EUB/AGS Earth Sciences Report 2006-08

Subsurface Geology and Facies Characterization of the Athabasca Wabiskaw-McMurray Succession: Firebag-Sunrise Area, Northeastern Alberta (NTS 74D/74E)

Alberta Energy and Utilities Board

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F. Hein, D.K. Cotterill[1], J. Weiss and H. Berhane

[1]Parallax Resources Ltd

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Author address:
Darrell K. Cotterill
Parallax Resources Ltd.
#32, 54030 Range Road 274
Spruce Grove, Alberta, T7X 3S9

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Alberta Energy and Utilities Board
Alberta Geological Survey
4th Floor, Twin Atria Building
4999–98th Avenue
Edmonton, Alberta
T6B 2X3
Canada

Tel: (780) 422-3767 (Information Sales)
Fax: (780) 422-1918
E-mail: EUB.AGS-infosales@gov.ab.ca
Website: www.ags.gov.ab.ca

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2. Digital photos of core with facies annotations.
3. Annotated wireline logs with facies associations.
4. Additional structure maps.

Acknowledgements

The Alberta Geological Survey (AGS) acknowledges the following contributions to this study: Travis Hurst, Jim Lobsinger and Randy Rice for assistance with log picks, core examination and description; Desmond Wynne for database conversions and metadata issues; and Cal Hill and C. Willem Langenberg for critical reviews of an earlier version of this report. Production assistance and computer graphics were by Maryanne Protz. Managers at the AGS, most notably Andrew Beaton and Rick Richardson, are thanked for their endorsement and support of this work.

1 Introduction

This study is an extension of previous ongoing work in the Surface Mineable Area (SMA) of the Athabasca Oil Sands deposit by the Alberta Geological Survey (AGS) and also of the Regional Geological Study (RGS) by the Alberta Energy and Utilities Board (EUB) in the subsurface area south and northwest of the SMA (Alberta Energy and Utilities Board, 2003). The present work was to ascertain if the stratigraphic nomenclature, as developed in the RGS, applies to the SMA, and if so, what is the facies description and paleogeographic interpretation for that area. The area of focus for the project was the eastern part of the SMA, extending into the surrounding subsurface area (Figure 1). The study was divided into two parts: the southern area being covered by the Lewis-Fort McMurray Earth Sciences Report (Hein and others, 2006), and the present Firebag-Sunrise Earth Sciences Report, which lies to the north (Figures 1 and 2). To maintain consistency between the two parts of the study, a buffer area of overlap is included in both reports, from Township 93, Ranges 3 to 8 West of the 4th Meridian (Figures 1 and 2).

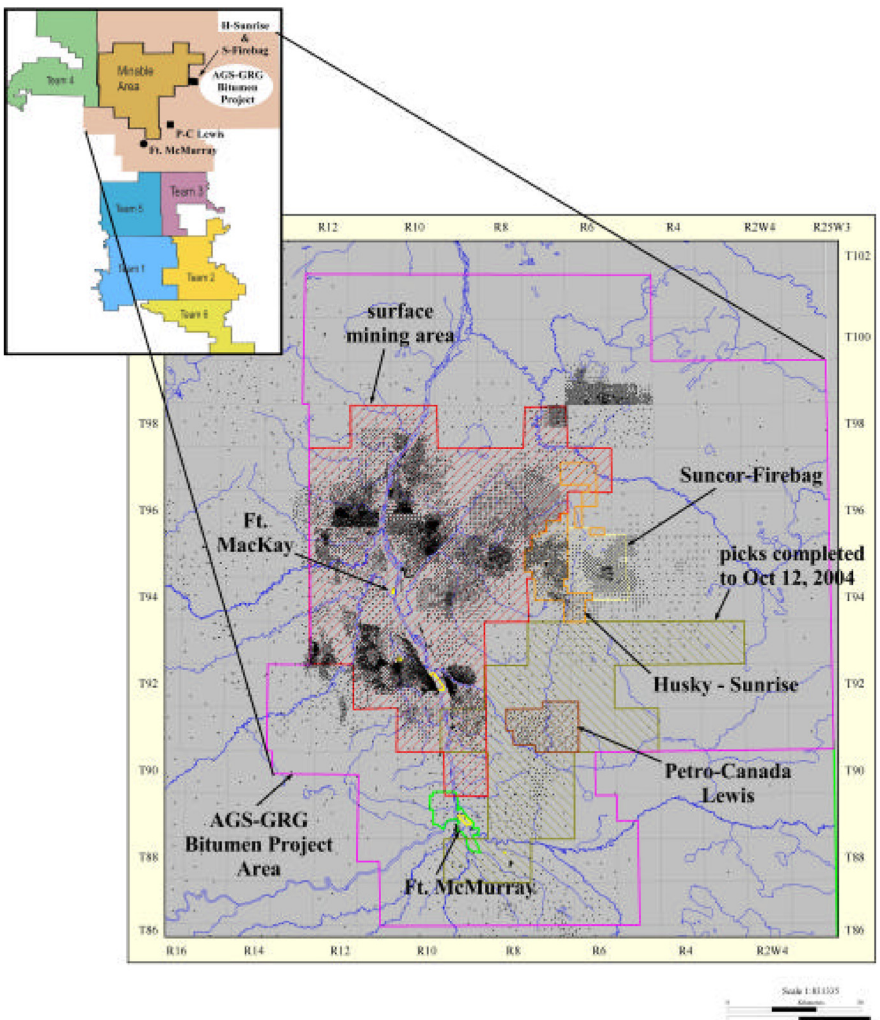


Figure 1. Map showing the subsurface areas covered in the joint AGS-GRG Bitumen Project, with the inset showing the previous Regional Geological Study (*RGS*) by the Alberta Energy and Utilities Board (2003). What was excluded from the RGS was the Surface Mineable (gold) and surrounding subsurface areas (brown), which were the focus of the joint AGS-GRG Bitumen Project.

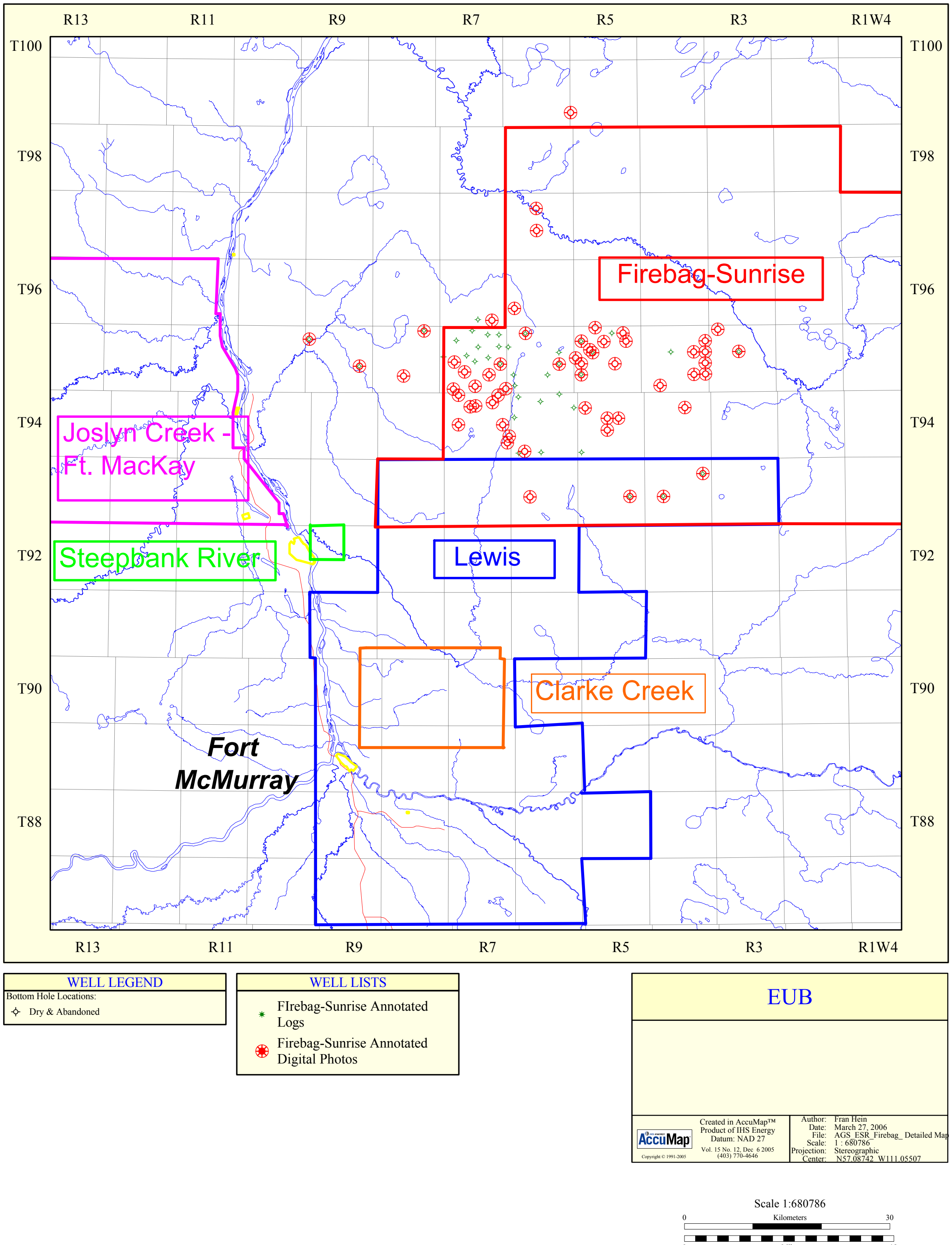


Figure 2. Recent AGS work in the Surface Mineable Area (SMA) of the Athabasca Wabiskaw-McMurray Succession near Fort McMurray, northeast Alberta. Outlines show detailed study areas, including Clarke Creek (Langenberg et al., 2003); Firebag-Sunrise (present study); Joslyn Creek–Fort MacKay (Flach and Hein, 2001); Lewis (Hein et al., 2006); and Steepbank River (Langenberg et al., 2002; Hein and Langenberg, 2003). Green symbols indicate well locations for which there are annotated logs, and red symbols well locations with annotated digital photographs (on CD). An index to the wells with core photos is in Appendix 2.

2 Previous Work

Recent government overviews concerning the Athabasca Wabiskaw-McMurray succession include historical and geological overviews largely of the Surface Mineable Area (Hein, 2000, 2004, 2006; Hein et al., 2001; Hein and Cotterill, 2006a, b) and a Regional Geological Study (RGS) in the subsurface by the Alberta Energy and Utilities Board (2003). Previous detailed geological work in the Firebag area was done by Erin Kimball as M.Sc. thesis work at the University of Alberta, which has been recently published (Kimball et al., 2004, 2005a, b).

Since about 1997, AGS has been conducting systematic facies characterization of outcrops and cores of the Wabiskaw-McMurray succession in the SMA. This work includes a facies atlas, comprehensive field guide, outcrop-subsurface correlation in the Joslyn Creek, Fort MacKay and Steepbank River areas, detailed seismic modelling in the Steepbank River-Clarke Creek region, and a stratigraphic framework and paleogeographic interpretation in the Lewis lease near Fort McMurray (Figure 2) (Hein et al., 2000, 2001, 2006; Flach and Hein, 2001; Hein and Dolby, 2001; Langenberg et al., 2002, 2003; Hein and Langenberg, 2003; Hein and Cotterill, 2005, 2006b). There is an existing regulatory need to tie the correlations and maps generated within the RGS to a regional lithofacies scheme that describes the different stratigraphic units on a scale that is appropriate for Steam-Assisted Gravity Drainage (SAGD) and other in situ schemes, particularly in the unknown subsurface area around the SMA.

3 Regional Stratigraphy of the Wabiskaw-McMurray Succession

The stratigraphic nomenclature for the Athabasca Wabiskaw-McMurray deposit is largely informal and evolutionary. A review of the development of this nomenclature is given in Hein and Langenberg (2003), Hein et al. (2006) and Hein and Cotterill (2006b). The Lower McMurray fluvial succession is distinguished from the overlying Upper McMurray estuarine and coastal plain complexes. The lower part of the Upper McMurray (mainly estuarine channel complexes) includes what industry workers have typically called 'Middle McMurray.'

The stratigraphic scheme builds upon previous AGS work since 1986 (cf. Wynne et al., 1994; Appendix 1), as well as incorporating work in the RGS (Alberta Energy and Utilities Board, 2003). The informal stratigraphic nomenclature for the Athabasca deposit includes Lower McMurray fluvial, Upper McMurray estuarine channel/bay-fill/coastal plain successions, Wabiskaw D incised valley-fill, Wabiskaw D regional marine shale, and Wabiskaw C marine succession. The Upper McMurray is further subdivided into the following regional sequences (in descending order): A1, A2, B1 and B2. In addition, McMurray channels are identified. In some of the regulatory work by the EUB, channel deposits of the Lower, 'Middle' or Upper McMurray are lumped together, designated as McMurray C Channel or McMurray Channel (cf. Alberta Energy and Utilities Board, 2003) (Figure 3; Table 1). In more detailed geological studies, especially where seismic is available, individual channels and channel complexes are mapped separately within the McMurray or Wabiskaw successions (cf. Paulsson et al., 1994; Langenberg et al., 2002, 2003; Zhang et al., 2002, 2005).

4 Study Approach

During the initial phases of study, a series of cores were pulled along a preliminary grid of cross-sections in the Suncor Firebag and Husky Sunrise project areas (Figures 4 and 5). General notes were posted to the map for documentation of emerging regional trends. Picks were made on log ASCII standard (LAS) file printouts of wireline logs using GeoOffice or on raster log images using Acculog. Picks were entered

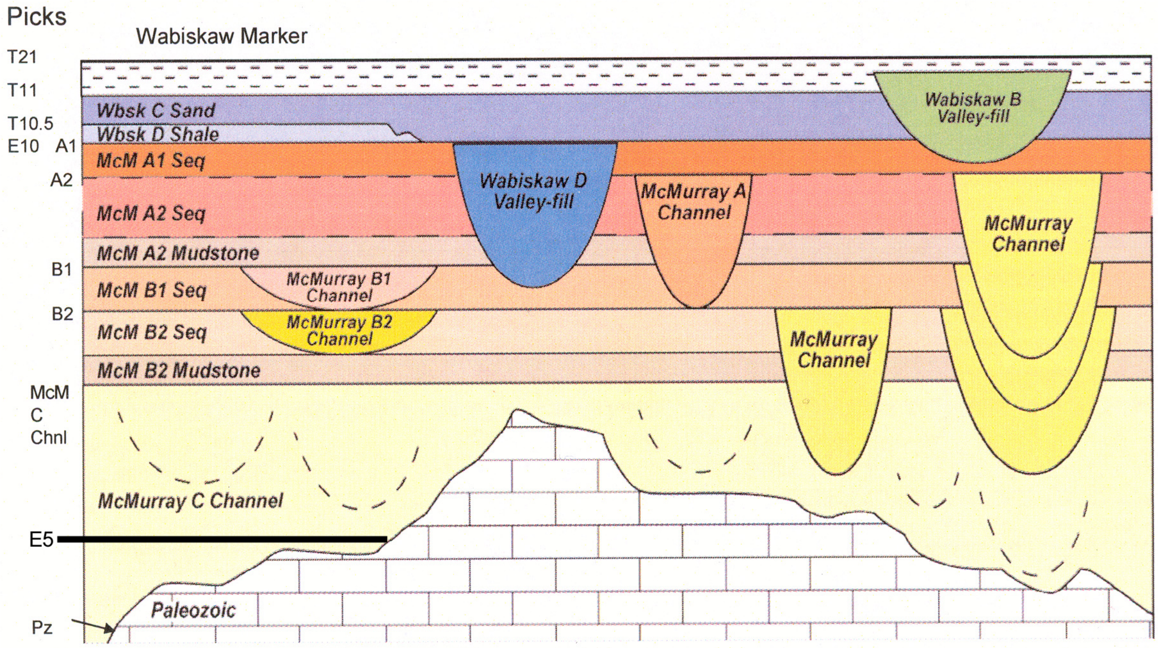


Figure 3. Stratigraphic model for the Athabasca Wabiskaw-McMurray deposit, showing the AGS and RGS picks, with the Wabiskaw Marker (T21) as a datum at the top, and schematic showing the geometric relationships between the different stratal units (modified from Wynne et al., 1994; Hein et al., 2001, 2002; Alberta Energy and Utilities Board, 2003). For a definition of the T and E surfaces, see Appendix 1.

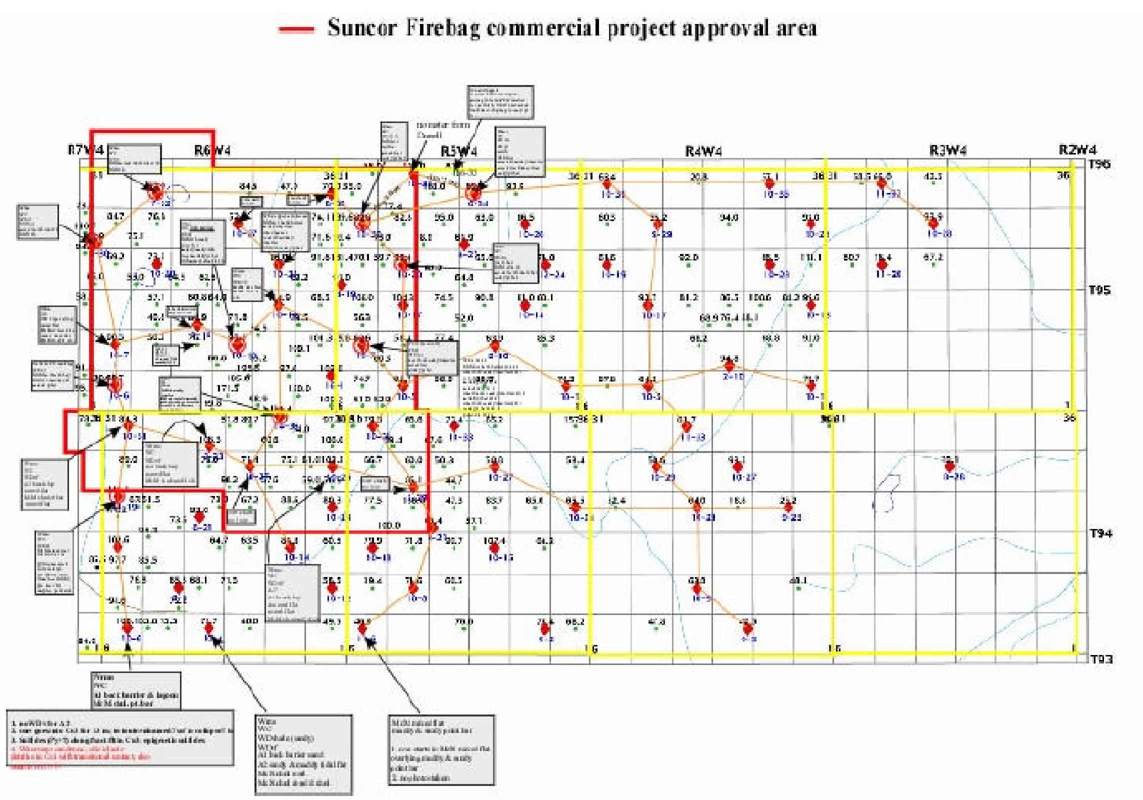


Figure 4. Posting map of the Firebag study area (Township 93–96, Ranges 3–7 West of the 4th Meridian), showing core control, total depths (TD) of wells and posting notes. Township-range grid is shown in bold yellow, and the Suncor Firebag commercial project approval area is shown in bold red.

Table 1. Characteristics of regional stratigraphic units in the Athabasca Wabiskaw-McMurray succession, northeast Alberta.

Age	AGS Stratigraphic Unit	Age	Age	AGS Stratigraphic Unit	RGS Stratigraphic Unit	Gamma Ray	Neutron	Density	Resistivity	Thickness Range	Mudstone/Shale Relationship	Fissility/Fracture	Mud/Shale-Component	Sand-Component	Cements	Organic
	(Carrigy & Kramers 1973)	(Burden (1984)		(Hein et al., 2000)	(Alberta Energy & Utilities Board, 2003)	API units	Porosity %	Porosity %	ohm-m	m	with Associated Sands		Composition	Main Constituents		Matter
	(Crerar, 2003)			(Langenberg et al., 2002)	Wabiskaw BVF Sand & Shale	60 to 75	up to 45	about 30	20 to 30	5 to 40	burrow fills, thin interbeds	none	kaolinite	litharenite*	calcite, minor siderite	
Middle		Middle	Middle													
Albian	Wabiskaw C	Albian	Albian	Wabiskaw C	Wabiskaw C Sand	60 to 90	up to 30	up to 30	< 15	~ 0.2 to 10	burrow fills, thin interbeds	none	montmorillonite, illite, kaolinite, chlorite	litharenite*, quartz, rock fragments, chert, glauconite	siderite	
					Wabiskaw C Mud	75 to 120	36 - 45	near 20	5 to 10	0.3 to 5	coarsen up into sands, less burrow-fills than A2	nonfissile	montmorillonite, illite, kaolinite, chlorite	litharenite*, quartz, rock fragments, chert, glauconite	rare siderite	abundant in clay matrix
Middle																
Albian	Wabiskaw D	Earliest Albian	Early Albian	Wabiskaw D	Wabiskaw D Shale	75 to 90	> 30 to > 45	27, but variable	2, often < 10	< 0.05 to 2		prominent platy	kaolinite	litharenite*	siderite	
					Wabiskaw D Sand	20 to 30	near 36	near 33	near 100	5 to 9	burrow fills, thin interbeds	prominent platy	kaolinite	litharenite*	siderite	
					Wabiskaw DVF Sand & Shale	30 - 50, > 70 (shalier)	> 30	27, but variable	< 10	< 0.1 to 25	burrow fills, thin interbeds	platy in shale	kaolinite	litharenite*	siderite	
Middle																
Albian	Upper McMurray		Aptian	Upper McMurray (upper pt)	McMurray A1 Sand	about 75	> 30	20 to 30	variable	0.05 to 0.4	burrow fills, thin interbeds		carbonaceous, kaolinite, illite	quartz, muscovite	rare siderite	abundant debris in mud matrix, rare coal seams
					McMurray A1 Mud	95 to 100	36 - 45	near 22	variable, > 20	0.1 to 0.3	coarsen up into sands, less burrow-fills than A2	none or octagonal	carbonaceous, kaolinite, illite	quartz, muscovite	rare siderite	abundant debris in mud matrix, rare coal seams
					McMurray A2 Sand	about 75	> 30	20 to 30	variable	0.05 to 0.4	burrow fills, thin interbeds		carbonaceous, kaolinite, illite	quartz, muscovite	rare siderite	abundant debris in mud matrix, rare coal seams
					McMurray A2 Mud	consistent ~120	36 - 45	near 22	near 10	1 to 2	coarsen up into sands, less burrow-fills than B1 & B2	none or octagonal	carbonaceous, kaolinite, illite	quartz, muscovite	rare siderite	abundant debris in mud matrix, rare coal seams
		Late Barremian			McMurray B1 Sand	about 75	> 30	20 to 30	variable	0.05 to 0.4	burrow fills, thin interbeds		carbonaceous, kaolinite, illite	quartz, muscovite	rare siderite	abundant debris in mud matrix, rare coal seams
		to Lake Aptian/			McMurray B1 Mud	90 to 120	near 45	20 to 30	variable	0.05 to 0.4	coarsen up into sands, heavily bioturbated	none or octagonal	carbonaceous, kaolinite, illite	quartz, muscovite	rare siderite	abundant debris in mud matrix, rare coal seams
		Earliest Albian			McMurray B2 Sand	30 to 45	> 30	> 30	variable	1 to 2	burrow fills, thin interbeds		carbonaceous, kaolinite, illite	quartz, muscovite	rare siderite	abundant debris in mud matrix, rare coal seams
					McMurray B2 Mud	90 to 120	near 45	near 22	8 to 10	1 to 2	coarsen up into sands, moderrate/heavily bioturbated	none or octagonal	carbonaceous, kaolinite, illite	quartz, muscovite	rare siderite	abundant debris in mud matrix, rare coal seams
Middle		Early														
Albian	Middle McMurray	Barremian	Aptian	Upper McMurray (lower pt)	McMurray C Channel Fine to Medium Sand	25 to 45	> 30	> 30	variable	~ 10 - 40+	burrow fills, interbeds;base of coarsen up; fining up caps; plugs	none or octagonal	kaolinite, illite	quartz, K-feldspar, muscovite	siderite	Mummified logs, communited coal debris, rare coal seams
					McMurray Channel Fine to Medium Sand	25 to 45	> 30	> 30	variable	~ 10 - 40+	burrow fills, interbeds;base of coarsen up; fining up caps; plugs	none or octagonal	kaolinite, illite	quartz, K-feldspar, muscovite	siderite	Mummified logs, communited coal debris, rare coal seams
Middle																
Albian	Lower McMurray	Late Valangian/	Aptian	Lower McMurray	McMurray Channel Pebbly/Coarse to Fine Sand	25 to 45	> 30	> 30	variable	~ 10 - 40+	burrow fills, interbeds;base of coarsen up; fining up caps; plugs	none or octagonal	kaolinite, illite	quartz, K-feldspar, muscovite, quartzite, carbonate	siderite, rare quartz	Mummified logs, communited coal debris, locally thick coal seams
		Hauterivian														
Barremian	pre-McMurray		Middle	pre-McMurray Sand		25 to 45	> 30	> 30	variable	~ 10 - 40+	burrow fills, interbeds;base of coarsen up; fining up caps; plugs	none or octagonal	kaolinite	quartz, K-feldspar, muscovite, quartzite, carbonate	siderite, rare quartz	Finely communited vegetal matter and debris
			Barremian	pre-McMurray Mud		90 to 120	near 45	near 22	8 to 10	1 to 2	coarsen up into sands, moderrate/heavily bioturbated	none or octagonal	mixed layer clays	quartz, muscovite	rare quartz, goethite	Finely communited vegetal matter and debris
														* litharenite includes sedimentary and metamorphic		
														rock fragments.		

