. and Hein, F.J. (2012): Overview of natural bitumen fields of the Siberian platform, Olenek uplift, Eastern Siberia, Russia; *in* AAPG studies in geology #64: heavy-oil and oil-sand petroleum systems in Alberta and beyond, F. J. Hein, D. Leckie, S. Larter, and J. R. Suter (ed.), American Association of Petroleum Geologists, p. 509–529.

Nagata, Y. (2003): Measurement of odor threshold by triangle odor bag method; Journal of Japan Air Cleaning Association, v. 41, no. 2, p. 17–25.

Ruth, J.H. (1986): Odour thresholds and irritation levels of several chemical substances: a review; American Industrial Hygiene Association, v. 47, p. 142–151.

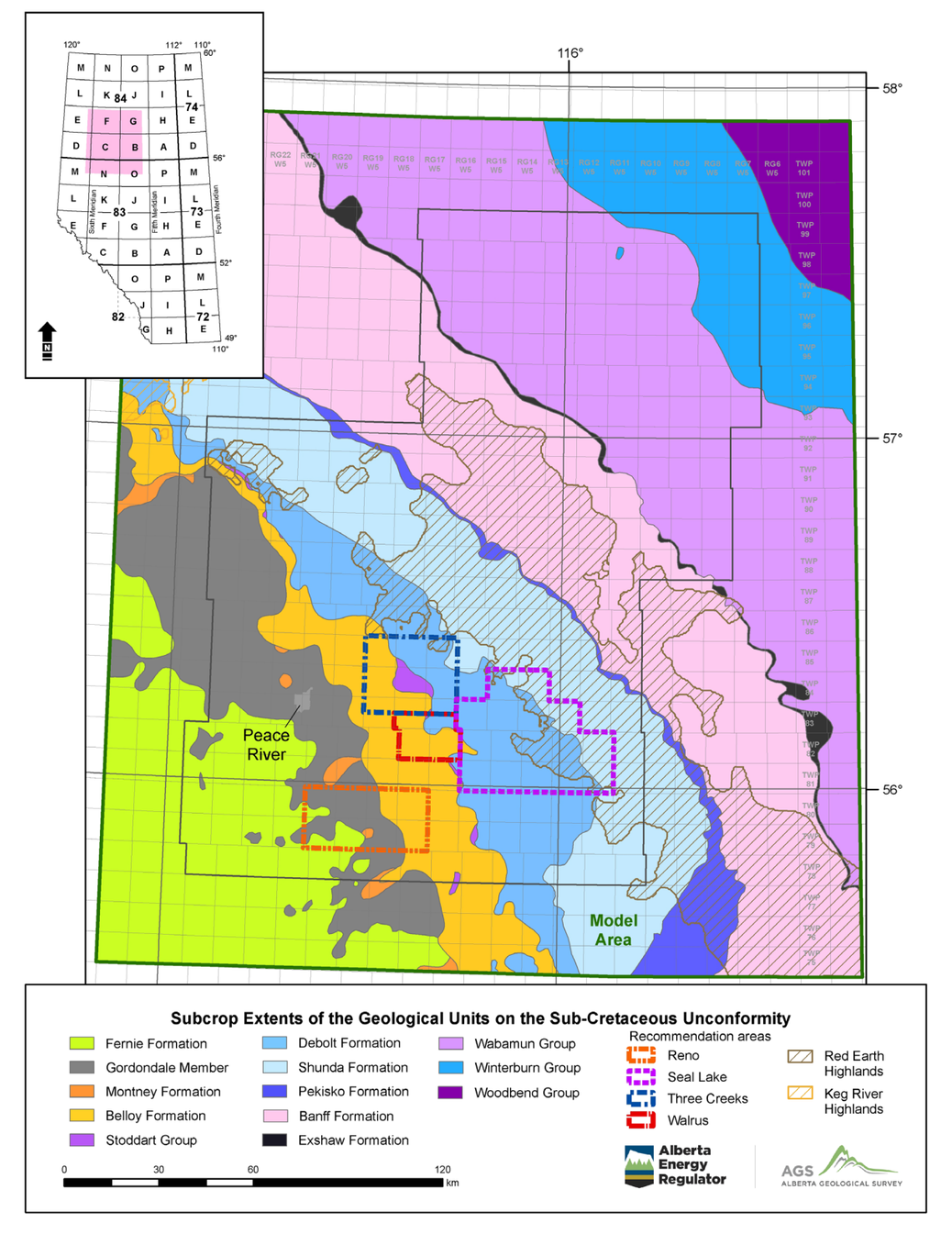

Figure 4. Map showing the subcrop areas of the geological units on the sub-Cretaceous unconformity, derived from the 3-D geological model.