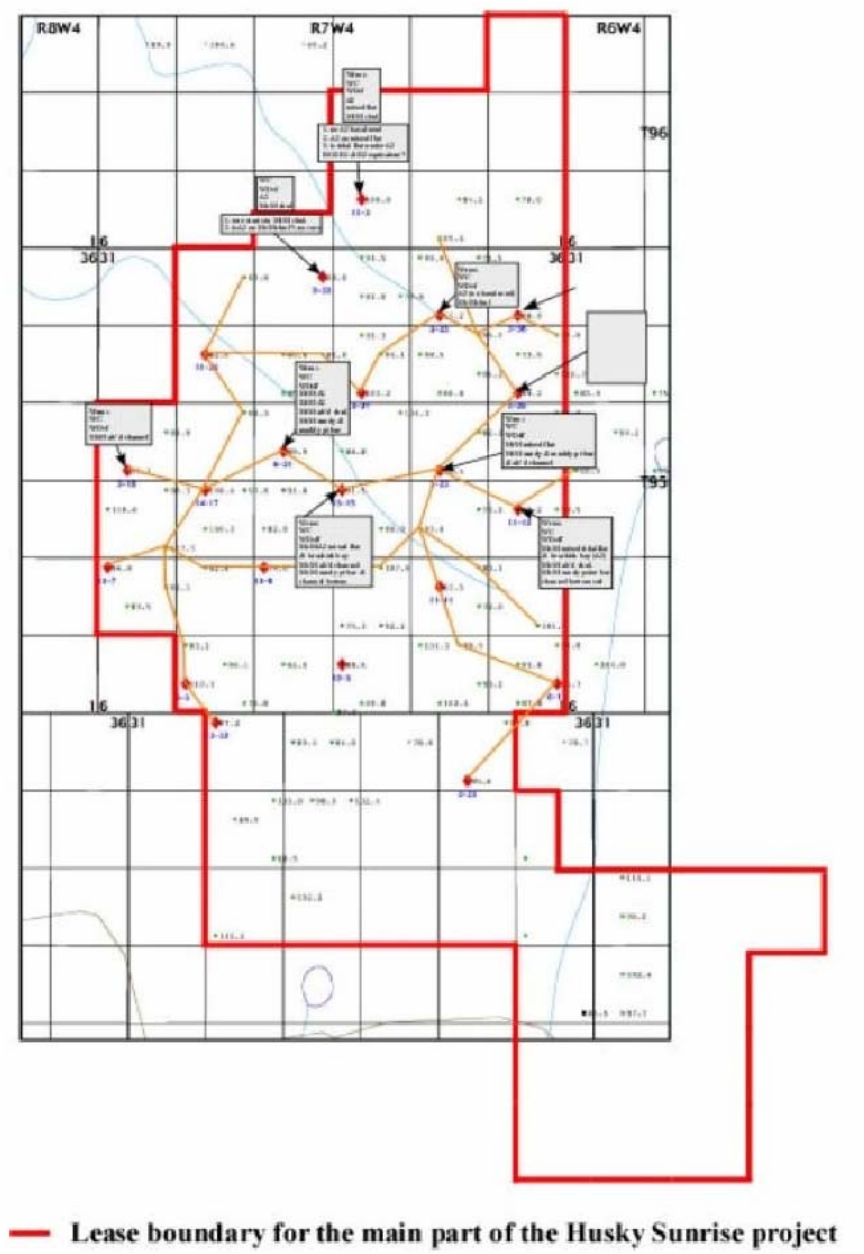


Figure 5. Posting map of the Sunrise study area (Township 94–96, Ranges 6–8 West of the 4th Meridian), showing core control, total depths (TD) of wells and posting notes. Township-range grid is shown in grey, and the Husky Sunrise commercial project approval area is shown in bold red.

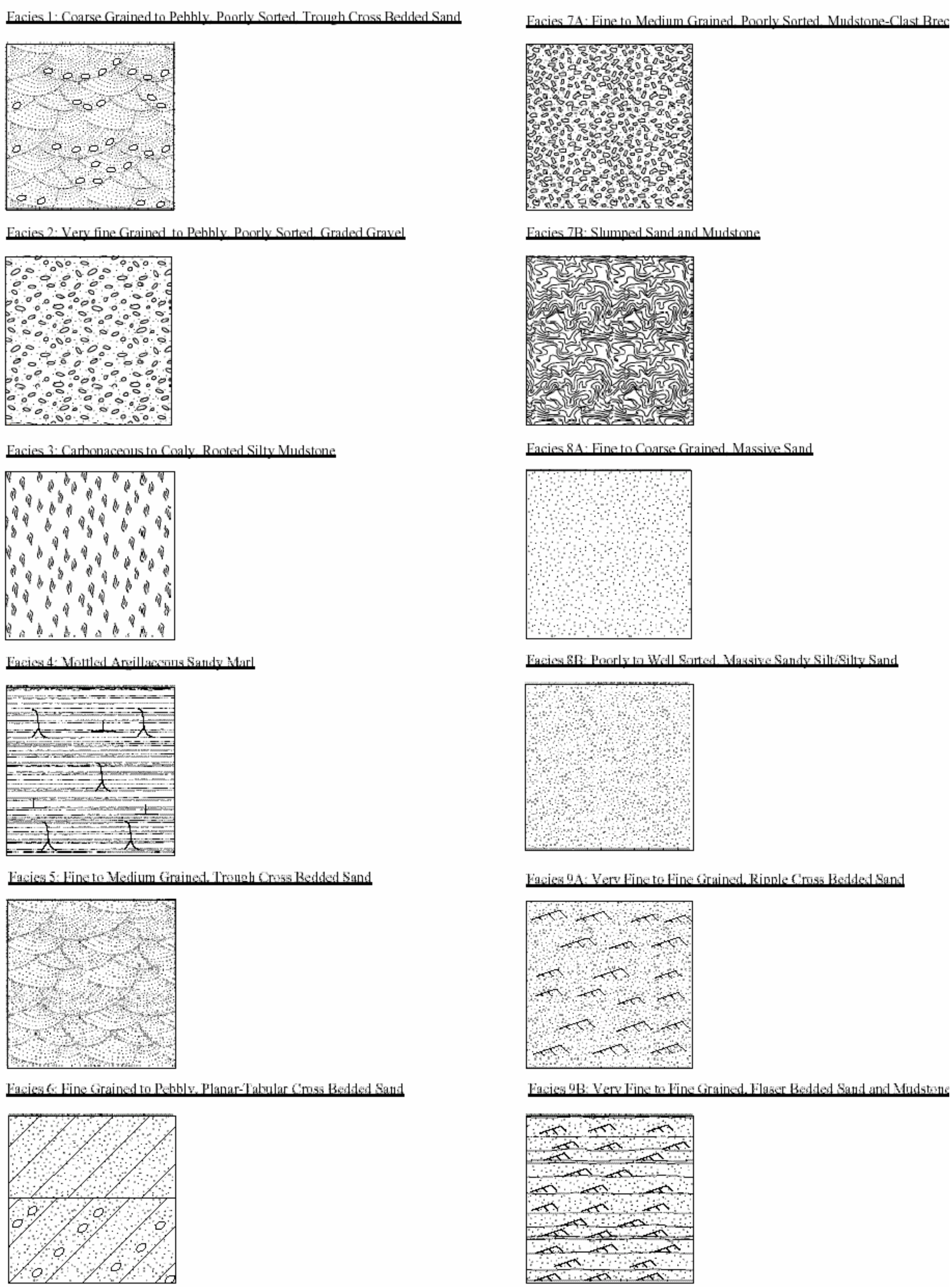
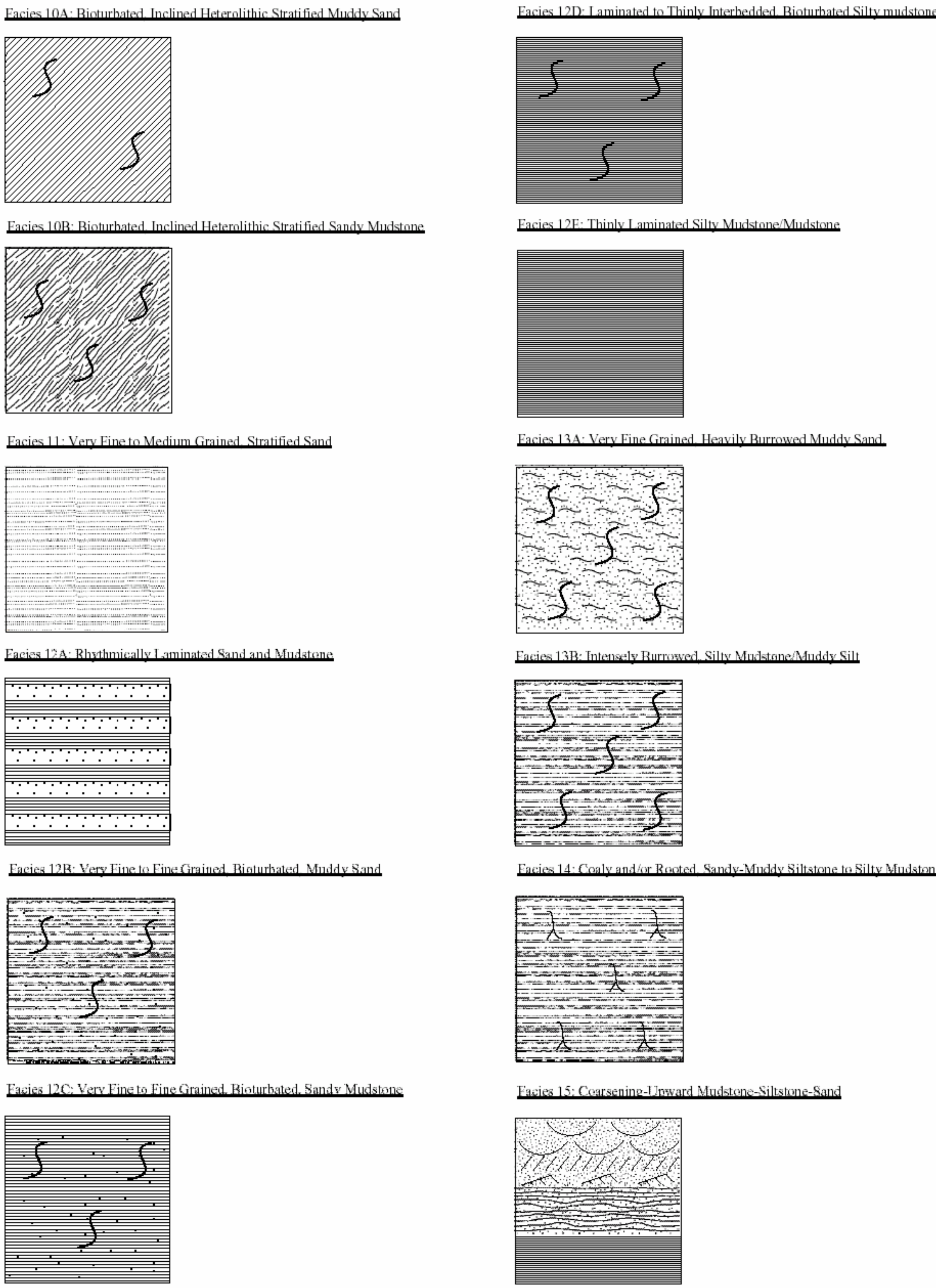


Figure 6. Facies classification scheme with sketch illustrating the dominant sedimentary features (from Hein et al., 2000).



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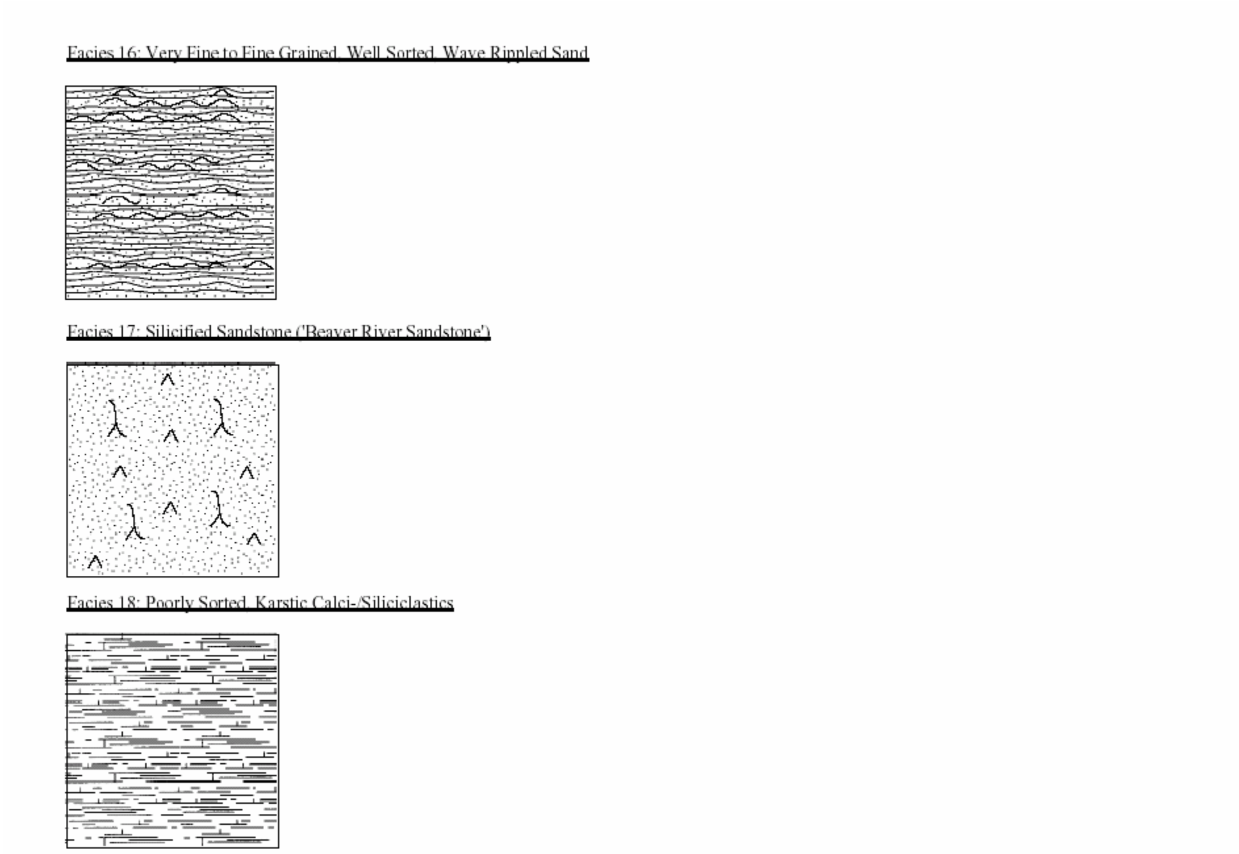

Figure 6. Facies classification scheme with sketch illustrating the dominant sedimentary features (from Hein et al., 2000).

Table 2. Lithofacies description and interpretation for the Athabasca Wabiskaw-McMurray succession, northeast Alberta

Facies	Lithology (rare)	Sorting	Sedimentary Structures	Bioturbation Intensity	Average Bed Thickness (range)	Paleo-Environment
1	pebbly coarse sand (gravel)	poor to very poor	trough crossbeds	none	1 m (0.1 - 9 m, multistory)	braided fluvial channel and bars
2	gravel (muddy)	v. poor to poor	massive or coarsening up sometimes chaotic	none	0.3 m (0.1 - 3 m)	braided fluvial channel, debris flow slope wash, colluvium
3	siltstone mudstone coal (carbona-ceous)	good to poor	massive or fining-up parallel lamination	none to moderate, mainly roots	0.75 m (0.05 - 3 m)	bog, slough, marsh, exposed floodplain, tidal flats, paleosols

Facies	Lithology (rare)	Sorting	Sedimentary Structures	Bioturbation Intensity	Average Bed Thickness (range)	Paleo-Environment
4	sand-silt-stone mudstone (calcareous)	moderate to poor	massive or laminated	moderate to heavy, roots pedogenic	0.3 m (0.05 - 2 m)	paleosols
5	fine - medium sand	good to moderate	trough crossbeds	rare to less common	0.75 m (0.5 - > 1 m)	fluvial and/or estuarine channel and bars
6	fine - pebbly sand	very good to moderate	planar-tabular crossbeds	rare to less common	0.75 m (0.5 - > 1 m)	fluvial and/or estuarine channel and bars
7A	mudstone clast breccia with sandy matrix	poor to very poor	massive, cross beds, rare IHS laminated	rare to very common	0.5 m (0.05 - 3 m, multistory)	fluvial and/or estuarine channel and bars
7B	sand, siltstone and/or mudstone	poor to very poor	slump structures convolute and folded beds	rare to less common	1.5 m (0.05 - 3 m, multistory)	slides, slumps and debris flows
8A	fine - coarse sand	moderate to good	massive	rare	0.5 m (0.05 - 3 m, multistory)	fluvial and/or estuarine channel
8B	siltstone and/or muddy siltstone	moderate to poor	massive	rare	0.02 m (0.01 - 0.3 m)	overbank in fluvial and estuarine valleys, inc. tidal flats; bay fills
9A	fine - very fine sand	good to very good	rippled (current, combined flow, ripple drift)	rare to uncommon	0.5 m (0.01 - 4 m, multistory)	fluvial and/or estuarine channel and bars, basal abandonment fill, and lower floodplain/tidal flat and bay-fills
9B	fine to very fine sand	good to very good	flaser rippled and linsen beds	rare to common	0.5 m (0.01 - 4 m, multistory)	tidal estuarine channel
10A	fine to very fine sand, with muddy interbeds	good to very good in beds	low-angle inclined bedding (IHS)	rare to very common	3 m (1 - > 15 m, multistory)	sandy tidal estuarine point bar
10B	mudstone with sandy interbeds	good to very good	low-angle inclined bedding (IHS)	rare to very common	3 m (1 - > 15 m, multistory)	muddy tidal estuarine point bar

Facies	Lithology (rare)	Sorting	Sedimentary Structures	Bioturbation Intensity	Average Bed Thickness (range)	Paleo-Environment
11	very fine to medium sand	good to excellent	horizontal lamination	rare to common	0.3 m (0.1 - 3 m, multistory)	fluvial and/or estuarine channel and bars, main abandonment fill, common in floodplain/tidal flat and bay-fills
12A	very fine to medium sand and silty mud	good to excellent	rhythmic tidal couplets and lamination little bioturba-tion	variable, absent to very common	2 m (0.2 - 5 m, multistory)	estuarine channel and bars, main abandonment fill, common in floodplain/tidal flat and bay-fills
12B	very fine to muddy sand	poor to very poor	biogenically churned some lamina-tion preserved	very high to intense	2 m (0.2 - 5 m, multistory)	estuarine channel and bars, main abandonment fill, common in floodplain/tidal flat and bay-fills
12C	sandy mudstone	poor to	bioturbated	very high to	2 m	estuarine channel
12D	silty mud-stone	very poor	churned	intense	(0.2 - 5 m, multistory)	and bars, main
12E	silty mud-stone & mudstone		lamination preserved in E			abandonment fill, common in floodplain/tidal flat and bay-fills
13A	muddy sand	poor to	biogenically	very high to	2 m	estuarine channel
13B	muddy silt	very poor	churned very little or no lamination preserved	intense	(0.2 - 5 m, multistory)	and bars, main abandonment fill, common in floodplain/tidal flat and bay-fills bay-fills
14	coaly or organic rooted, paleosols sandy mudstone silty mud-stone	poor to moderate	massive or laminated, roots, pedogenically churned	rare to high (pedogen-esis)	0.3 m (0.1 - 0.75 m)	paleosols in overbank settings, including tidal flats
15	mud, silt, sand	good	coarsening-up, laminated and crossbedded	rare to high	1 m (0.5 - 3 m)	crevasse splays off channels into overbank areas; and bay-fills

Facies	Lithology (rare)	Sorting	Sedimentary Structures	Bioturbation Intensity	Average Bed Thickness (range)	Paleo-Environment
16	very fine to fine sand	good to excellent	wave ripples, swaley cross-beds	rare to high	0.25 m (<0.01 - 0.75m)	oxbow lakes, flooded tidal flats, bay-fills
17	silicified sandstone and silt-stone	good to very poor	pedogenic, roots laminated	rare - com-mon rooted locally	0.25 m (<0.01 - 0.75m)	early cemented seds. paleosols on highs
18	carbonate karst blocks mixed with clastic infill/ slumps	poor to very poor	laminated, massive rippled, slumped brecciated	rare	2 m (<0.01 - > 5m, multi-story)	karst breccia and colluvium within caves or slumped slope material

into Excel spreadsheets, which were then migrated into an Access database following data validation and assigning of unique key identifiers.

In the description of core, the facies classification scheme as published in Hein et al. (2000) was used (Figure 6; Table 2). Although this scheme was developed largely for outcrops and core within the SMA, it was found during the core-logging phases of this work that this scheme is still appropriate. To determine relative proportions of facies in the Firebag-Sunrise area, the thicknesses of the different facies were measured in 55 cores, and then a relative thickness per cent (%) was calculated for each core interval examined. For comparison purposes, a similar computation was done for the recent core logged by AGS, which was largely the basis for the facies atlas (Hein et al., 2000). In this case, the 291 cores were not re-examined; rather, the facies thickness percentages were calculated on the printouts of the original Applecore logs of both the outcrop and core section descriptions. For the analyzed archival data, facies percentages were calculated separately for the fluvial (mainly Lower McMurray), estuarine (lower part of the Upper McMurray) and coastal plain and bay fill (upper part of the Upper McMurray) successions. Summary results of the facies percentages are given in Table 3 and plotted in Figures 7 to 9.

Representative digital core photos (339) were taken of the different facies as seen in core from the Firebag-Sunrise study area, which were input into PowerPoint for facies annotation and cataloguing. Wireline logs were colour coded for facies association and stratigraphic interpretation, with notes appended to the logs as needed. The annotated, coloured logs were then imported into PowerPoint, in which a schematic index was created to show the well and depth location of the corresponding digital photos. Structure and isopach mapping in the study area was done in ArcGIS from picks in the Access database. ArcGIS mapping specifications are given in Appendix 3.

The picks table, digital photographs, annotated raster logs and digital maps are included on the CD. The colour legends for the interpreted facies associations on representative wireline logs are given in Appendix 3. Note that due to incompatibilities between colour schemes and differing scales of facies definition between AGS and EUB offices, there is a discrepancy and two legends are used on the annotated wireline logs included on the CD. If only colours are used on the logs (i.e., no superimposed patterns), these were done by AGS and the AGS legend is used. If the annotated logs show both striped and coloured patterns, these were done by EUB and the EUB legend is used. A summary of which legend to use for each annotated log is given in Appendix 2.

5 Facies Description and Interpretation

The facies classification and descriptions (Figure 6, Table 2) aided in the interpretation of facies associations and larger stratigraphic units that were annotated on the wireline logs (Table 1, see annotated logs on CD). Highlights of the main features of the different facies are discussed below, with overall comparisons given to archival data concerning facies in the McMurray Formation in the SMA (Table 3, Figures 8 and 9).

What mainly distinguishes the McMurray Formation in the Firebag-Sunrise area are the local effects of increased accommodation space along the eastern margin of the Bitumen Basin on the development of individual facies. The study area shows dramatically increased thicknesses and local abundances of slides, slumps, organic mudstones and coals, mudstone intraclast breccias, paleosols and rooted horizons. Elsewhere within the SMA these facies are largely absent, or very thin where locally preserved. At Firebag-Sunrise, there is also a common correlation of syn-sedimentary faults and folds (shown by over-steepened crossbedding and convolute lamination) with inclined heterolithic stratified (IHS) units, which has not been noticed elsewhere in the SMA. Since these aspects of the facies are much more obvious in the Firebag-Sunrise area, emphasis was based on characterization of the individual facies, rather than the larger-scale facies associations.

The larger-scale facies associations in the Firebag-Sunrise area are the same to those described in detail in the RGS (Table 1) and for the Lewis area immediately south (Hein et al., 2006). The general distribution of the different facies associations for the Firebag-Sunrise area is discussed in the next section dealing with mapping of stratigraphic units (Section 6).

5.1 Facies 1. Coarse-Grained to Pebbly Trough Crossbedded Sand

Facies 1 is generally confined to the lowermost portion of the McMurray succession, often directly overlying the sub-Cretaceous unconformity. Coarse-grained to pebbly, trough crossbedding occurs within quartz sand of this facies (Figure 10). Granules and pebbles commonly occur as thin laminae along cross strata or as lags at the base of beds. Very thin discontinuous lenses of coaly debris and coal occur within the crossbeds in rare to minor amounts. On gamma-ray logs, the facies typically appear as clean, blocky sand. In core, Facies 1 is recognized by the common occurrence of granules and pebbles dispersed within the sand and by the tangential and variably scoop-shaped, low to high-angle crossbeds, that crosscut one another at different orientations (Figure 10). Beds average about75 cm thick.
The development of this facies is less common in the Firebag-Sunrise area compared to the rest of the McMurray Formation in the SMA (Figure 9, Table 3). In the Firebag-Sunrise area, Facies 1 averages about 2% of the core thickness (Figure 7), locally reaching 18%. This facies is most abundant within the Lower McMurray Fluvial Facies Association, being less common within the Upper McMurray Estuarine Facies Association (Figure 8, Table 3). Facies 1 is interpreted as being deposited from pebbly sand and gravel dunes that migrated along the bottoms of river channels (Lower McMurray), or within the lower and swifter courses of the main estuarine channels (Upper McMurray).

5.2 Facies 2. Pebbly Sand and Gravel

Facies 2 is a relatively uncommon facies in the Lower McMurray Formation. This facies is characterized by pebbly sand or gravel, that is either clast or matrix-supported, can be massive, chaotic or graded (fining or coarsening-up). Bed thicknesses average about 25 cm. Less commonly, carbonaceous material (including coalified wood debris and organic mudstone intraclasts) occur within the pebbly sand and gravel. On gamma-ray log traces, the facies have a clean, blocky sand response; in units with an

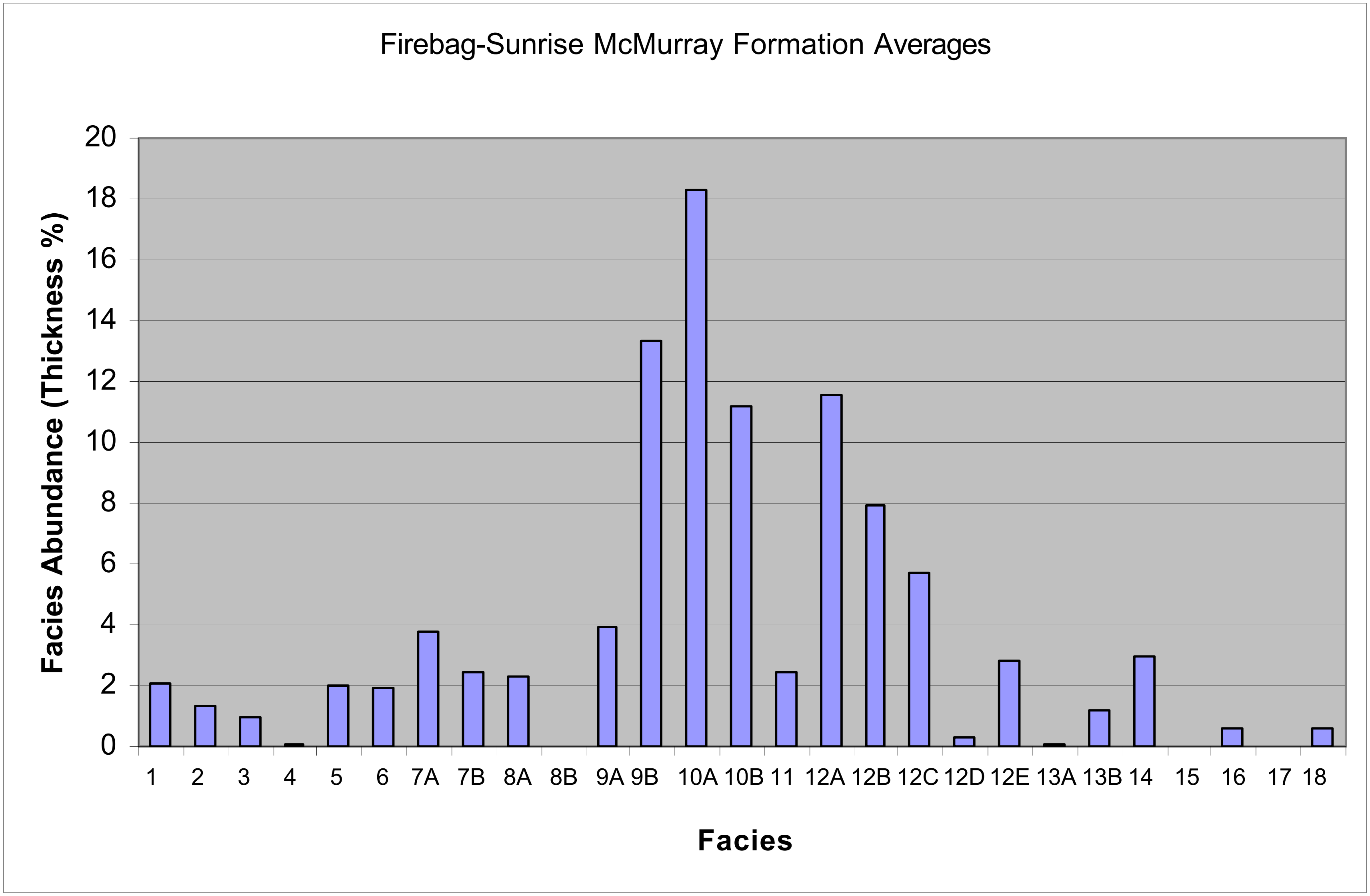

Figure 7. Facies histogram, in thickness per cent, for the different facies in the Firebag-Sunrise study area (number of core = 55).

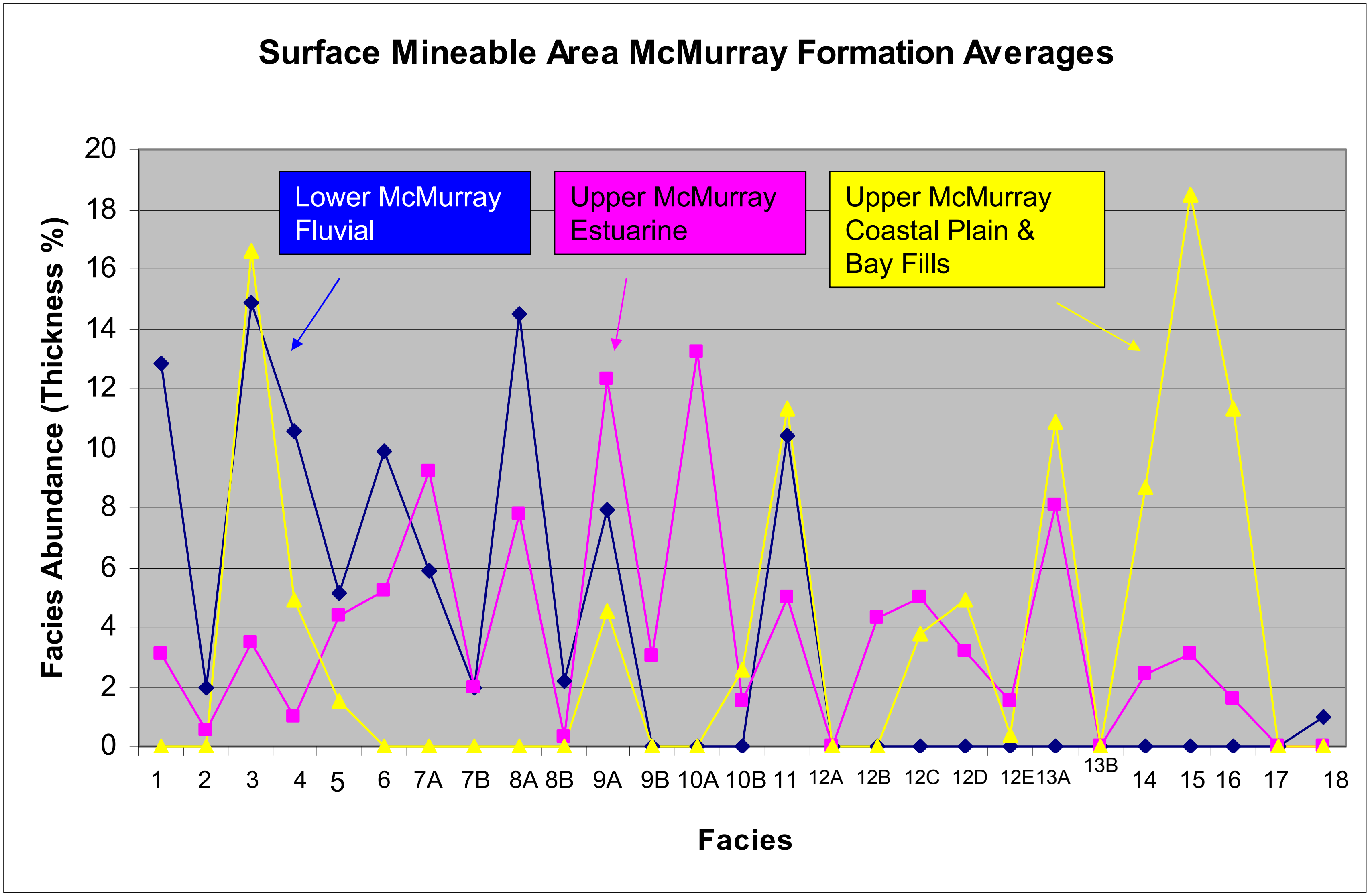

Figure 8. Facies histogram, in thickness per cent, for the different facies in the McMurray Formation of the Surface Mineable Area, showing average values for Lower McMurray Fluvial Association (number of core = 291) (blue); Upper McMurray Fluvio-Estuarine and Estuarine Facies Associations (number of core = 291) (pink); and Upper McMurray Coastal Plain and Bay-Fill Facies Associations (number of core = 265) (yellow). Core descriptions are from EUB archived data.

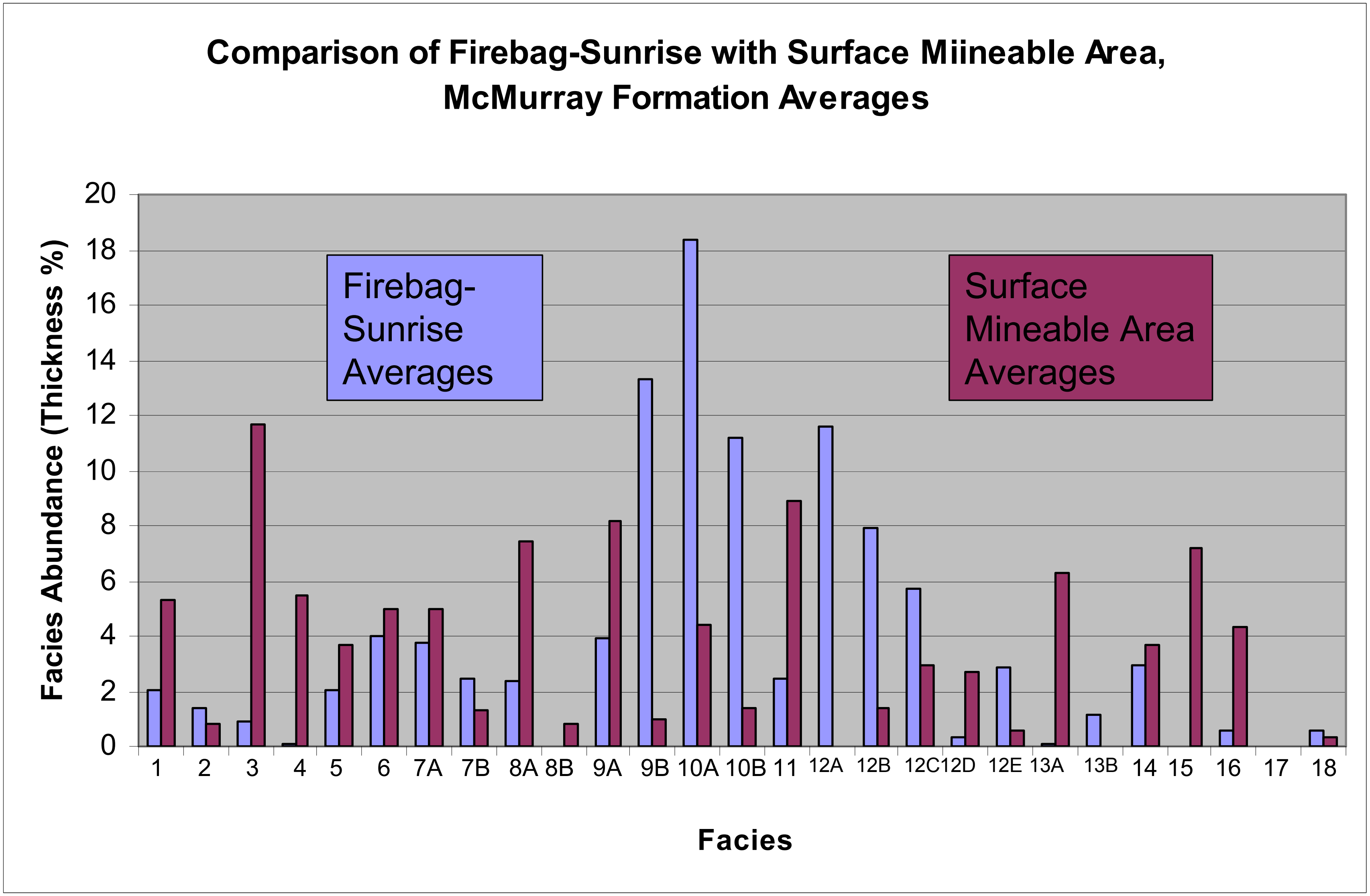

Figure 9. Facies histogram, in thickness per cent, showing a comparison for average values from the Firebag-Sunrise area (blue) and average values for the McMurray Formation in the Surface Mineable Area (pink).

Table 3. Facies percentages in the Firebag-Sunrise area compared with the McMurray Formation in the Surface Mineable Area.

Data Set/Facies Classification	1	2	3	4	5	6	7A	7B	8A	8B	9A	9B	10A	10B	11	12A	12B	12C	12D	12E	13A	13B	14	15	16	17	18
Firebag-Sunrise McMurray Formation Averages	2.07	1.36	0.93	0.05	2.02	3.99	3.76	2.42	2.33	0	3.95	13.33	18.33	11.2	2.48	11.58	7.91	5.69	0.31	2.85	0.05	1.16	2.96	0	0.6	0	0.58
Surface Mineable Area McMurray Formation Averages	5.3	0.8	11.7	5.5	3.7	5	5	1.3	7.4	0.8	8.2	1	4.4	1.4	8.9	0	1.4	2.9	2.7	0.6	6.3	0	3.7	7.2	4.3	0	0.34
Lower McMurray Fluvial Complex	12.8	2	14.9	10.6	5.1	9.9	5.9	2	14.5	2.2	7.9	0	0	0	10.4	0	0	0	0	0	0	0	0	0	0	0	1
Upper McMurray Estuarine Complex	3.1	0.5	3.5	1	4.4	5.2	9.2	2	7.8	0.3	12.3	3	13.2	1.5	5	0	4.3	5	3.2	1.5	8.1	0	2.4	3.1	1.6	0	0.03
Upper McMurray Coastal Plain & Bay-Fill Complex	0	0	16.6	4.9	1.5	0	0	0	0	0	4.5	0	0	2.6	11.3	0	0	3.8	4.9	0.4	10.9	0	8.7	18.5	11.3	0	0

Figure 10. Core photograph showing facies in Lower McMurray Fluvial Facies Association overlain by Upper McMurray Estuarine Facies Association: core location AA/13-09-095-07W4, 197.4–204.9 m. Core boxes are each 75 cm long.

abundance of mud matrix or mud clasts, a shale log-response is seen. In core, Facies 2 is recognized by the common occurrence of granules and a pebble mixed in the sand, the massive to chaotic fabric, and in some cases a fining or coarsening-up trend within individual beds.

The development of this facies is about the same in the Firebag-Sunrise area compared to the rest of the McMurray Formation in the SMA (Figure 9, Table 3). Here, Facies 2 averages about 1.4% of the core thickness (Figure 7), locally reaching a maximum of 28%. This facies is mainly within the Lower McMurray Fluvial Facies Association (Figure 8, Table 3). Local thickened units of this facies occur along the sub-Cretaceous unconformity, particularly in areas affected by karstification of the underlying Devonian carbonates. Facies 2 is interpreted as being deposited from coarse-grained, sediment gravity flows (including slides, slumps and debris flows) that were associated with subaerial mass-wasting or with subsurface karstification dissolution and collapse. Locally, the fining up and better sorted, clast-supported pebbly sand and gravel are part of the bedload transport deposits within the lower part of the fluvial channels in the Lower McMurray Fluvial Facies Association.

5.3 Facies 3. Carbonaceous Silty Mudstone to Coal

Facies 3 is a relatively uncommon facies in the Lower McMurray and Upper McMurray successions.

This facies consists of carbonaceous silty mudstone that commonly grades up into a coal (Figure 11), with average observed bed thicknesses around 25 cm. On sonic-density/neutron-density log traces, if the facies development is thick enough (i.e. ~ > 30 cm), there is the usual 'coal response,' with sharp deflections on both density curves to the left. In core, Facies 3 is recognized by the dark grey to black colouration, the high organic content, presence of stratification and, in the true coals, the beginning of cleat development.

On average the development of this facies is much less, in the Firebag-Sunrise area compared to the rest of the McMurray Formation in the SMA (Figure 9, Table 3). In the Firebag-Sunrise area, Facies 3 averages about 1% of the core thickness (Figure 7), although locally very thick horizons are preserved, with a maximum of 18% of the core thickness. This facies occurs both within the Lower McMurray Fluvial Facies Association and within the Upper McMurray Estuarine/Coastal Plain Facies Associations (Figure 8, Table 3). Local thickened units of this facies occur above units along the sub-Cretaceous unconformity, which are affected by karstification. Facies 3 is interpreted as forming mainly in vegetated overbank areas, including shallow lakes, bays, bogs and swamps. The locally thickened coals may be related to continued down warping and rapid subsidence of swampy areas that overlie karstic sinkholes. During sedimentation, these sinkholes were deeper lakes that were cut off from coarse clastics, which may have been anaerobic, allowing the preservation of thick organic mucks, now represented by coaly units.

5.4 Facies 4. Mottled Argillaceous Sandy Marl

Facies 4 is rare, comprising < 1% (maximum 3%) of the core thickness reviewed in the Firebag-Sunrise area. It is also rare elsewhere in the McMurray Formation of the SMA, where it usually occurs in the Lower McMurray just above the contact with the underlying Devonian carbonates. In the Firebag-Sunrise study area this facies was only seen interbedded with or overlying Facies 18 karst breccia. Because of this relationship in the Firebag-Sunrise area, the mottled argillaceous sandy marl is interpreted here as being deposited within karst lakes or ponds that likely formed in flooded areas along the pre-Cretaceous karstic landscape.

5.5 Facies 5. Fine to Medium-Grained, Trough Crossbedded Sand

Facies 5 is a finer-grained version of Facies 1 and is common in the Lower McMurray and Upper McMurray successions. The facies is notable to its well-defined trough crossbedding that is developed within clean quartz sands (Figure 10). This facies lacks the fine-grained, interbedded mud laminae that are associated with the Facies 9B flaser beds. Facies 5 beds average about 25 cm thick, but may range from a few centimetres to about a metre in thickness. Although rare, a few granules and pebbles may occur along cross sets or as lags at the base of beds, but if the proportion of the coarse fraction increases significantly then the unit is classified as Facies 1. Coaly debris occurs in rare to moderate amounts. On gamma-ray logs the facies typically appears as clean, blocky sand. In core, Facies 5 is recognized by the tangential and variable, scoop-shaped, low to high-angle crossbeds that crosscut one another (Figure 10). This facies is commonly interbedded with mudstone breccia (Facies 7A) or may be associated with other laminated or crossbedded sands (Facies 6, 9A, 9B, 10A, 10B and 11).

The development of Facies 5 is similar in the Firebag-Sunrise area compared to the rest of the McMurray Formation in the SMA (Figure 9, Table 3). In the Firebag-Sunrise area, Facies 5 averages about 2% of the core thickness (Figure 7), locally attaining 13% of the core thickness. This facies is most abundant within the Lower McMurray Fluvial Facies Association and within the Upper McMurray Estuarine Facies Association (Figure 8, Table 3). It also occurs in the Upper McMurray Coastal Plain Facies

Figure 11. Core photograph showing Facies 3 coal overlain by tidal flat sands and muds of the Upper McMurray Coastal Plain Facies Association; in turn, overlain by Wabiskaw D Valley-Fill: core location AA/03-35-094-07W4, 196.35–200.0 m. Core boxes are each 75 cm long.