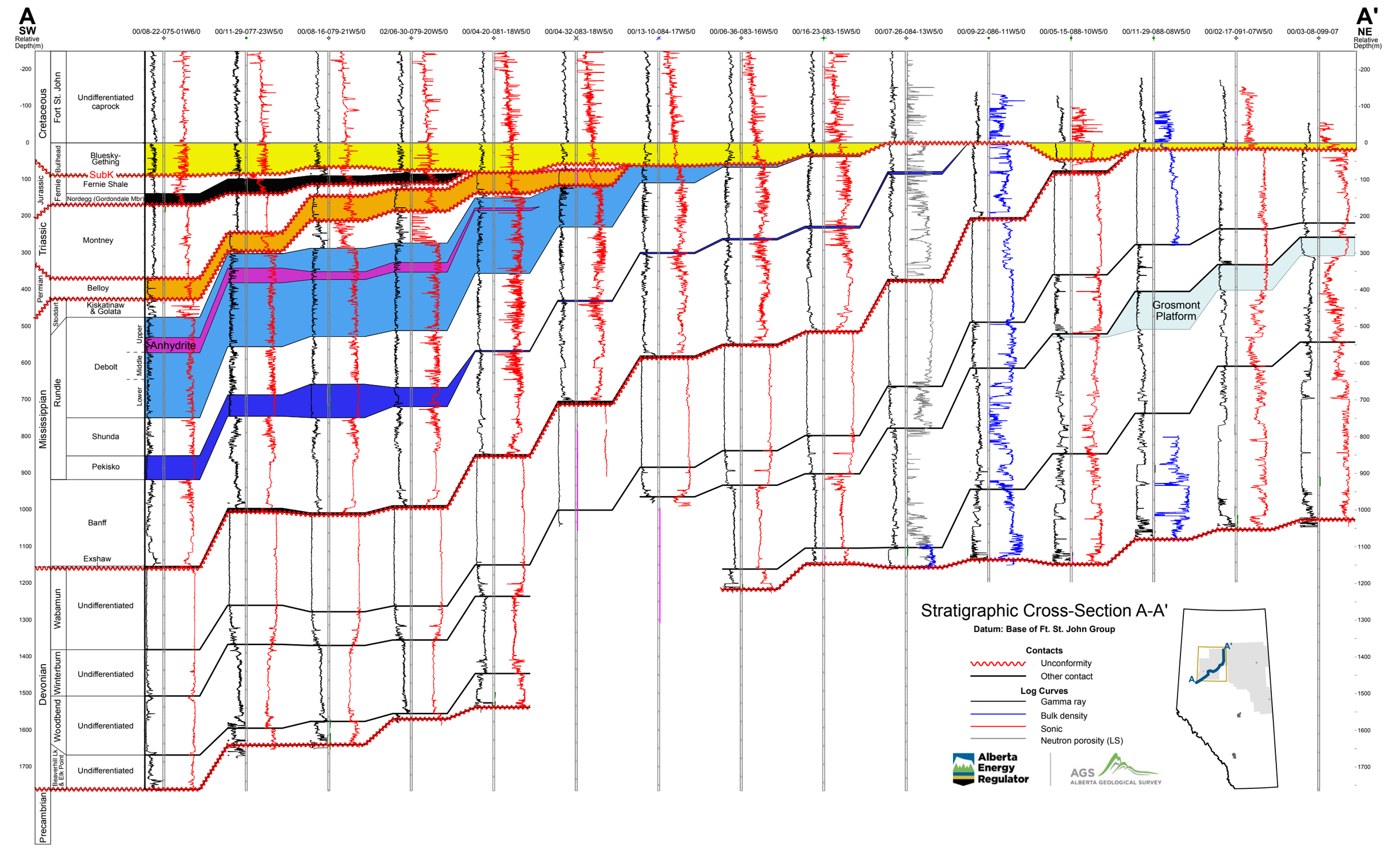

Figure 5. Map showing the subcrop areas of the geological units on the sub-Cretaceous unconformity, derived from the 3-D geological model.