Association (Table 3, Figure 8), as part of coarsening-upward, progradational bay-fill parasequences, or as local coarsening-upward crevasse splays. Facies 5 is interpreted as being deposited from sand dunes that migrated along the bottoms of river or estuarine channels and lower point-bar surfaces; less commonly they may be part of tidal flows, storm surges or flood flows within the estuarine and coastal plain complexes.

5.6 Facies 6. Fine to Medium-Grained, Planar-Tabular Crossbedded Sand

In the Firebag-Sunrise area, Facies 6 is a finer-grained version of a similar facies developed elsewhere in the Lower and Upper McMurray successions in the SMA (where it is often granule to pebbly sand). Here at Firebag-Sunrise, the facies is notable for its well-defined, high-angle, mainly unidirectional, crossbedding that is developed mainly within fine to medium-grained, clean quartz sands (Figure 10). Less commonly this type of crossbedding has been observed in sandy mud (Figure 16). Beds average about 50 cm thick, but may range from a few dm to 2 m in thickness. A few granules and pebbles may rarely occur as lags at the base of beds; coaly debris is in rare to moderate amounts. On gamma-ray logs, the facies typically appears as clean, blocky sand. In core, Facies 6 is recognized by the parallel, straight-lined crossbeds that intersect the base of the crossbed set at high angles (Figure 10). Paleoflows are mainly unidirectional; less commonly, bi-directional in large-scale herringbone crossbedding. Facies 6 is commonly interbedded with mudstone breccia (Facies 7A) or may occur with other crossbedded sands (Facies 5, 9A, 9B, 10A and 10B).

The development of Facies 6 in the Firebag-Sunrise area is somewhat less compared to the rest of the McMurray Formation in the SMA (Figure 9, Table 3). Facies 6 averages about 2% of the core thickness (Figure 7), locally attaining 18% of the core thickness. This facies is most abundant within the Lower McMurray Fluvial Facies Association and within the Upper McMurray Estuarine Facies Association (Figure 8, Table 3). Facies 6 is interpreted as being deposited from two-dimensional sand waves that migrated along the bottoms of river or estuarine channels, and on lower to upper braid or point-bar surfaces; less commonly, they may be part of tidal flows, storm surges or flood flows within the estuarine and coastal plain complexes.

5.7 Facies 7A. Mudstone Clast Breccia

Facies 7A consists of intraclasts of mudstone, which form either clast-supported breccias or sand beds with dispersed mudstone clasts (Figures 12 to 14). The facies is notable for its well-defined, light grey to tan mud clasts within clean quartz sands. The contrast between the two lithologies can be quite dramatic in core, where the sand is often bitumen-stained, whereas the mud clasts lack bitumen. Individual clasts are angular 'rafts' or may be irregularly convoluted or folded. Internally, most of the mud clasts are bioturbated to some degree (rare to heavy). Beds average about 50 cm thick, but may range from a few cm to > 2 m in thickness. A few granules and pebbles rarely occur within the breccias or as lags at the base of beds. On gamma-ray logs, the facies typically appears as muddy sand, or in cases where the proportion of clasts is high, as mud or alternating mud and sand. This facies is most commonly interbedded with inclined heterolithic stratified sand and mud (Facies 10A and 10B), or may be associated with karst breccias (Facies 18) and slumped material (Facies 7B). In other cases, mudstone clast breccia is associated with other crossbedded sands (Facies 5, 6).

The development of Facies 7A in the Firebag-Sunrise area is about the same as its development in the McMurray Formation in the SMA (Figure 9, Table 3). Facies 7A averages about 4% of the core thickness, locally reaching a maximum of 24% of the core thickness in the Firebag-Sunrise area (Figure 7). This facies is within the Lower McMurray Fluvial Facies Association and the Upper McMurray Estuarine Facies Association (Figure 8, Table 3). Facies 7A is interpreted as being deposited from slumping and/or erosion and redeposition of mud beds from overbank and bar areas into lower parts of river or estuarine channels. These sites of resedimentation include cutbanks along meandering channels and from higher to lower portions of dipping point-bar surfaces. In cases where the mud-clast breccia occurs with Facies 18 karst breccia, Facies 7A is interpreted as being slump and sediment gravity flows associated with sinkhole collapse and infill in karst areas.

5.8 Facies 7B. Slumped Sand and/or Mudstone

Facies 7B consists of packages of beds of sand and/or mudstone that have undergone synsedimentary deformation, showing internal faults and folds. As with the mudstone clast breccias (Facies 7A), the contrast of internal fold and fault structures is dramatic in most of the core where this facies occurs, since the resedimented mud beds generally lack bitumen staining, whereas the interbedded sands and sand-matrix are commonly bitumen stained (Figures 12 to 14). Folds are sharp, tight chevrons or more open and convoluted geometries. Commonly the folds are larger than the dimensions of the core, and are evident only by the occurrence of systematic changes in bedding orientation, clast fabric or over-steepened crossbedding (Figures 14 to 16). On gamma-ray logs, facies can appear either sandy or muddy, depending upon the proportion of the interbedded sand or mud that was folded. Facies 7A slump facies is commonly interbedded with inclined heterolithic stratified sand and mud (Facies 10A, 10B), or may be associated with mud-clast (Facies 7A) and karst (Facies 18) breccias. Less commonly, the slumped sand and mudstone are associated with crossbedded sand (Facies 5, 6).

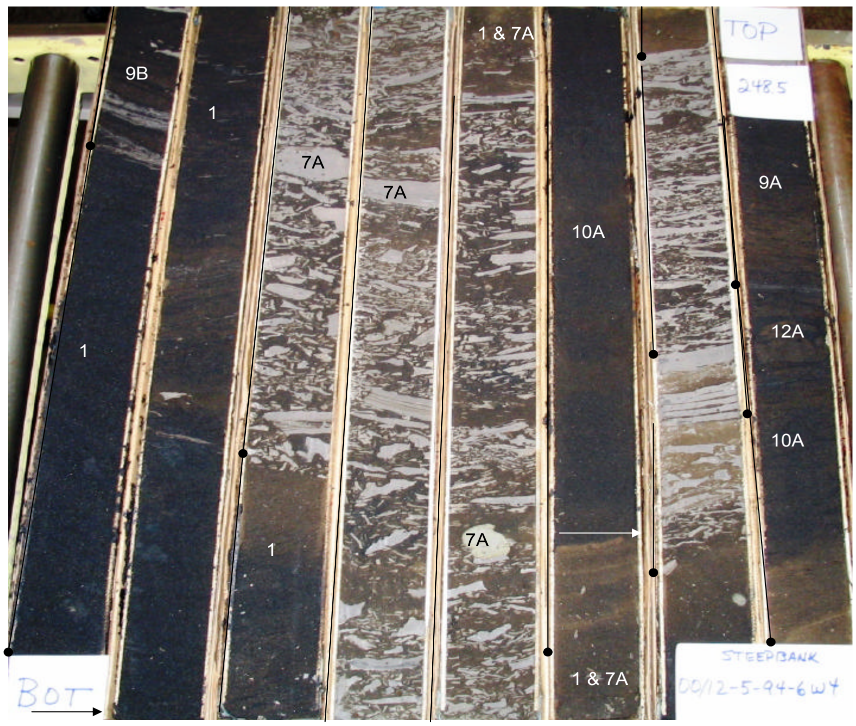

Figure 12. Core photograph showing facies in Upper McMurray Fluvio-Estuarine Facies Association: core location 00/12-05-094-06W4, 248.5–254.5 m. Core boxes are each 75 cm long.

The overall development of Facies 7B in the Firebag-Sunrise area is about the same as its development elsewhere in the McMurray Formation in the SMA (Figure 9, Table 3). Facies 7B averages about 2.5% of the core thickness in the Firebag-Sunrise area. What differs significantly is that in areas of increased accommodation, up to 38% of a core may be slumped, where individual slumps exceed 12 m in thickness. These thicker occurrences of the slumped sand and mudstone are within the Lower McMurray. Thinner slump facies also occur higher upsection within the Lower McMurray Fluvial Facies Association and within the Upper McMurray Estuarine Facies Association (Figure 8, Table 3). Facies 7B has a similar origin as the Facies 7A mud-clast breccias, interpreted as a result of sliding and slumping of material along steep cutbanks and dipping point-bar surfaces, or in the thicker occurrences these may be slumped/ slide material at the front of deltas that debouched into the Bitumont Basin.

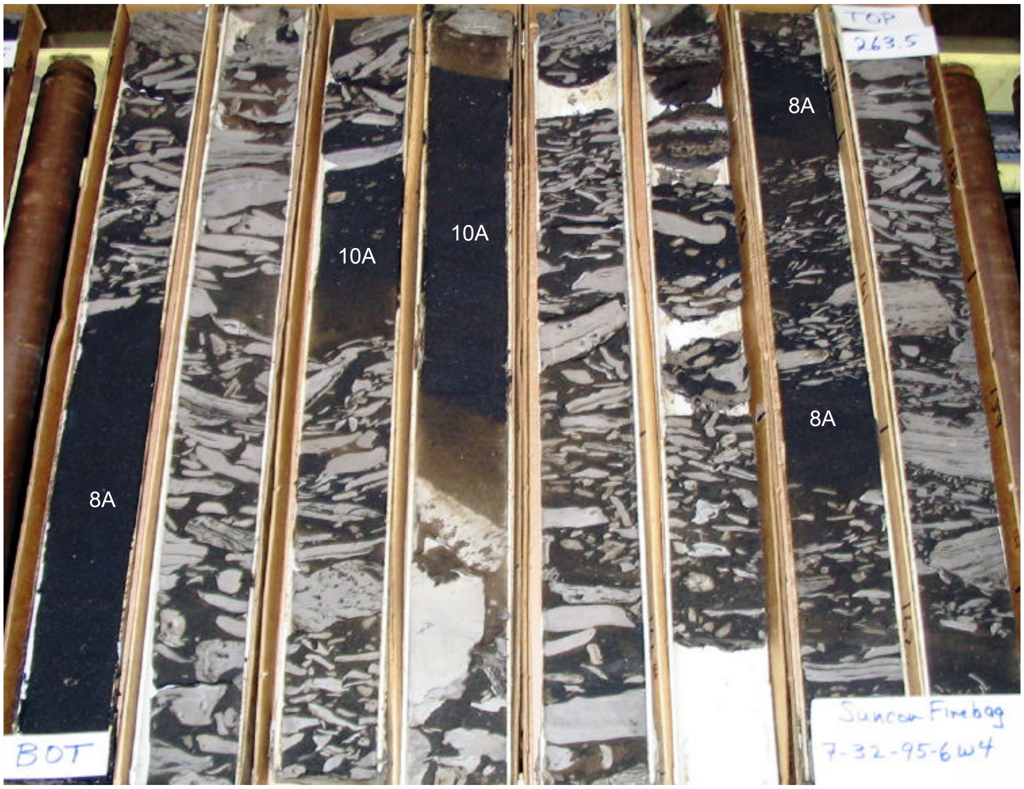

Figure 13. Core photograph showing facies in Upper McMurray Estuarine Facies Association: core location AA/07-32-095-06W4, 263.5–269.5 m. Core boxes are each 75 cm long.

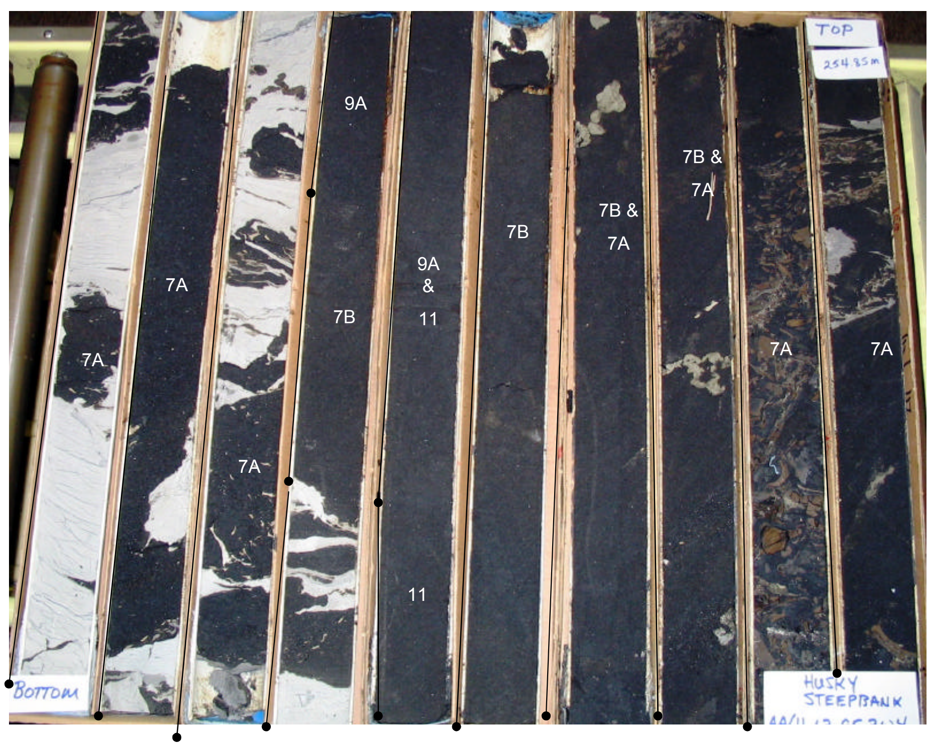

Figure 14. Core photograph showing facies in Upper McMurray Estuarine Facies Association: core location AA/11-13-095-07W4, 254.85–262.35 m. Core boxes are each 75 cm long.

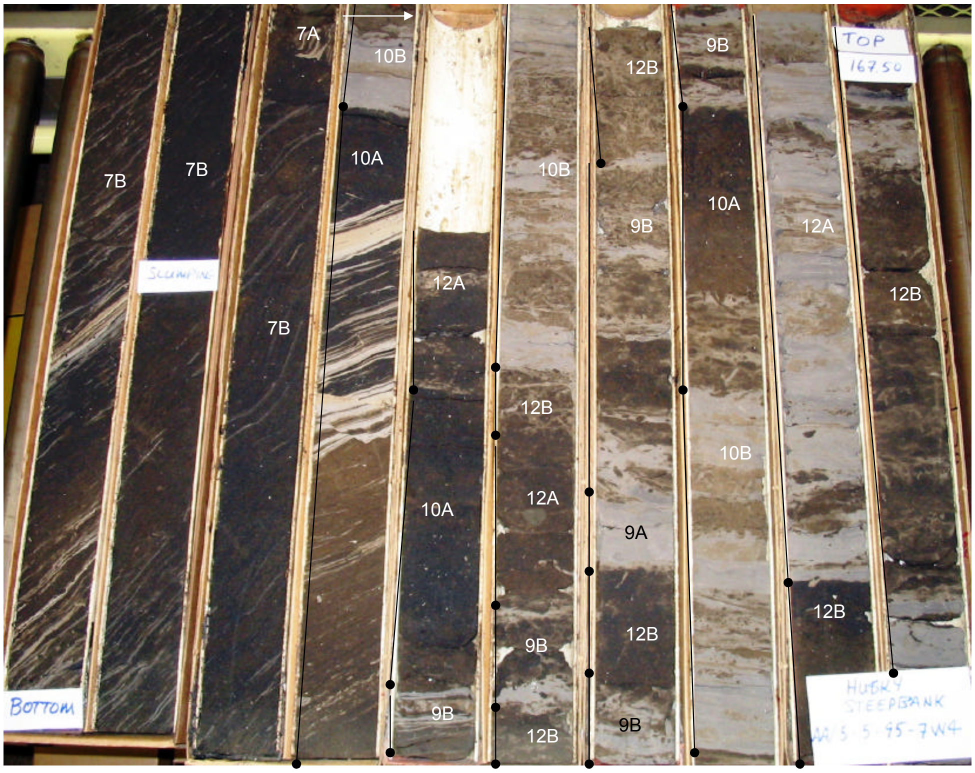

Figure 15. Core photograph showing facies in Upper McMurray Estuarine Facies Association: core location AA/05-05-095-07W4, 167.5–175 m. Core boxes are each 75 cm long.

Figure 16. Core photograph showing facies in Upper McMurray Estuarine Facies Association: core location AA/05-05-095-07W4, 175.3–183.55 m. Core boxes are each 75 cm long.

5.9 Facies 8A. Fine to Coarse-Grained Massive Sand and Facies 8B Massive Silt

Facies 8A consists fine to coarse grained sand that is apparently structureless and does not appear to have any relict burrows or a biogenic fabric. If the sand or silt has relict burrows or a pervasive bioturbation texture, then it would be classified as one of the more heavily burrowed facies (Facies 12B to 12E, Facies 13A, 13B, depending upon the relative degree of bioturbation and grain size). On gamma-ray logs the massive sand Facies 8A appears to be a clean (low gamma ray) sand. Most commonly this facies is associated with the mudstone clast (Facies 7A) (Figures 13 and 19) and karstic (Facies 18) (Figure 14) breccias, and with the slumped sand and/or mudstone units (Facies 7B). Only one occurrence of the Facies 8B massive silt was noted in core in the Firebag-Sunrise area.

Facies 8A is less common in the Firebag-Sunrise area compared with its occurrence in the McMurray Formation in the SMA (Figure 9, Table 3). Facies 8A averages about 2% of the core thickness in the Firebag-Sunrise area (Figure 7). As with the Facies 7B slumps, what differs significantly is that in areas of increased accommodation along the unconformity up to 26% of individual cores may be massive, locally exceeding 10 m in thickness (Figures 15 and 16). Facies 8A is interpreted to have a similar origin as the Facies 7A mud-clast breccias and Facies 7B slumped units, most likely a result of sediment slumping and liquefaction, with rapid redeposition that prohibited the development of primary sedimentary structures. Similar to the slump Facies 7B units, increased thicknesses of massive, slumped and liquefied sands may be related to failure of delta-front foresets along the eastern margin of the Bitumont Basin.

5.10 Facies 9A. Very Fine to Fine-Grained Ripple Crossbedded Sand

Facies 9A consists very fine to fine-grained sand that shows a variety of small-scale crossbedding, including ripples, ripple drift (Figures 12, 14, 15, 19 and 23) and rare small-scale herringbone types. On gamma-ray logs, the rippled sand Facies 9A appears to be a clean (low gamma ray) sand. In the Firebag-Sunrise area Facies 9A is ubiquitous, found in every stratigraphic unit. Facies 9A rippled sand is in the Lower McMurray Fluvial Facies Association, the Upper McMurray Estuarine Facies Association and the Upper McMurray Coastal Plain Facies Association.

Facies 9A is less common in the Firebag-Sunrise area compared with its occurrence in the McMurray Formation in the SMA. Facies 9A averages about 4% of the core thickness in the Firebag-Sunrise area, compared with nearly double that (8.2% on average) in the other occurrences in the SMA (Figure 9, Table 3). In some cases, the rippled units in the Firebag-Sunrise area can account for up to 22% of the thickness within individual cores. The same preponderance of a ripple-dominated package was also observed locally in some outcrops of the McMurray Formation along the Athabasca River (Hein et al., 2000). Facies 9A rippled sand is common in all the different facies associations, and as such, this facies is not diagnostic of any particular environment. Facies 9A rippled sand is interpreted as being deposited from mainly unidirectional flows capable of transporting very fine to fine-grained sand. Less commonly, in the case of the small scale herringbone crossbedding, bidirectional tidal current flows were dominant.

5.11 Facies 9B. Very Fine to Fine-Grained Flaser-Bedded Sand and Mud

Facies 9B consists of very fine to fine-grained sand that is interlaminated with mud, that together form crossbedded units. Flaser beds include a variety of small-scale crossbedding, such as ripples, ripple drift and small-scale herringbone types. Less commonly, there is interlamination of sand and mud on larger-scale trough crossbedding (called 'linsen' bedding). On gamma-ray logs, the flaser-bedded Facies 9B appears to be clean sand if the proportion of sand is high; in other cases, where the proportion of

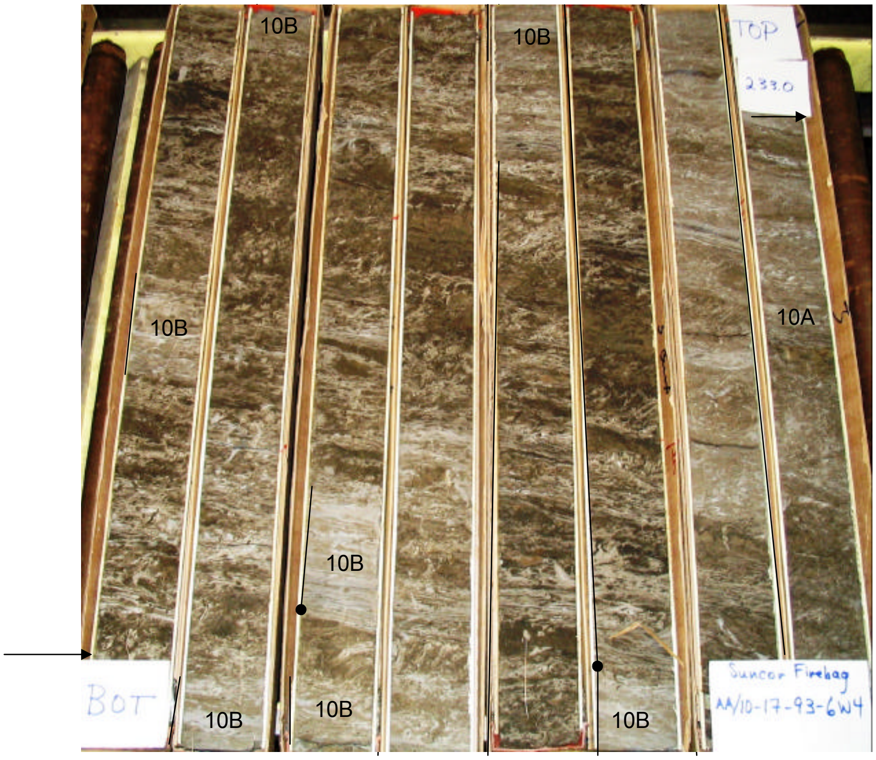

Figure 17. Core photograph showing facies in Upper McMurray Estuarine Facies Association: core location AA/10-17-093-06W4, 233–239 m. Core boxes are each 75 cm long.

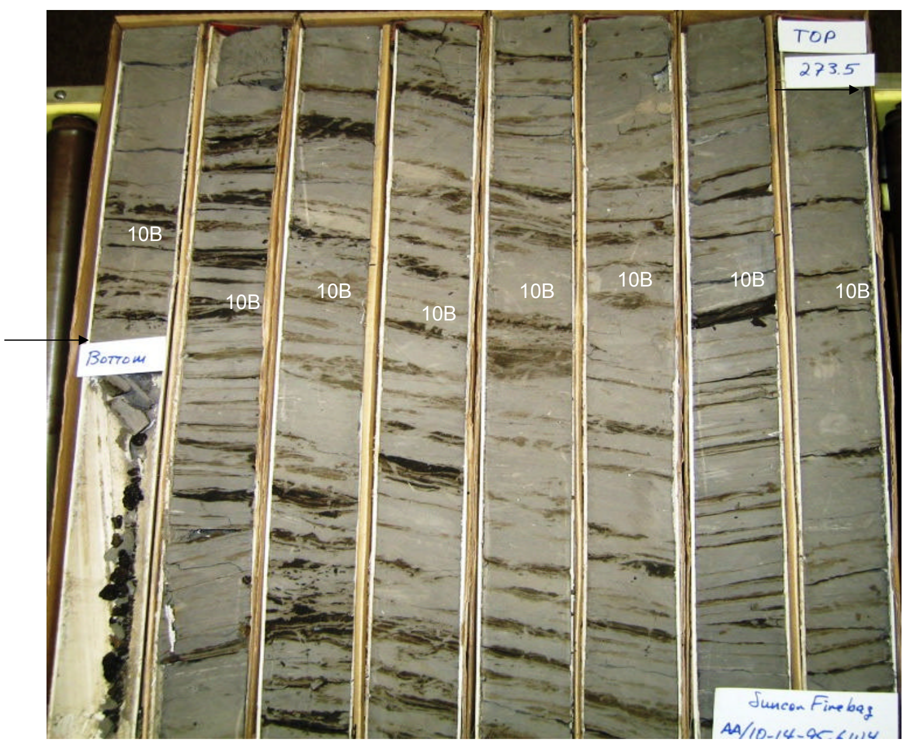

Figure 18. Core photograph showing facies in Upper McMurray Estuarine Facies Association (Facies 10B): core location AA/10-14-095-06W4, 273.5–279.13 m. Core boxes are each 75 cm long.

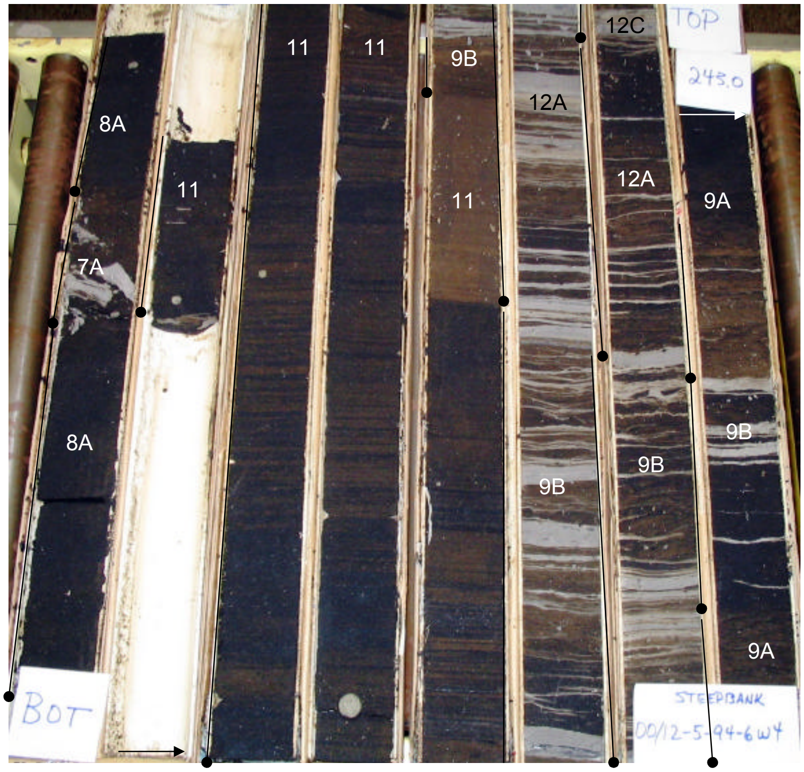

Figure 19. Core photograph showing facies in Upper McMurray Estuarine/Coastal Plain Facies Association: core location 00/12-05-094-06W4, 243–248.25 m. Core boxes are each 75 cm long.

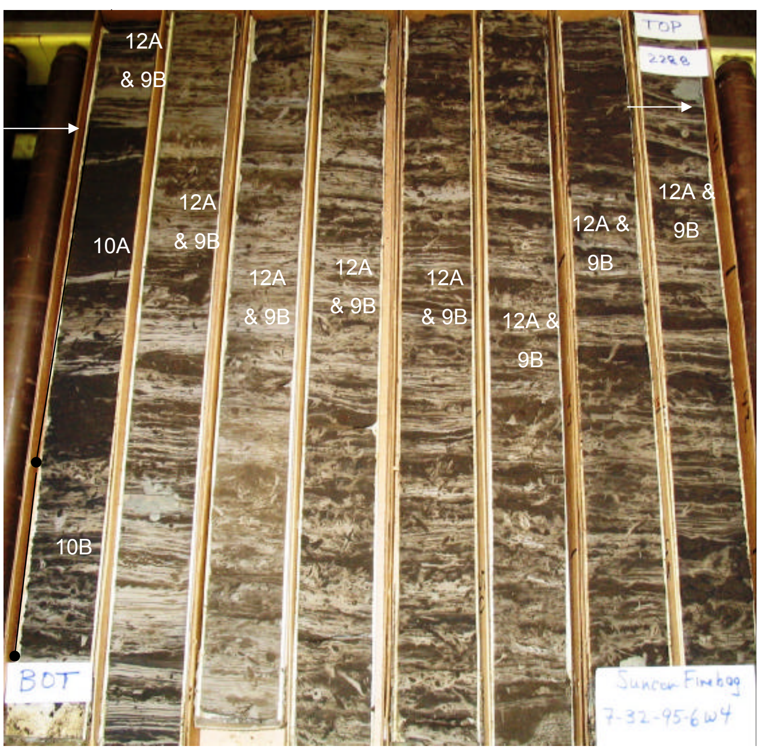

Figure 20. Core photograph showing facies in Upper McMurray Estuarine/Coastal Plain Facies Association: core location AA/07-32-095-06W4, 228.8–234.8 m. Core boxes are each 75 cm long.

Figure 21. Core photograph showing facies in Upper McMurray Estuarine/Coastal Plain Facies Association: core location AA/11-11-095-07W4, 203.05–210.55 m. Core boxes are each 75 cm long.

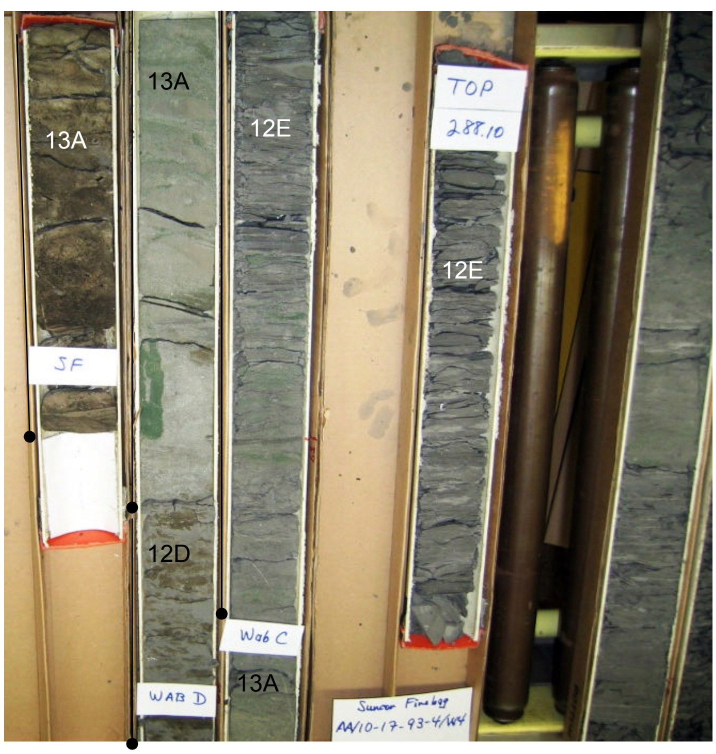

Figure 22. Core photograph showing facies in Upper McMurray Estuarine/Coastal Plain Facies Association, overlain by Wabiskaw D and Wabiskaw C successions: core location AA/10-17-093-04W4, 288.1–290.35 m. Core boxes are each 75 cm long.

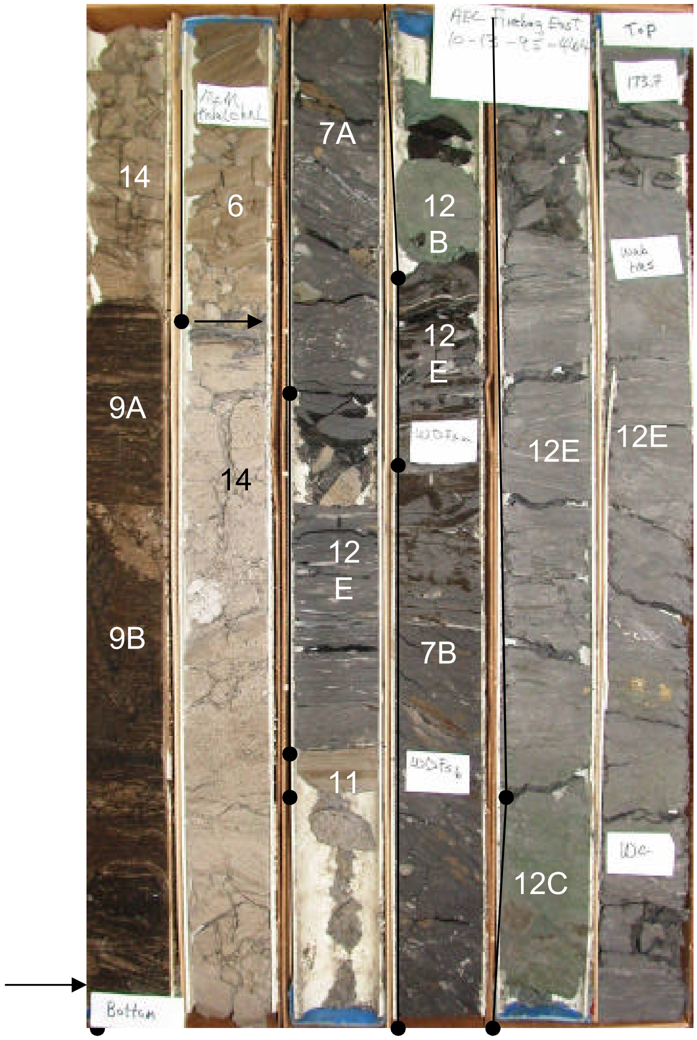

Figure 23. Core photograph showing facies in Upper McMurray Coastal Plain Facies Association, overlain by Wabiskaw D, Wabiskaw C and Regional Marine Shale units: core location AA/10-13-095-04W4, 173.7–178 m. Core boxes are each 75 cm long.

mud is high, it appears as a dirty sand or mud (high gamma ray). In the Firebag-Sunrise area, Facies 9B flaser-bedded sand and mud is ubiquitous, particularly within the Upper McMurray Estuarine Facies Associations (Figures 12, 15, 16, 19, 20 and 23).

Facies 9B is much more common in the Firebag-Sunrise area compared with its occurrence elsewhere in the McMurray Formation in the SMA. Facies 9B averages about 13% of the core thickness in the Firebag-Sunrise area (Figure 7), locally reaching 38% of individual cores. Typically in other cores and outcrops of the Upper McMurray Estuarine Facies Associations in the SMA, this is a relatively minor facies, averaging only about 3% (Figure 9, Table 3). The flaser-bedded Facies 9B sand and mud are interpreted as being deposited from bi- and unidirectional flows capable of transporting very fine to fine-grained sand by traction. The finer, muddy crossbeds formed at slack times during suspension fall out in tidal flat and tidal channel complexes. The higher proportion of this facies is interpreted as due to better preservation of tidal flat and tidal channel deposits in the Firebag-Sunrise area compared with the SMA.

5.12 Facies 10A. Bioturbated, Inclined, Heterolithic Stratified Muddy Sand

Facies 10A is a sand-dominated unit comprising of interbedded sand and mudstone, at low-inclined angles (from 5 to 10 degrees), that shows low to high degrees of bioturbation (Figure 10, 12 and 17). The sand-dominated inclined heterolithic stratification (IHS) may internally show a variety of stratification and crossbedding types. Facies 10A is one end member of the IHS units, and grades into the mud-dominated Facies 10B. In some cases there is a rhythmic alternation of Facies 10A and 10B. Facies 10A in the Firebag-Sunrise area is largely associated with Facies 10B, 7A (Figures 13 and 17), and 7B, but also occurs with a variety of other facies within the Upper McMurray Estuarine Facies Associations (Facies 1, 5, 6, 9A, 9B, 12, 13 and 14). On gamma-ray logs, Facies 10A typically appears as a sandy to muddy, fining-upward unit, often with a 'serrated log pattern,' representing abrupt alterations of sand and mud beds.

Facies 10A is more common in the Firebag-Sunrise area, where it averages about 18% of the core thickness in the Firebag-Sunrise area (Figure 7), compared with only about 13% for the Upper McMurray elsewhere in the SMA (Figure 9, Table 3). As with the Facies 7B slumps, what differs significantly is that in some areas of increased accommodation on the unconformity up to 52% of individual core intervals may be sandy IHS, which is a much higher proportion of this facies occurrence than is typical of the McMurray succession (Figures 15 and 16). Thinner units of Facies 10A are interpreted as being deposited mainly from traction current and tidal flows that deposited crossbedded sands on lateral accretion surfaces of point-bars within meandering estuarine channels. During slack flows, suspension fall-out resulted in deposition of the mud interlaminae. A tidal influence is clearly evident in the development of this facies, with stronger current and tidal flows dominant over suspension fall out. In the case of the exceptionally thick occurrences of Facies 10A, these units may represent tidally influenced deltas that preferentially formed in areas of increased accommodation and continued subsidence, in areas of affected by salt-dissolution and underlying karstification.

5.13 Facies 10B. Bioturbated, Inclined, Heterolithic Stratified Sandy Mud

Facies 10B is a mud-dominated unit comprising interbedded mud and sand, at low-inclined angles (from 5 to 10 degrees), that shows low to high degrees of bioturbation (Figures 17 and 18). The mud-dominated inclined heterolithic stratification (IHS) may internally show a parallel lamination or mud-dominated flaser bedding with sand. IHS Facies 10B is one end member of the IHS units, and grades into the sand-dominated Facies 10A. In some cases, there appears to be a cyclical alternation of both Facies 10A and 10B (Figure 17). Facies 10B in the Firebag-Sunrise area is largely associated with Facies 10A (Figures 15, 16 and 17) Facies 7A and Facies 7B, but also occurs with a variety of other facies within the Upper McMurray Estuarine Facies Associations (Facies 1, 5, 6, 9A, 9B, 12, 13 and 14) (cf. Figures 16 and 20). On gamma-ray logs, Facies 10B typically appears as a muddy, fining-upward unit, often capping the sandy IHS Facies 10A.

Facies 10B is much more common in the Firebag-Sunrise area, where it averages about 11% of the core thickness in the Firebag-Sunrise area (Figure 7), compared with only about 1.5% for the Upper McMurray elsewhere in the SMA (Figure 9, Table 3). As with the Facies 10B sandy IHS, what differs significantly is that in areas of increased accommodation space up to 68% of individual core intervals may be muddy IHS This is an exceptionally higher proportion of this facies occurrence than is typical of the McMurray succession (Figures 15 and 16). The distinction in Facies 10B mud is that suspension fall-out dominates over traction current and tidal flow. As with Facies 10A, thinner units of Facies 10B are interpreted as being deposited on lateral accretion surfaces of point-bars within meandering estuarine channels. In the case of the exceptionally thick and dominant occurrences of this facies, these units represent tidally-influenced deltas or bay-head deposits that preferentially formed in areas of increased accommodation.

5.14 Facies 11. Very Fine to Medium-Grained, Stratified Sand

Facies 11 is well sorted, stratified sand with well developed parallel stratification (Figures 14 and19). Facies 11 in the Firebag-Sunrise area is largely associated with rippled sands Facies 9A (Figure 14) and flaser-bedded sand and mud Facies 9B (Figure 19). On gamma-ray logs, Facies 11 typically appears as clean, blocky sand.

Facies 11 is less common in the Firebag-Sunrise area, where it averages about 2.5% of the core thickness in the Firebag-Sunrise area (Figure 7), compared with about 9% for the McMurray Formation elsewhere in the SMA (Figure 9, Table 3). In some cases, individual cores may show a much higher percentage of this facies, where locally it can reach 23% . Facies 11 stratified sands are interpreted as being deposited from strong traction currents able to transport very fine to medium-grained sand. The common occurrence of the stratified Facies 11 sands, with both the rippled Facies 9A sand and Facies 9B flaser sand and mud, indicate that stratified Facies 11 sand is largely part of the tidal channel and tidal flat complexes of the Upper McMurray Estuarine and Coastal Plain Facies Associations in the Firebag-Sunrise area.

5.15 Facies 12A. Rhythmically Laminated Sand/Mud to Facies 12E Laminated Silt and Mud

Facies 12A is well sorted sand, often with good parallel stratification, that alternates with laminated mud in varying proportions and scales of laminae thicknesses (Figures 15, 16, 19 and 20). As with the IHS Facies 10A and 10B units, the variety of Facies 12A to 12E is a gradational classification scheme, based on both grain size and degree of bioturbation (Figure 6). The coarsest grained and least bioturbated unit is Facies 12A, with the finest grained and least bioturbated unit being Facies 12E. If primary sedimentary structures are totally obliterated, then the unit is classified as Facies 13A or 13B, depending on the grain size. On gamma-ray logs, Facies 12A can appear as clean sand, whereas Facies 12E shows a shale response.

Facies 12A, 12B and 12C units are much more common in the Firebag-Sunrise area, where they range, on average, from about 5.5% to 12% of the core thickness (Figure 7), compared with rare occurrences for the McMurray Formation elsewhere in the SMA (Figure 9, Table 3). Individual cores may show a much higher percentage of these facies, where locally it can exceed 50% of a given core interval. Facies 12A to 12E laminated and bioturbated stratified sand and mud is interpreted as being deposited from strong traction currents able to transport very fine to medium-grained sand, alternating with suspension fall out of fines during slack periods. These laminated and bioturbated sand and mud units are commonly associated with the stratified Facies 11, the rippled Facies 9A and flaser-bedded Facies 9B units.
This suggests that these facies may be part of the tidal channel and tidal flat complexes of the Upper McMurray Estuarine and Coastal Plain Facies Associations in the Firebag-Sunrise area. Other deposits are interpreted as bay-fills of the Upper McMurray Coastal Plain Facies Association.

5.16 Facies 13A. Heavily Burrowed Muddy Sand and Facies 13B Intensely Burrowed Muddy Silt/Silty Mud

Facies 13A is poorly sorted muddy sand, in which most of the primary sedimentary structures have been obliterated through bioturbation (Figure 22). As with the IHS Facies 10A and 10B units, the Facies 13A grades into Facies 13B, as a function of grain size. On gamma-ray logs, Facies 13A appears as a dirty sand or shale response, depending upon the amount of admixed mud, whereas Facies 13B shows a shale response.

In the Firebag-Sunrise area, these heavily bioturbated units are rare (usually around 1% of the core thickness) (Figure 7). This is similar to the Facies 13A and 13B occurrences elsewhere in the McMurray Formation of the SMA, where they are one of the less common facies (~ 6%, Figure 9, Table 3). Locally in the Firebag-Sunrise area, the completely bioturbated/churned units can exceed 25%. The thicker Facies 13A and 13B units are associated mainly with both the rippled Facies 9A and flaser-bedded Facies 9B, or with the Facies 12E well-laminated silty mud/muddy silt. These associations indicate that these facies may be part of the tidal channel and tidal flat complexes or bay-fills associated with the Upper McMurray Coastal Plain Facies Association.

5.17 Facies 14. Coaly and/or Rooted Sandy Silt/Silty Mudstone

Facies 14 is a relatively uncommon facies in the Lower McMurray and Upper McMurray successions. This facies consists of carbonaceous sandy silt/silty mudstone (Figure 24) that locally may be rooted, or shows pedogenic structures associated with paleosols (Figure 23). The facies averages about 30 cm thick, although locally it can be up to 1 m thick. Silty mudstones may be mottled, nodular or concretionary, with local siderite cement. Organic content tends to be high, and some zones show well-defined, coaly, vertical to subvertical root traces. Very thin carbonaceous laminations are common.

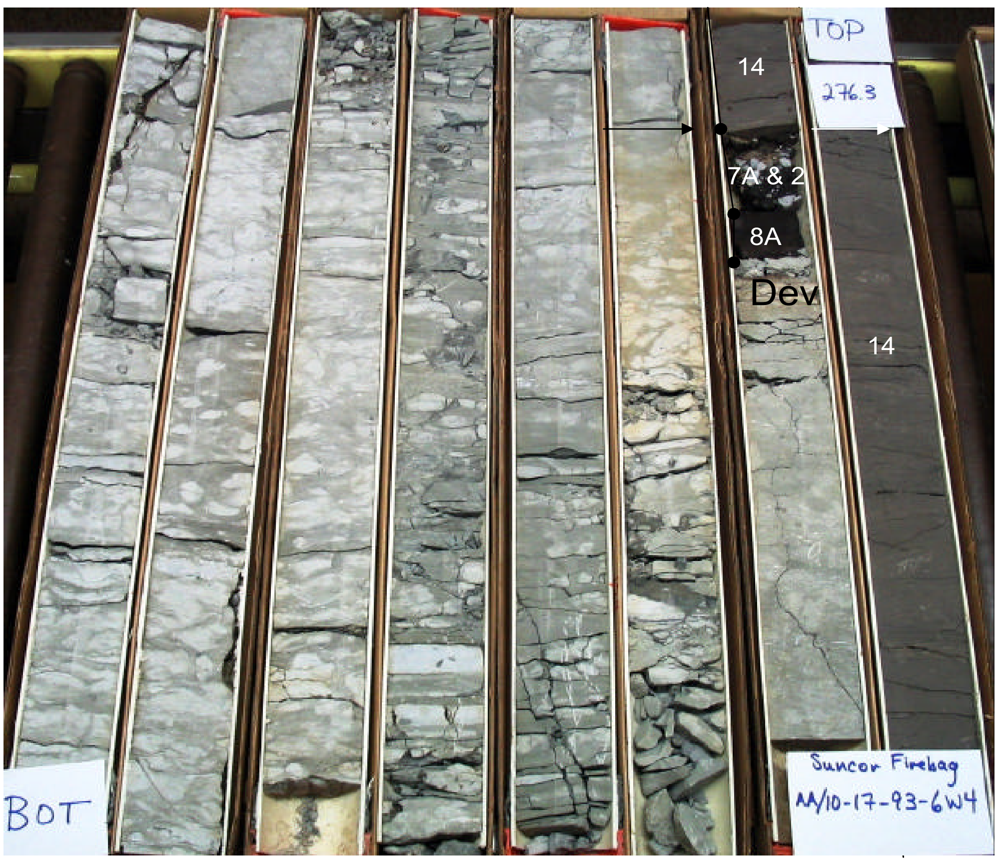

Figure 24. Core photograph showing facies in Lower McMurray Fluvial Facies Association, underlain by the Devonian Moberly limestone, with local vuggy porosity due to karstification, minor fracturing (some with bitumen infill) and minor sideritization (orange colouration): core location AA/10-17-093-06W4, 276.3–282.3 m. Core boxes are each 75 cm long.

The development of this facies is about the same, on average, in the Firebag-Sunrise area compared to the rest of the McMurray Formation in the SMA (Figure 9, Table 3). In the Firebag-Sunrise area, Facies 3 averages about 3% of the core thickness. Locally, in coaly zones, it may comprise up to half the cored interval. This facies occurs both within the Lower McMurray Fluvial Facies Association and within the Upper McMurray Estuarine/Coastal Plain Facies Association (Figure 8, Table 3). Local thickened units of this facies occur above units along the sub-Cretaceous unconformity, which are affected by karstification. As with Facies 3, the Facies 14 coaly, pedogenic and/or rooted silty and mudstone is interpreted as forming mainly in vegetated overbank areas. Such settings would include floodplains to fluvial and estuarine channels, tidal flats and exposed areas of the coastal plain successions.

5.18 Facies 16. Very Fine to Fine-Grained, Wave-Rippled Sand

Facies 16 is a relatively rare facies in the Upper McMurray successions of the Firebag-Sunrise areas, where it is on average < 1% of the core examined (Figure 7, Table 3). This facies consists of wave-rippled, well-sorted, very fine to fine-grained sand. Beds average about 10 cm thick, rarely reaching about 75 cm. The facies is more common in the Upper McMurray Coastal Plain Facies Association, and locally within some of the McMurray A2 units it can be over 25% of the cored interval.