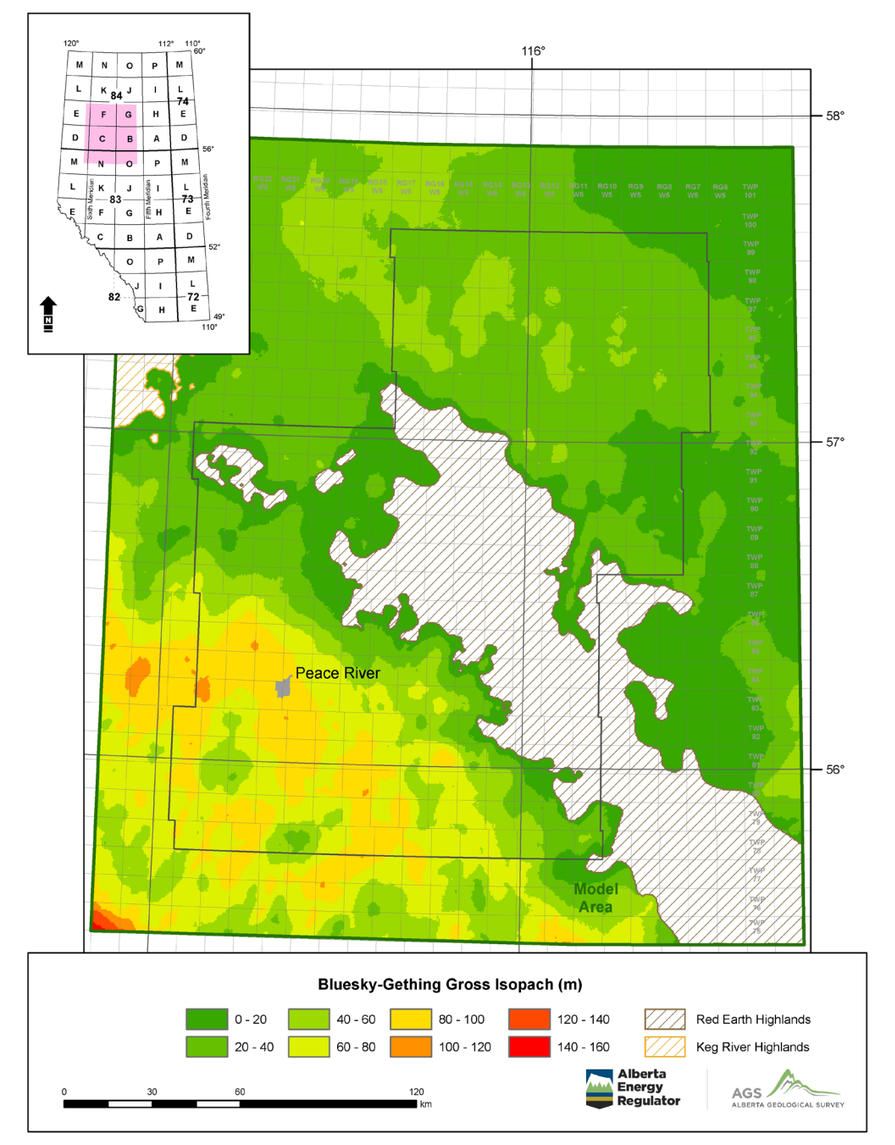

Figure 6. Gross isopach map of the Bluesky-Gething and its relationship to the Red Earth Highlands, derived from the 3-D geological model.