The development of this facies is about the same, on average, in the Firebag-Sunrise area compared to the rest of the McMurray Formation in the SMA (~ 4%, Figure 9, Table 3). The wave-rippled sands are associated with tidal flat sediments, or with bay-fill parasequences, and are interpreted as forming from oscillatory waves in more open water areas, such as oxbow lakes within the estuarine systems or within bays of the coastal plain complexes.

5.19 Facies 18. Poorly Sorted Karstic Calci-/Siliciclastics

Facies 18 is a relatively rare facies occurring along the sub-Cretaceous unconformity of the Firebag-Sunrise areas, where it is on average < 1% of the core examined (Figure 7, Table 3). This facies consists of a chaotic mixture of clasts of both carbonate and quartz compositions, often admixed with other organic debris. Internal structures include breccia fabrics, dissolution textures, internal folds and faults (Figures 25 and 26). In cores that penetrate further down into the Devonian succession, it is apparent that Facies 18 grades downsection into unaltered and fresh limestone.

The development of this facies is about the same, on average, in the Firebag-Sunrise area compared to the rest of the McMurray Formation in the SMA, where it is also rarely seen (~ 1%, Figure 9, Table 3). Locally, however, the karst units may reach maximum values of about 20% of the core that is recovered from this interval.

6 Stratigraphic Units: Descriptions, Mapping and Interpretations

Well coverage for the Firebag-Sunrise study area is shown in Figure 27, with a structure map for top of the Paleozoic (paleotopography on sub-Cretaceous unconformity surface) given in Figure 28. Isopach maps of the various stratigraphic units discussed below are in Figures 29 to 35, with digital versions of all maps included on the CD.

In the Firebag-Sunrise area, the different mappable stratigraphic units within the Wabiskaw-McMurray succession are: McMurray Channel, McMurray A2 sequence, McMurray A1 sequence, Wabiskaw D Valley-fill, Wabiskaw D Shale and Wabiskaw C (Figure 3). Units identified in the Regional Geology Study (Alberta Energy and Utilities Board, 2003), but which are missing in the Firebag-Sunrise area, include the McMurray B1, McMurray B2, McMurray A Channel and Wabiskaw B Valley-fill, interpreted to be absent due to nondeposition. Because of the absence of the McMurray B2 sequence, only McMurray

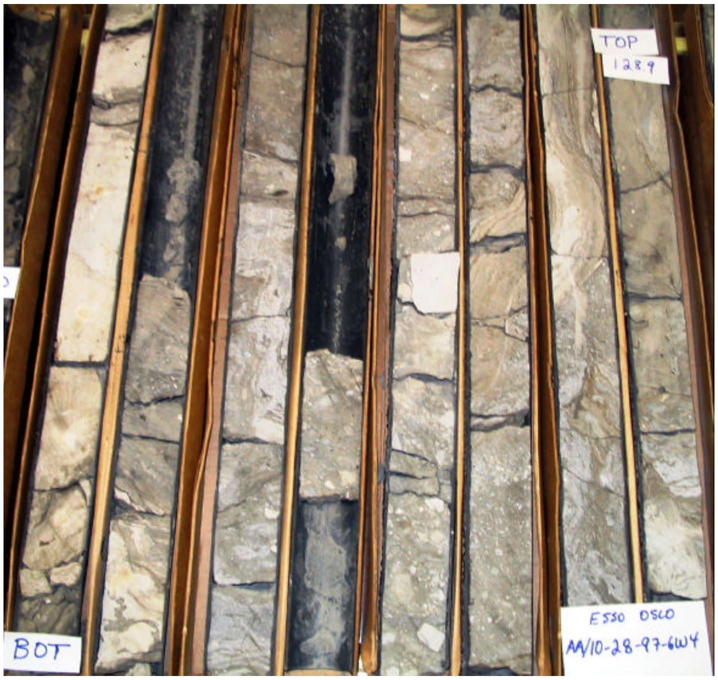

Figure 25. Core photograph showing mixed clastics and carbonate lithologies along the sub-Cretaceous unconformity, with local brecciation, prominent vertical and oblique folds, fracture fills and sideritization (orange colouration): core location AA/10-28-097-06W4, 128.9–134 m. Core boxes are each 75 cm long.

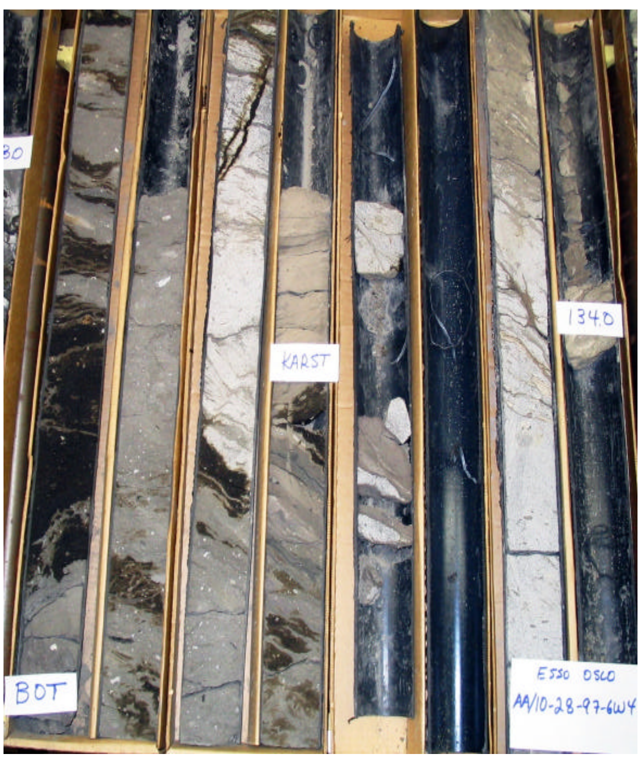

Figure 26. Core photograph showing mixed clastics and carbonate lithologies along the sub-Cretaceous unconformity, with over-steepened crossbedding, synsedimentary faults, local brecciation, prominent subvertical fracture-fills (some with bitumen infill) and sideritization (orange colouration): core location AA/10-28-097-06W4, 134–138.05 m. Core boxes are each 75 cm long.

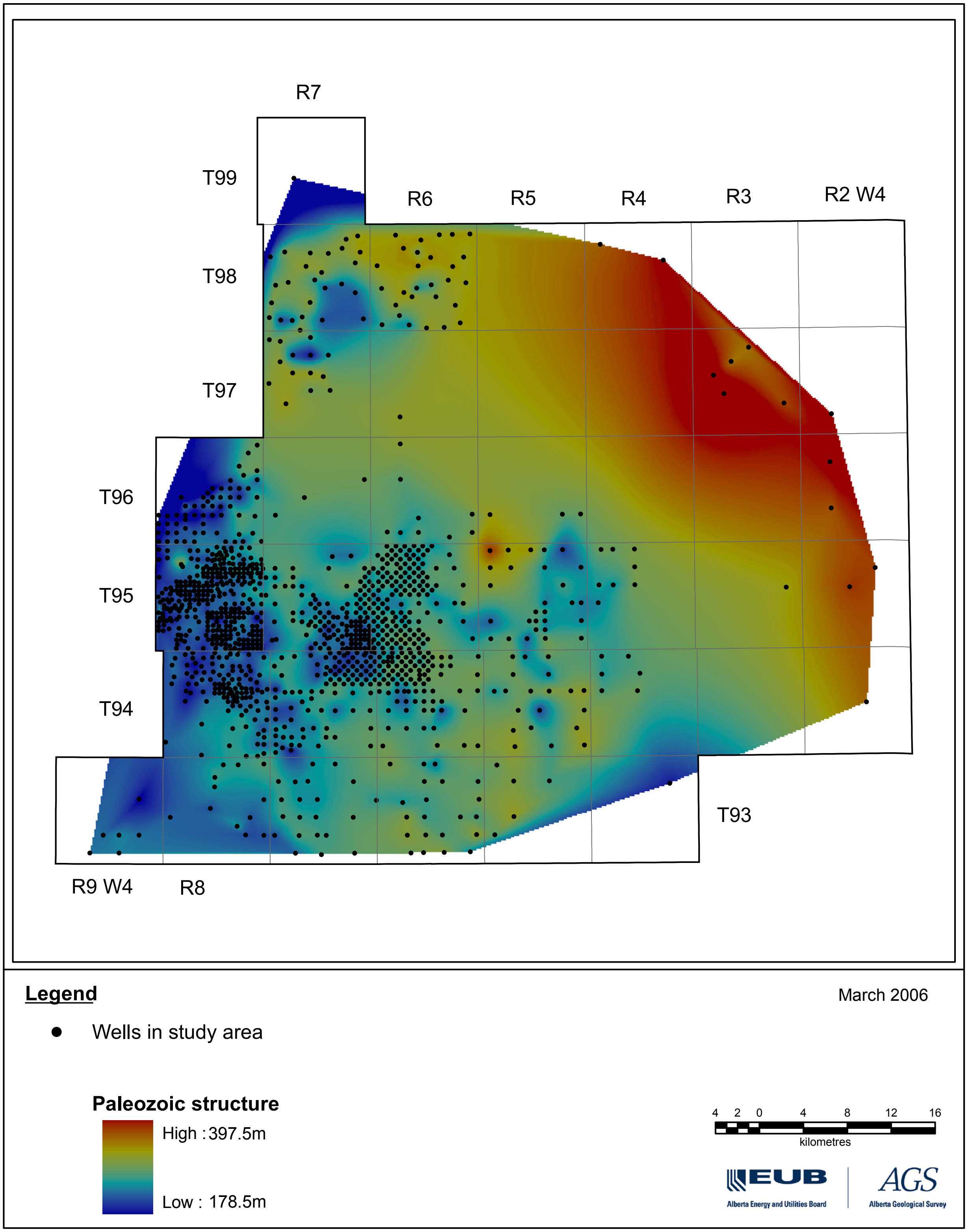

Figure 27. The Firebag-Sunrise structure map on the top of the Paleozoic, with dots showing well control for the area.

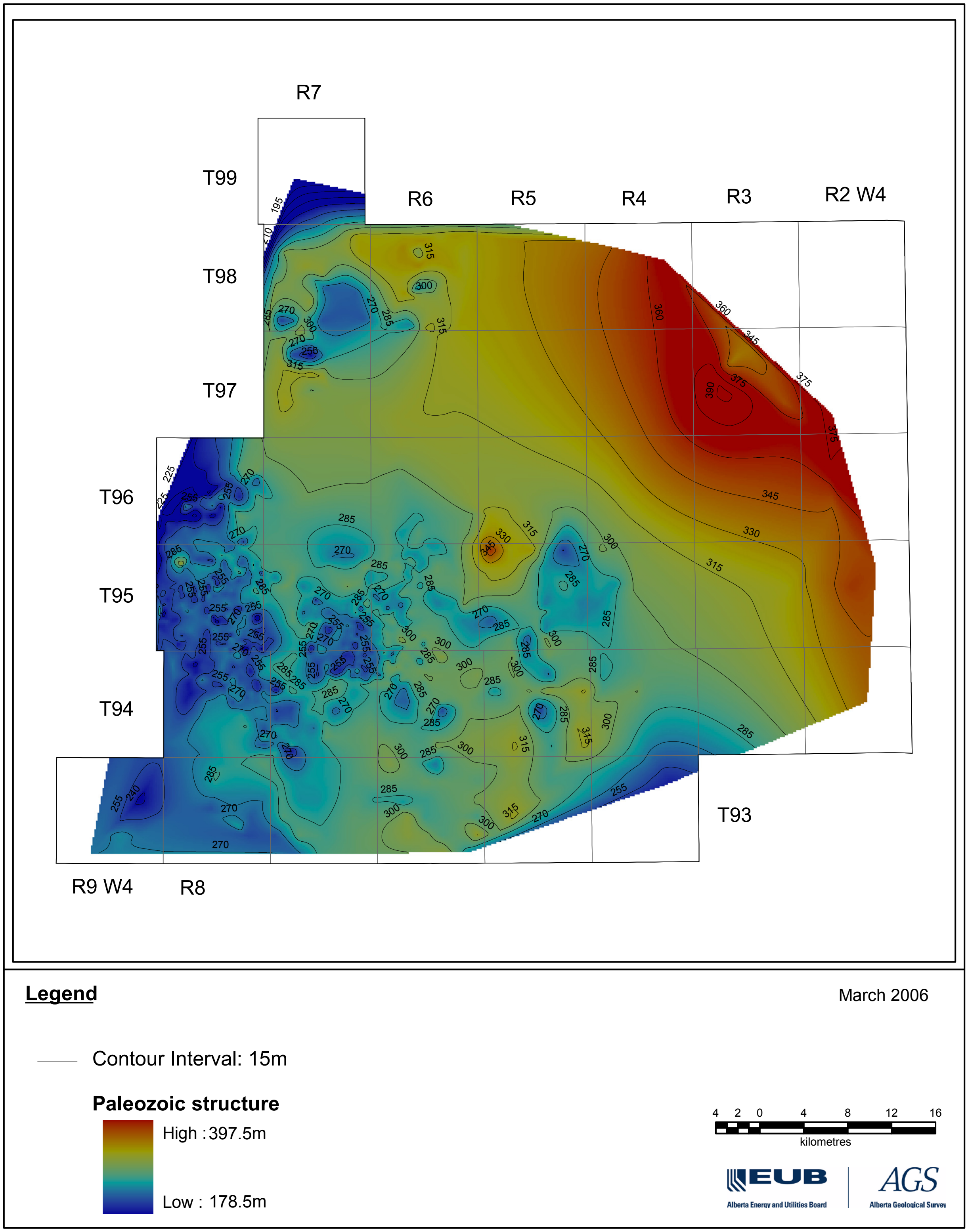

Figure 28. Structure map on the top of the Paleozoic.

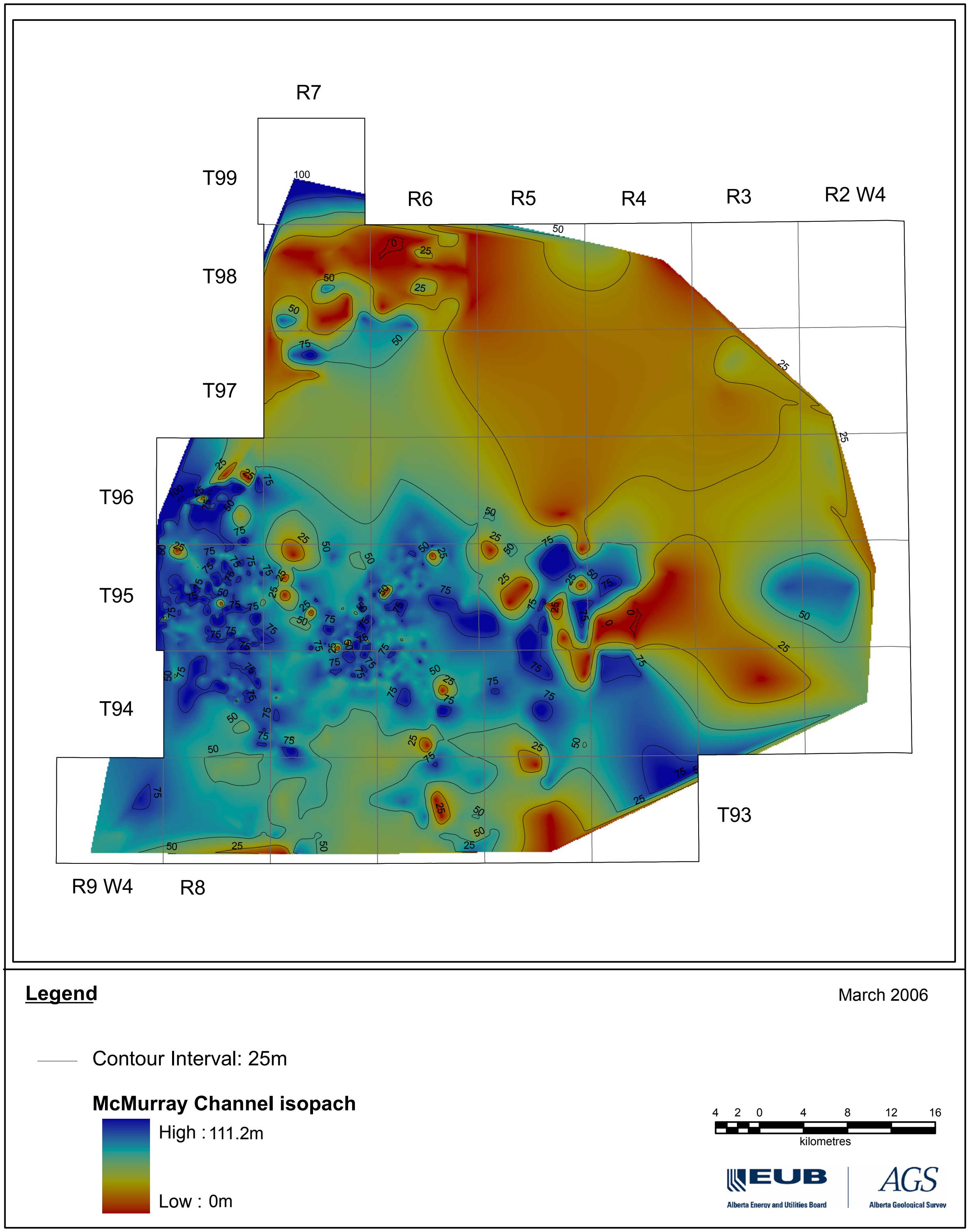

Figure 29. McMurray Channel isopach map.

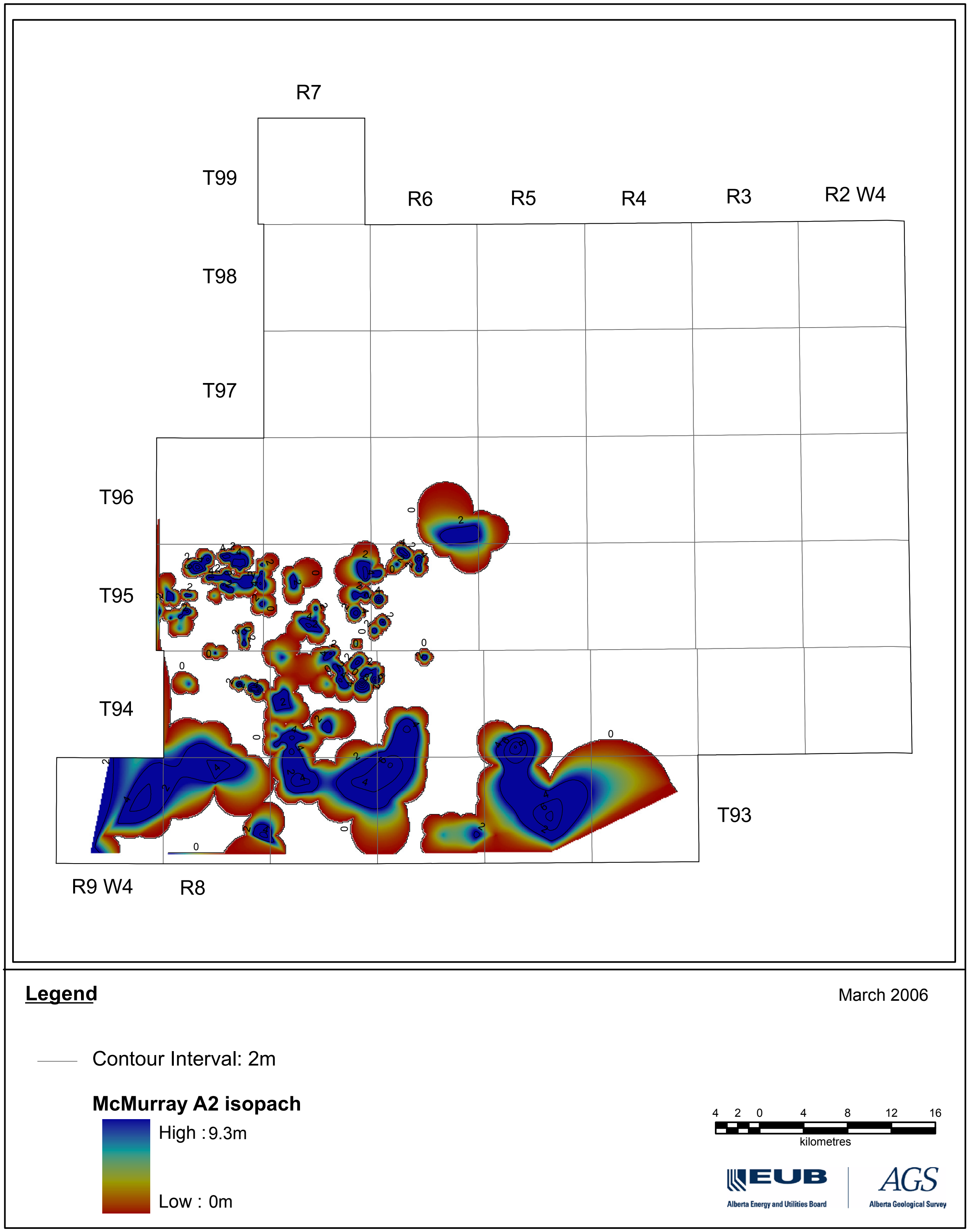

Figure 30. McMurray A2 isopach map.

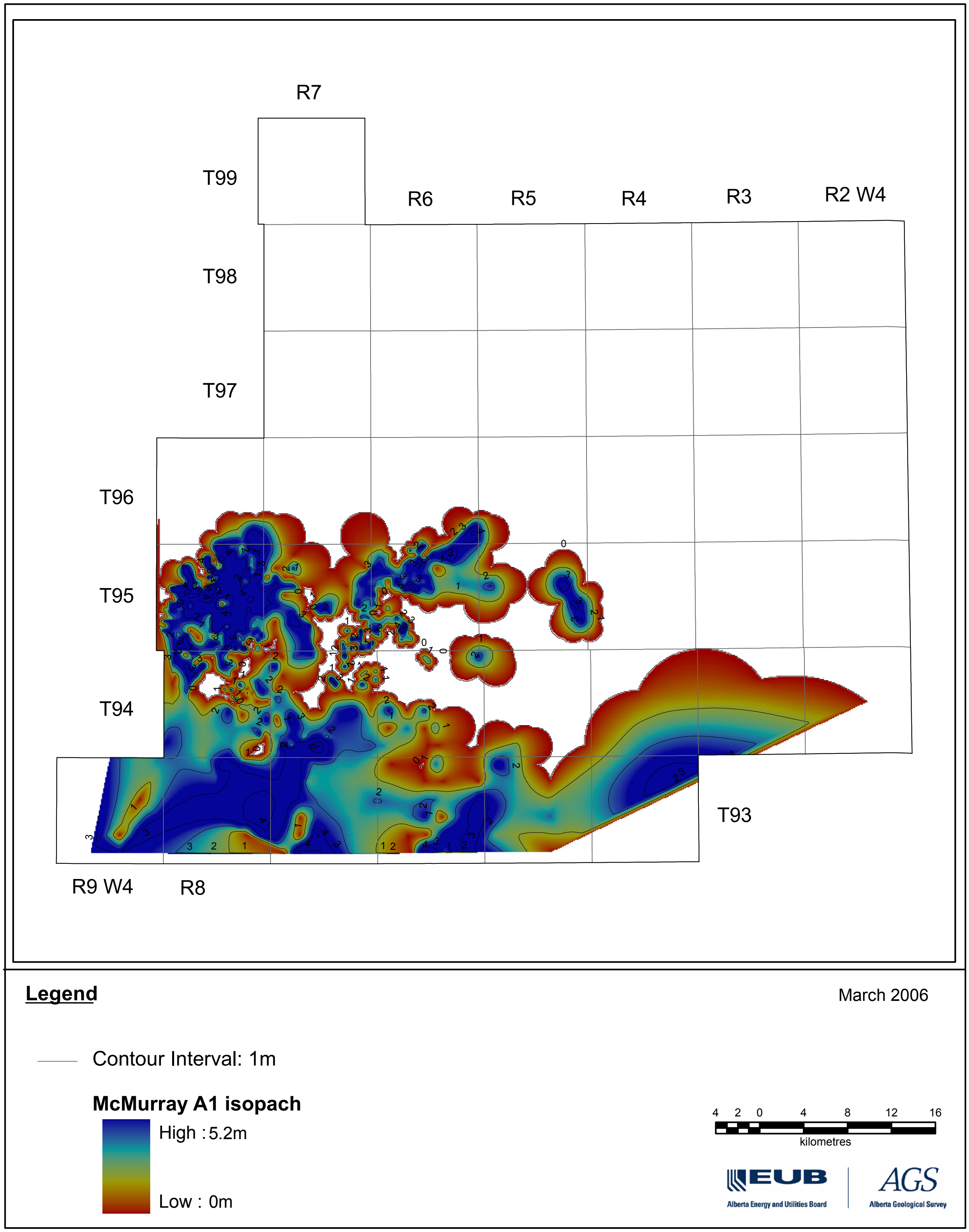

Figure 31. McMurray A1 isopach map.

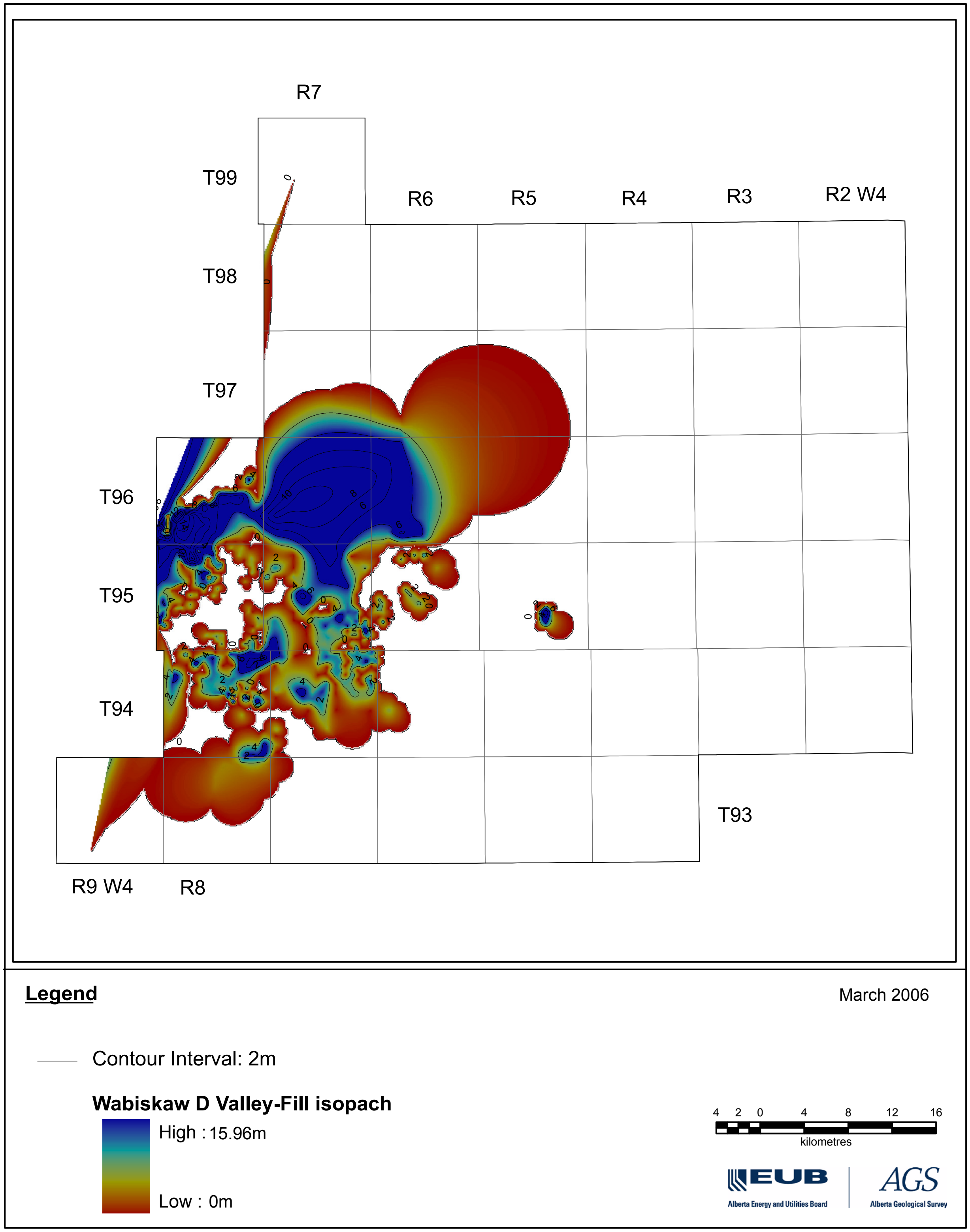

Figure 32. Wabiskaw D Valley-Fill isopach map.

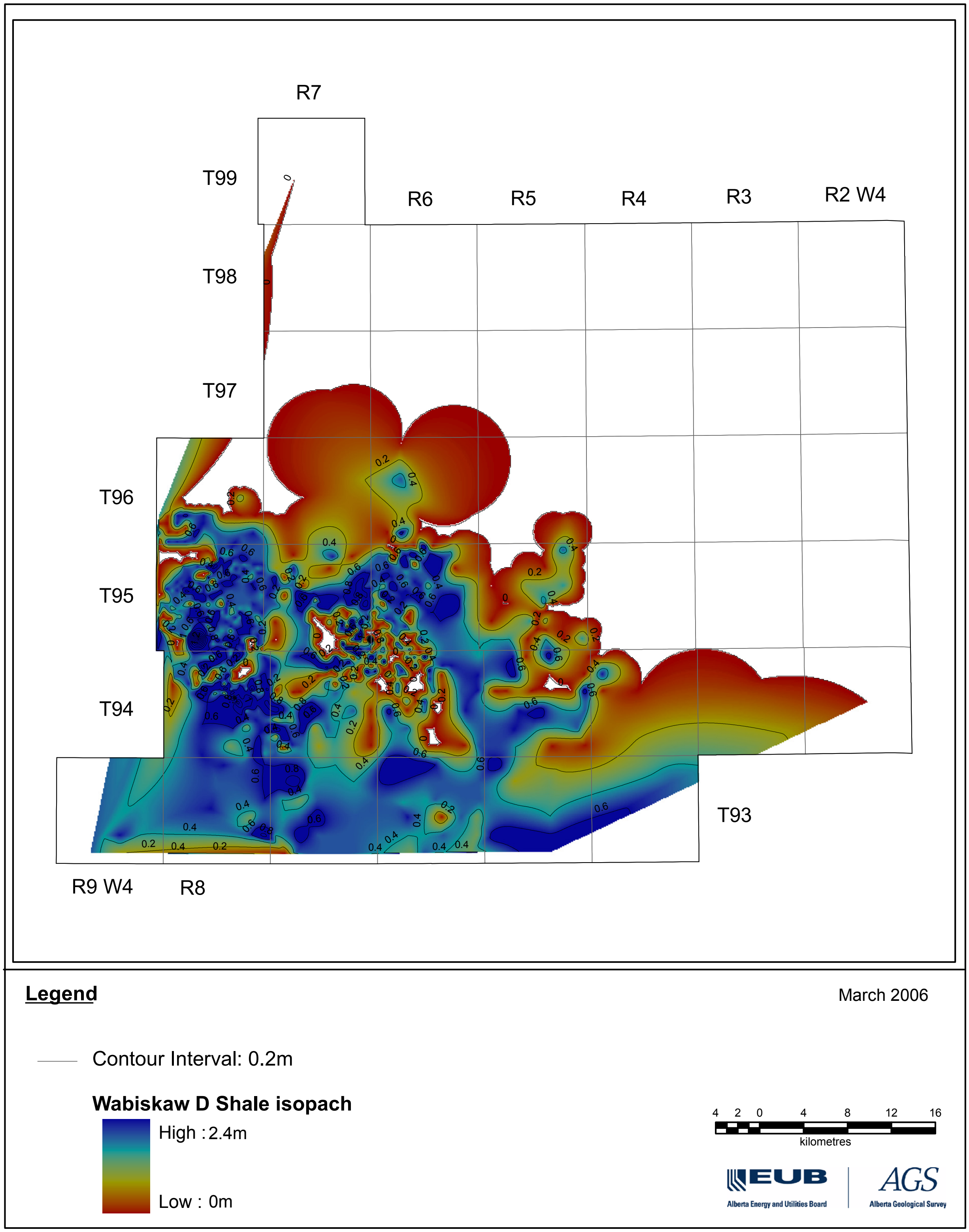

Figure 33. Wabiskaw D Shale isopach map.

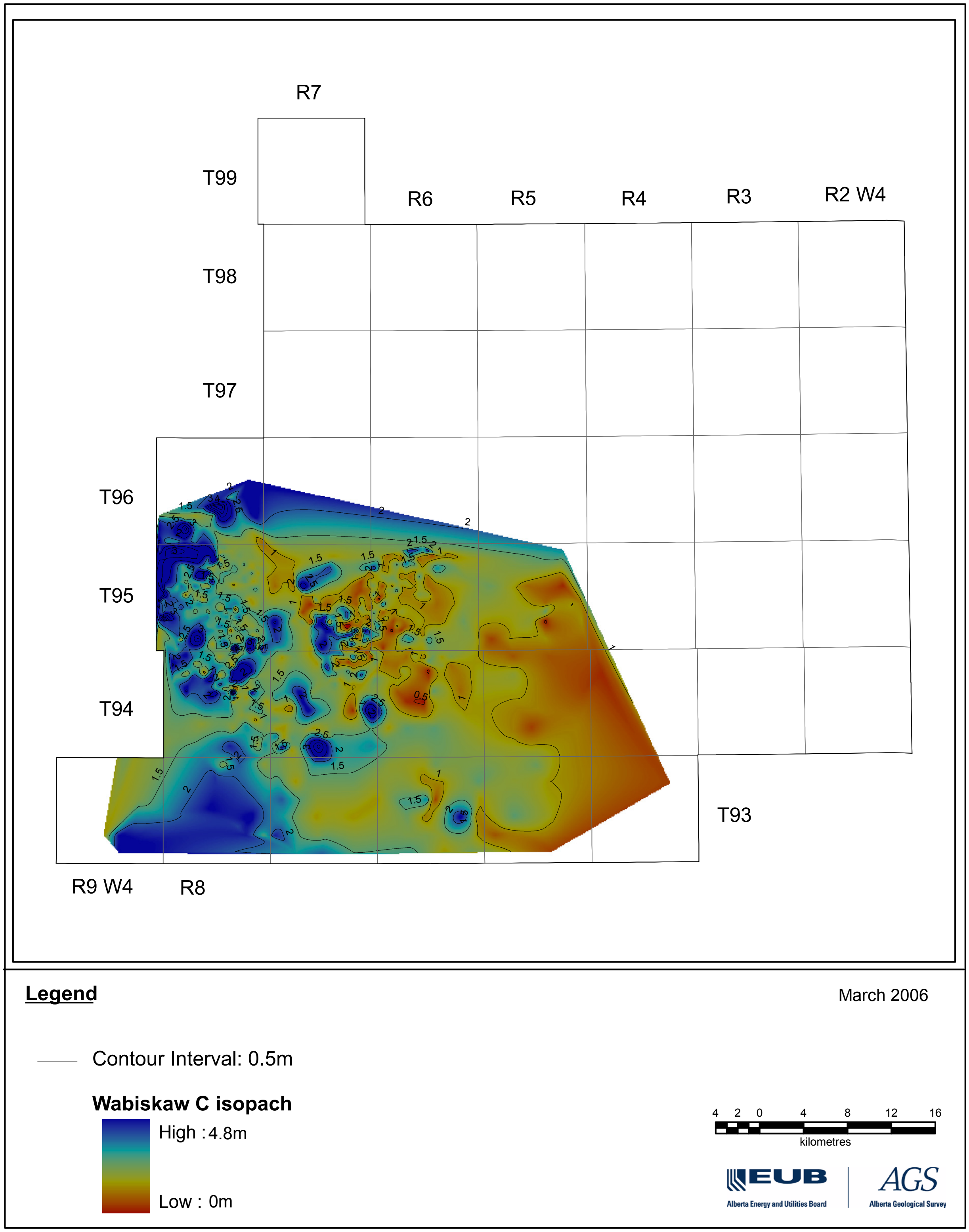

Figure 34. Wabiskaw C isopach map.

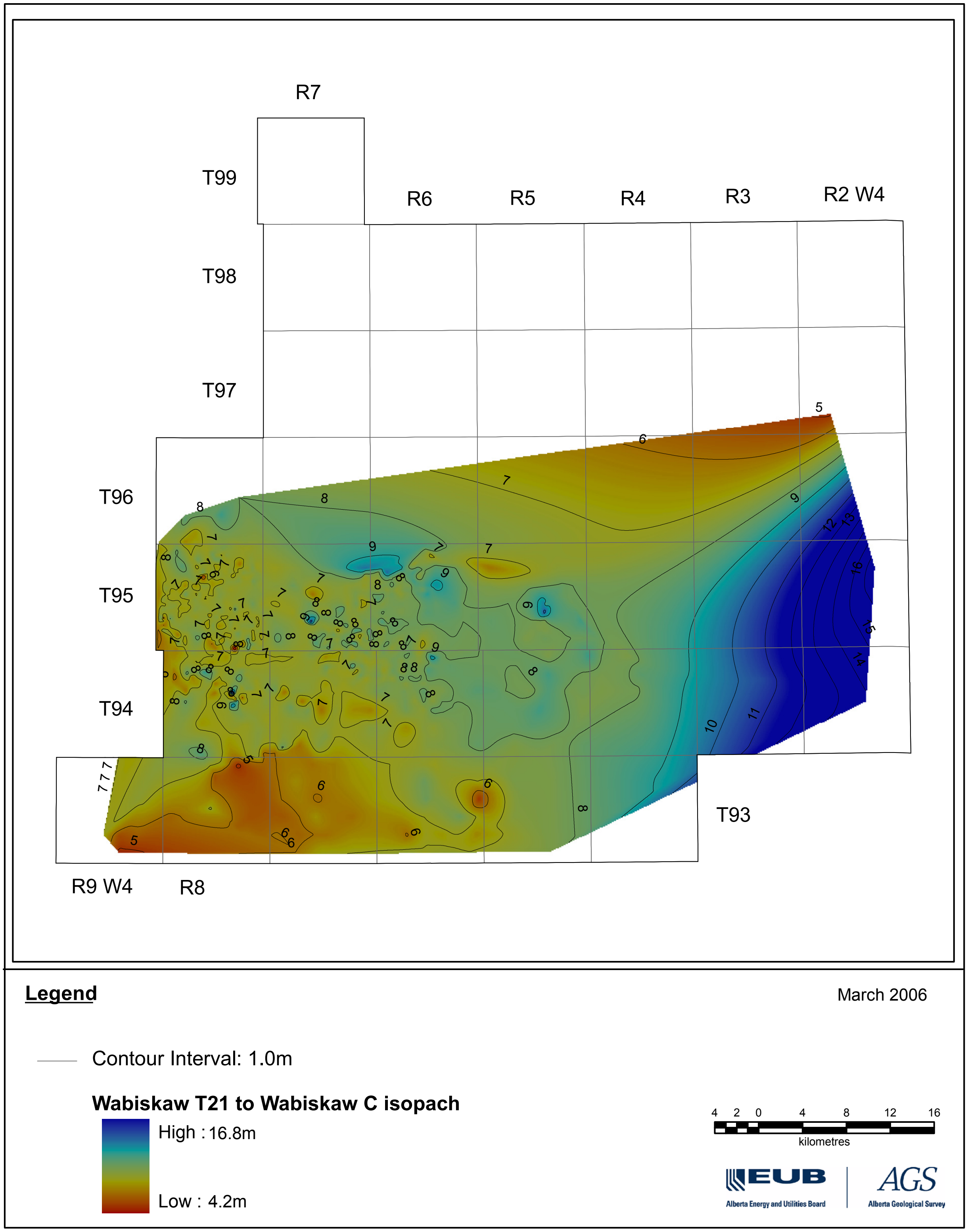

Figure 35. Wabiskaw T21 to Wabiskaw C isopach map.

Channel is recognized (i.e., McMurray C Channel is not identified). All stratigraphic units have been previously described and interpreted in the RGS with the main characteristics of the different units summarized in Table 1.

McMurray Channel includes the various channel/point-bar, overbank and associated abandonment fill and tidal flat successions of different facies associations, including the Lower McMurray Fluvial Facies Association (including Lower McMurray Channels) and the Upper McMurray Estuarine Facies Association. Because the McMurray Channel includes units that originate from different stratigraphic levels, 'McMurray Channel' is not a unique entity, but rather a composite stratigraphic unit. However, the distinction of 'McMurray Channel' is a useful concept, in that it portrays the distribution of the channelled successions and generally identifies the main bitumen reservoirs within the study area.

The isopach map of the McMurray Channel deposits (Figure 29) shows that the channel sediments generally align with the main structural lows along the sub-Cretaceous unconformity. An irregular pattern occurs in the Firebag-Sunrise area, largely reflective of irregularities on the unconformity surface (Figure 28). This irregular drainage is due to superposition of fluvial and estuarine drainage patterns onto antecedent irregular karst paleotopography. The Firebag-Sunrise main channel deposits reach 112 m in thickness, with the thickest and most extensive deposits in Township 96, Range 8W4 and in a broad band from Township 93, Range 4W4 to Township 95, Range 6W4 (Figure 29). The thick accumulation in Township 96, Range 8W4 occurs near the intersection between the Firebag-Sunrise channel trends and the eastern edge of the Bitumont Basin.

McMurray A2 sequence includes the various tidal channel/tidal flat, bay-fill and transgressive back-barrier successions that are within the Upper McMurray Estuarine and Coastal Plain Facies Associations. The A2 sequence is the first mappable coarsening-upwards/cleaning-upwards parasequence in the area, and has a patchy preservation, largely in the southern part of the study area. The base of the A2 mudstone usually occurs 15 to 20 metres below the base of the Wabiskaw Marker (T21), and is distinguished from the overlying A1 sequence by its stratigraphic position and a different log character (Table 1; Alberta Energy and Utilities Board, 2003).

The isopach map of the McMurray A2 deposits (Figure 30) shows that the parasequence sediments generally align with the underlying paleotopographic lows in Townships 93 and 94, Ranges 5 to 9W4. The McMurray A2 sequence commonly reaches 5 metres, locally greater than 9 metres. The thickest deposits occur in Township 96, Ranges 5 to 6 W4; and the east band Township 93, Ranges 4 to 9W4.

McMurray A1 includes a mixture of tidal channel/tidal flat, bay-fill and transgressive back-barrier successions that overlie similar deposits of the McMurray A2 sequence. The McMurray A1 sequence is the second mappable coarsening-upwards/cleaning-upwards parasequence in the area. The McMurray A1 occurs generally 10 to 15 metres below the base of the Wabiskaw Marker (T21), and is distinguished from the underlying A2 sequence by its stratigraphic position and a different log character (Table 1; Alberta Energy and Utilities Board, 2003). In core, the A1 sequence is usually similar to the A2, but is generally thinner, lacking the abundant trace fossils, and the basal mudstone may be present. In cases where this A1 mudstone is absent, it is difficult to distinguish it from the underlying A2.

The isopach map of the McMurray A1 deposits (Figure 31) shows that the parasequence sediments do not align with the McMurray A2 trends, but correlate with thickness trends in the underlying McMurray Channel (Figure 29, 30 and 31). The McMurray A1 sequence commonly reaches 3 metres, locally greater than 5 metres. The thickest and most extensive deposits are centred in Township 95, Range 8W4 and Township 93, Range 8W4, both of which occur near the edge of Bitumont Basin.

Wabiskaw D Valley-fill and Wabiskaw D Shale are separated for mapping purposes. This is because of the data coverage for the two units. The distribution of points for the Wabiskaw D Valley-Fill is somewhat confined in the study area, mainly occurring in a seven-township area on the western edge of the study area (Figure 32); whereas the Wabiskaw D Shale is located mainly in the lower third of the study area (Figure 33). Also, thicks in the Wabiskaw D Valley-Fill do not correspond to thicks in the Wabiskaw D Shale (Figures 32 and 33). This makes mapping difficult.

The isopach map of the Wabiskaw D Valley-Fill deposits (Figure 32) shows that the Wabiskaw D Valley Fill crosscuts trend in the underlying McMurray Channel, A1 and A2 deposits; the thickest accumulation also does not correlate with a paleotopographic low on the sub-Cretaceous unconformity, but rather lies south of a prominent low on the Devonian surface (Figures 28 and 32). The Wabiskaw D Valley-Fill is quite variable in its thickness distribution, with the maximum thickness of about 16 m (Figure 32). The Wabiskaw D Shale sequence averages < 1 metre thick, as regional background shale deposits, mainly preserved in the southern part of the Firebag-Sunrise study area (Figure 33).

Wabiskaw C sequence includes the various muddy, shaly and sandy, immature litharenites that unconformably overlie the McMurray succession. The Wabiskaw C is distinguished from the underlying Wabiskaw D and McMurray successions by its stratigraphic position and distinctive log character (Table 1; Alberta Energy and Utilities Board, 2003). The base of the Wabiskaw C is marked by the major unconformity, the T10.5 surface that occurs at the top of the Wabiskaw D succession (Appendix 1). In cases where the Wabiskaw D is missing, the Wabiskaw C sits unconformably above the E10 surface at the top of the McMurray (Appendix 1). The Wabiskaw C grades up into the first regional marine shale of the Clearwater Formation. Locally, it is difficult to identify the top of the Wabiskaw C where most of the sands have been reworked into the overlying marine shale.

The isopach map of the Wabiskaw C deposits (Figure 33) shows that the units crosscut trends in the underlying Wabiskaw D and McMurray deposits. The Wabiskaw C commonly reaches 4 metres in the west and thinning to generally < 50 centimetres to the north-northeast (Figure 34). The thickness of the interval from the top of the Wabiskaw C to T21 Marker shows a reverse pattern to the Wabiskaw C isopach, being thinner to the west-southwest and thicker to the east (Figure 35). This is interpreted as a result of younger Wabiskaw deposits draping over the Wabiskaw C.

7 Wabiskaw-McMurray Depositional Model: Subsurface Firebag-Sunrise Area

The Lower McMurray deposits represent a fluvial low-stand systems tract of braided bar and channel complexes, largely infilling lows on the unconformity, and flowed westward emptying into the Bitumont Basin (Figures 36, 37A and B). Through time, with continued overall transgression, paleotopographic features became blanketed, and by late Upper McMurray time more nearshore coastal plain conditions prevailed, with fully marine deposits in Wabiskaw C time. Within this stratigraphic model for the Athabasca Wabiskaw-McMurray, paleogeographic evolution of the Lewis-McMurray subsurface study is as follows.

At Time 1, during lowstand and early transgressive conditions, fluvial/fluvio-estuarine McMurray Channel sediments were deposited within a major valley that migrated from southeast to northwest across the study area (Figure 37B), branching and rejoining with smaller tributaries, and eventually debouching into areas of increased accommodation along the eastern margin of the Bitumont Basin. The southern part of the Firebag-Sunrise area has a very complex McMurray Channel isopach pattern, interpreted to be largely a result of amalgamation of smaller tributary channels and crevasse splays. Without seismic, mapping of individual channel-splay sequences is very difficult if not impossible.