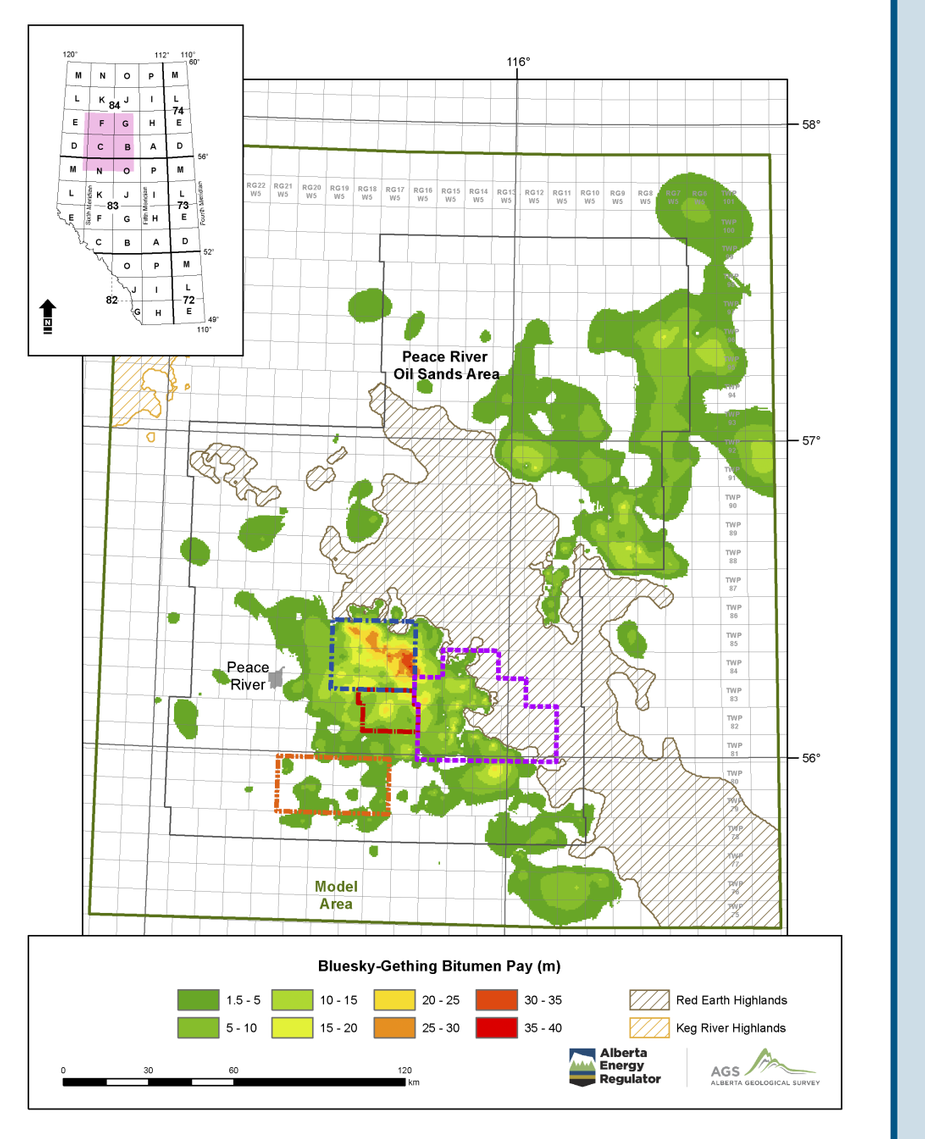

Figure 7. Bitumen pay thickness map for the Bluesky-Gething deposits using a ≥6% mass bitumen cut-off.