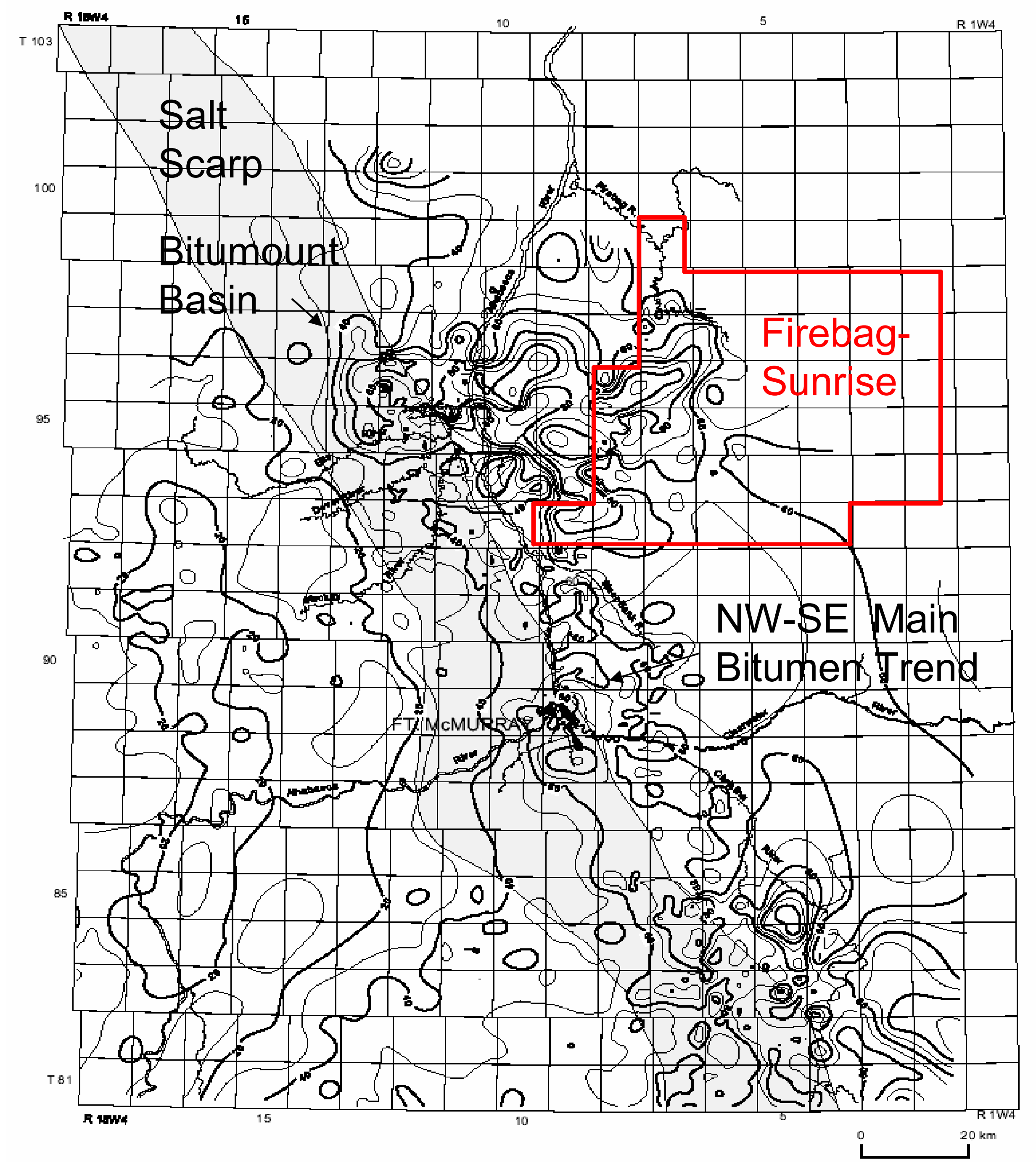

Figure 36.McMurray Formation isopach map illustrating the Firebag-Sunrise study area (boxed in red outline) in relation to the eastern margin of the Bitumont Basin, the northwest-southeast main bitumen trend, and the Salt Scarp (shaded) (modified from Hein et al., 2000).

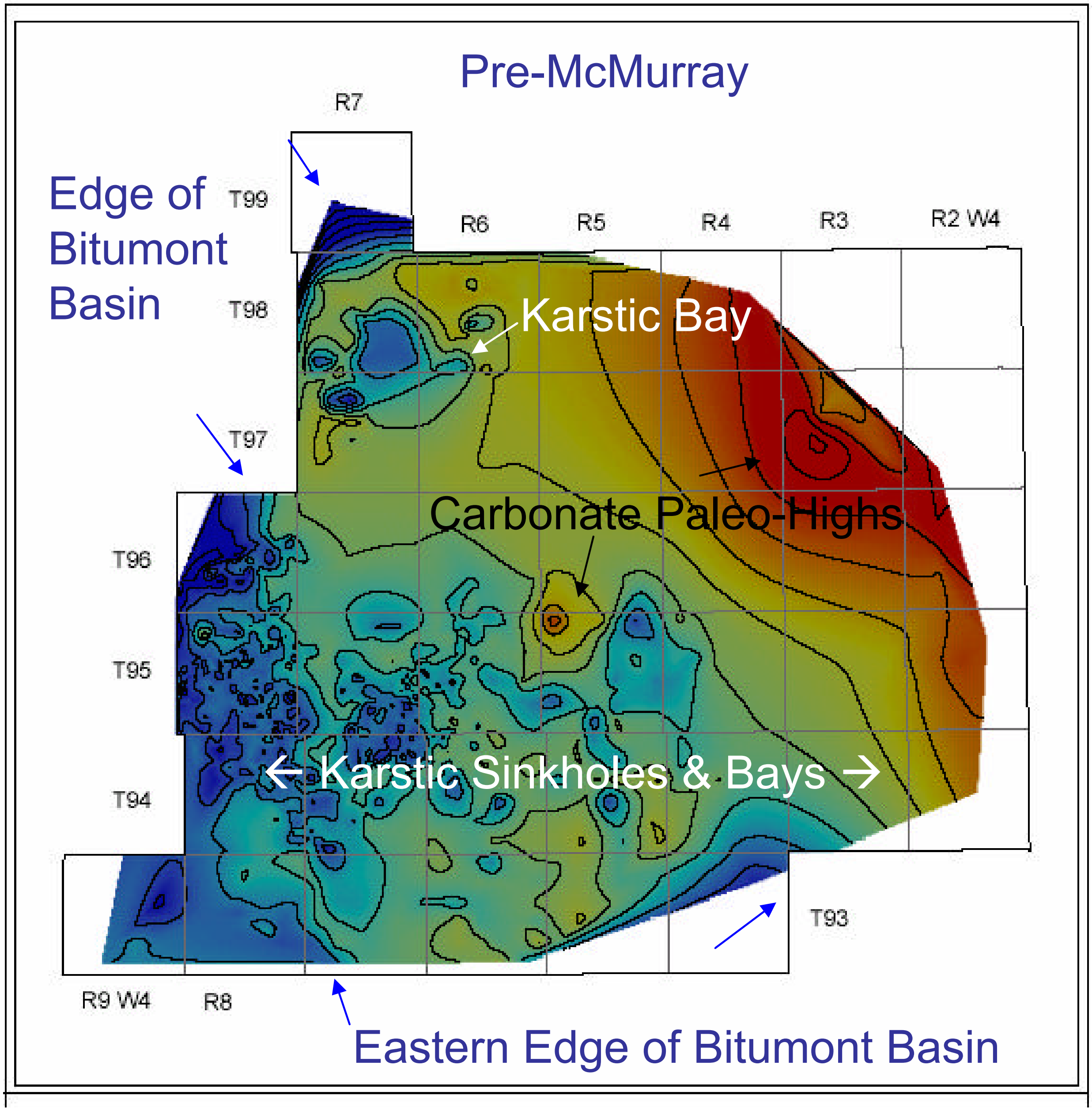

Figure 37A. Paleogeography of the Wabiskaw-McMurray in the Firebag-Sunrise area, including A) pre-McMurray topography, B) McMurray Fluvial and Estuarine Channel, C) McMurray A2, D) McMurray A1, E) Wabiskaw D Valley-Fill, F) Wabiskaw D Shale and G) Wabiskaw C units.

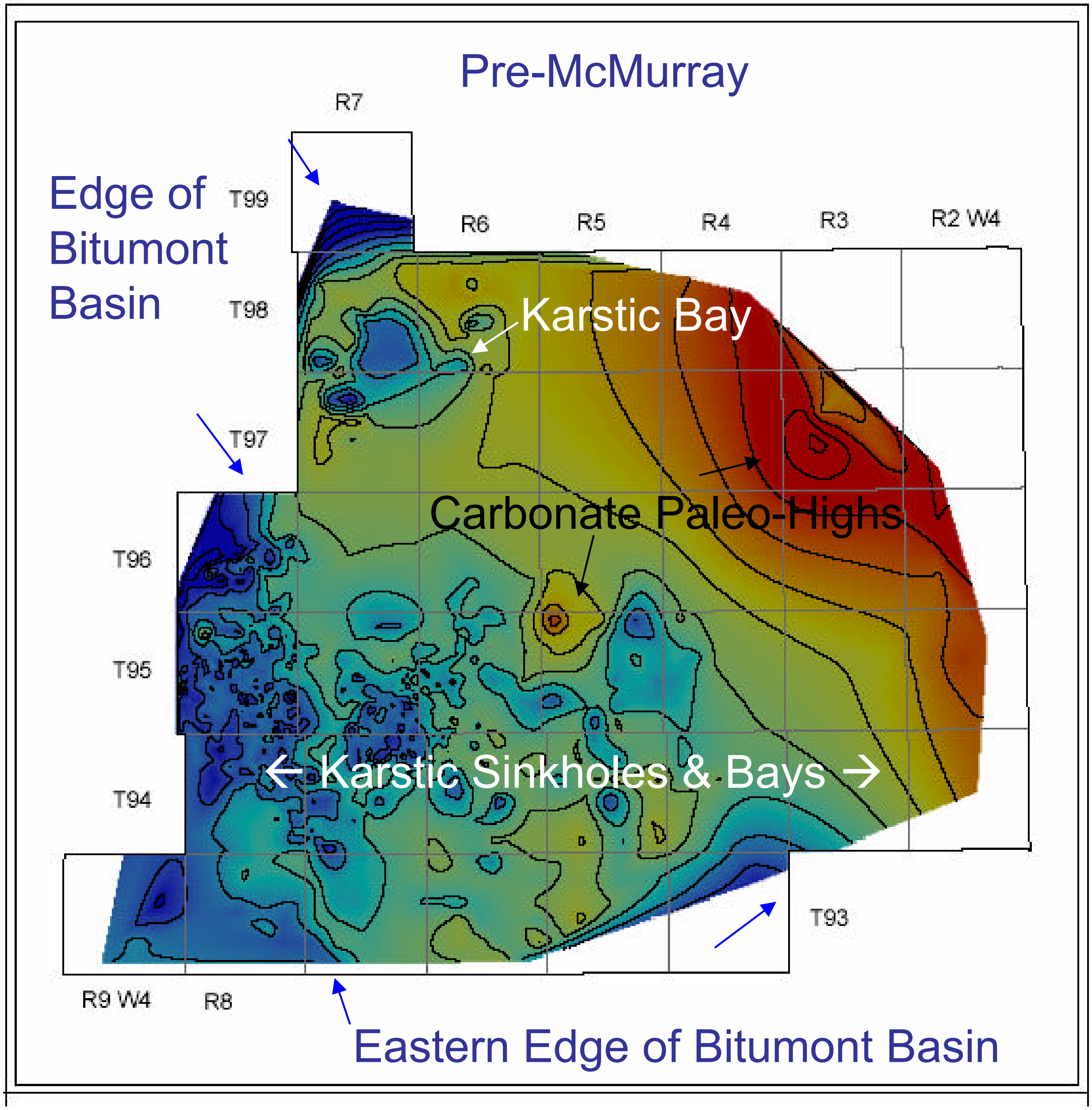

Figure 37B. Paleogeography of the Wabiskaw-McMurray in the Firebag-Sunrise area, including A) pre-McMurray topography, B) McMurray Fluvial and Estuarine Channel, C) McMurray A2, D) McMurray A1, E) Wabiskaw D Valley-Fill, F) Wabiskaw D Shale and G) Wabiskaw C units.

The whole system may be a large westward building delta complex that fed into the eastern edge of the Bitumont Basin. A modern analogue is the Rhine-Muese delta complex of the Netherlands, which shows very complex channel and interdistributary patterns (Figure 38).

At Time 2, during early transgressive phases, the McMurray A2 sequences were deposited. Most of this stratigraphy is not present due to either nondeposition or nonpreservation, associated with younger erosional events. The isopach pattern of the McMurray A2 with zero-edges is very complex and patchy. Few trends are apparent. One is a string of thickened units that track in an arcuate band at the southern limit of the study area. These may represent a possible transgressive, coarsening-up, bay-fill pulse, similar to reworked marine bars but wholly within the bay-fill setting. These occur at the southern edge of the Bitumont Basin, where it intersects the northwest-trending main valley trend of the McMurray Formation in the SMA (Figure 37C).

At Time 3, during middle transgressive phases, the McMurray A1 sequences were deposited. Although more stratigraphy is preserved compared with the underlying A2 sequence, large portions in the east-central and northern part of the study area are not represented in the stratigraphy due either to nondeposition or erosion. A band of thickened A1 units occurs across Township 93 along the southern limit of the study area. This represents a transgressive, coarsening-up, washover deposits deposited behind an inferred barrier complex along the southern margin of the Bitumont Basin that is not preserved. The northern thickened band of A1 units across Township 95 may represent similar bay and back-barrier deposits that flanked the eastern margin of the Bitumont Basin (Figure 37D).

At Time 4, during maximum transgressive phases, the Wabiskaw D sequences were deposited, with the Wabiskaw D Shale representing the maximum flooding surface. The isopach map of the initial Wabiskaw D Valley-Fill succession shows a large circular depression, with a western outlet into the main Bitumont Basin. This is interpreted as a flooded, bay-estuarine complex (Figure 37E). The overlying Wabiskaw D Shale is mainly preserved as blanket deposition in the southern part of the study area, with isolated areas of nondeposition in the southeast, and mainly absent to the north (Figure 37F). Although well coverage is sparse, it is possible that some barriers to transgression formed along the eastern margin of the Bitumont Basin at this time, such that only flooding occurred to the south in the Firebag-Sunrise area.

At Time 5, during waning transgressive and beginning regressive phases, the Wabiskaw C sand was deposited. Although there is sparse data coverage in some areas, the overall isopach map of the Wabiskaw C succession shows mainly a north-south trend to the west, and irregular, blanket deposition across the south-central and southeastern study area (Figure 37G). The north-trending thickened units may represent marine bar complexes along the southeastern edge of the Bitumont Basin, whereas the central and eastern areas may represent more flooded nearshore estuaries and bays.

8 Comparison to Regional Geological Study

- In general, the stratigraphic model developed in the RGS (Alberta Energy and Utilities Board, 2003) can be used to map the different stratigraphic units within the Wabiskaw-McMurray succession in the Firebag-Sunrise subsurface area.
- Mappable stratigraphic units in the study area include McMurray Channel, McMurray A2 sequence, McMurray A1 sequence, Wabiskaw D Valley-fill, Wabiskaw D Shale and the Wabiskaw C.
- Contrasting with the RGS, in the Firebag-Sunrise study area, the McMurray A Channel, McMurray B1, McMurray B2 and Wabiskaw B Valley-fill are absent, interpreted largely due to nondeposition. Because of the absence of the McMurray B2 sequence, only McMurray Channel is recognized (i.e., McMurray C Channel is not identified).

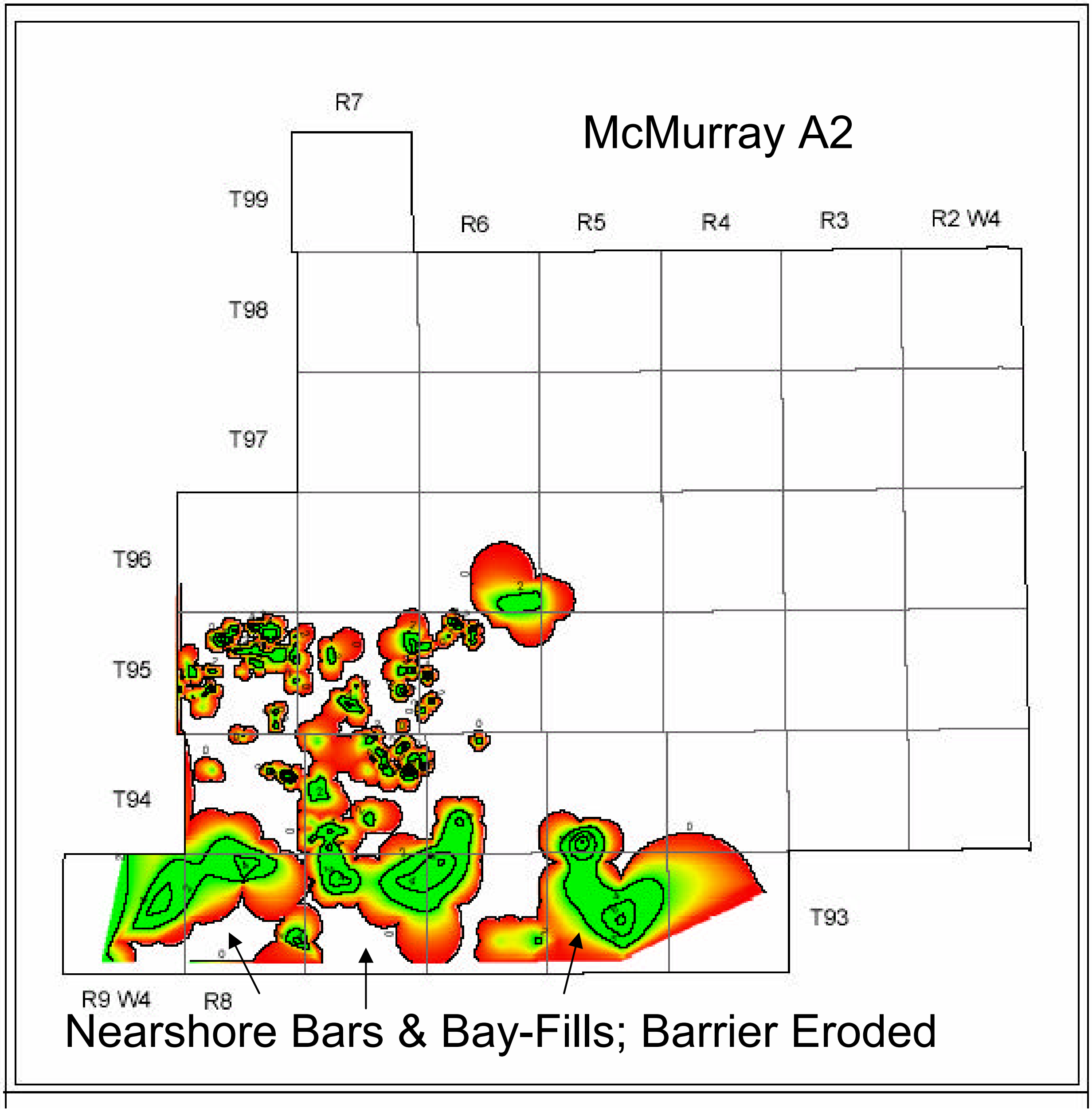

Figure 37C. Paleogeography of the Wabiskaw-McMurray in the Firebag-Sunrise area, including A) pre-McMurray topography, B) McMurray Fluvial and Estuarine Channel, C) McMurray A2, D) McMurray A1, E) Wabiskaw D Valley-Fill, F) Wabiskaw D Shale and G) Wabiskaw C units.

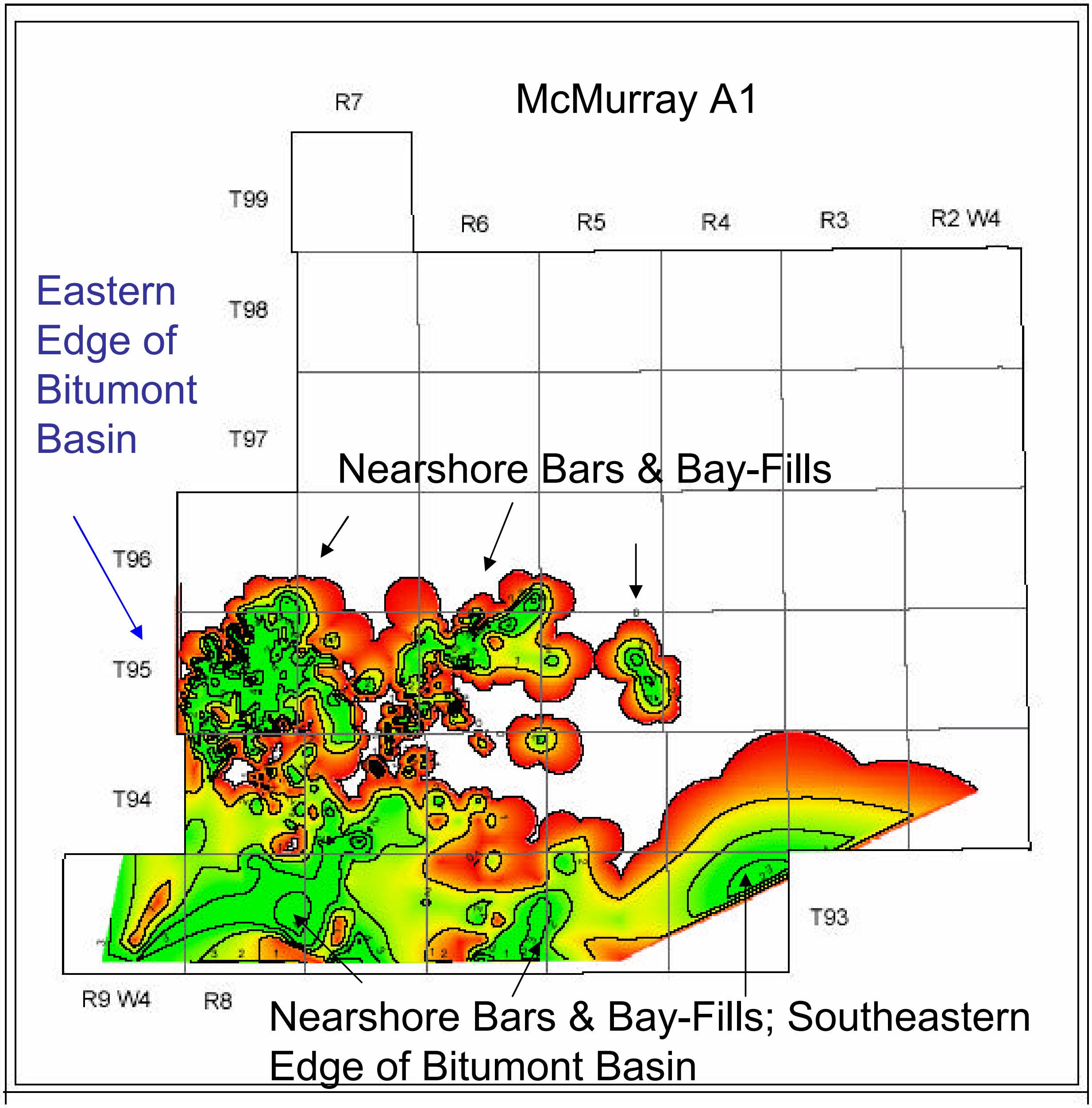

Figure 37D. Paleogeography of the Wabiskaw-McMurray in the Firebag-Sunrise area, including A) pre-McMurray topography, B) McMurray Fluvial and Estuarine Channel, C) McMurray A2, D) McMurray A1, E) Wabiskaw D Valley-Fill, F) Wabiskaw D Shale and G) Wabiskaw C units.

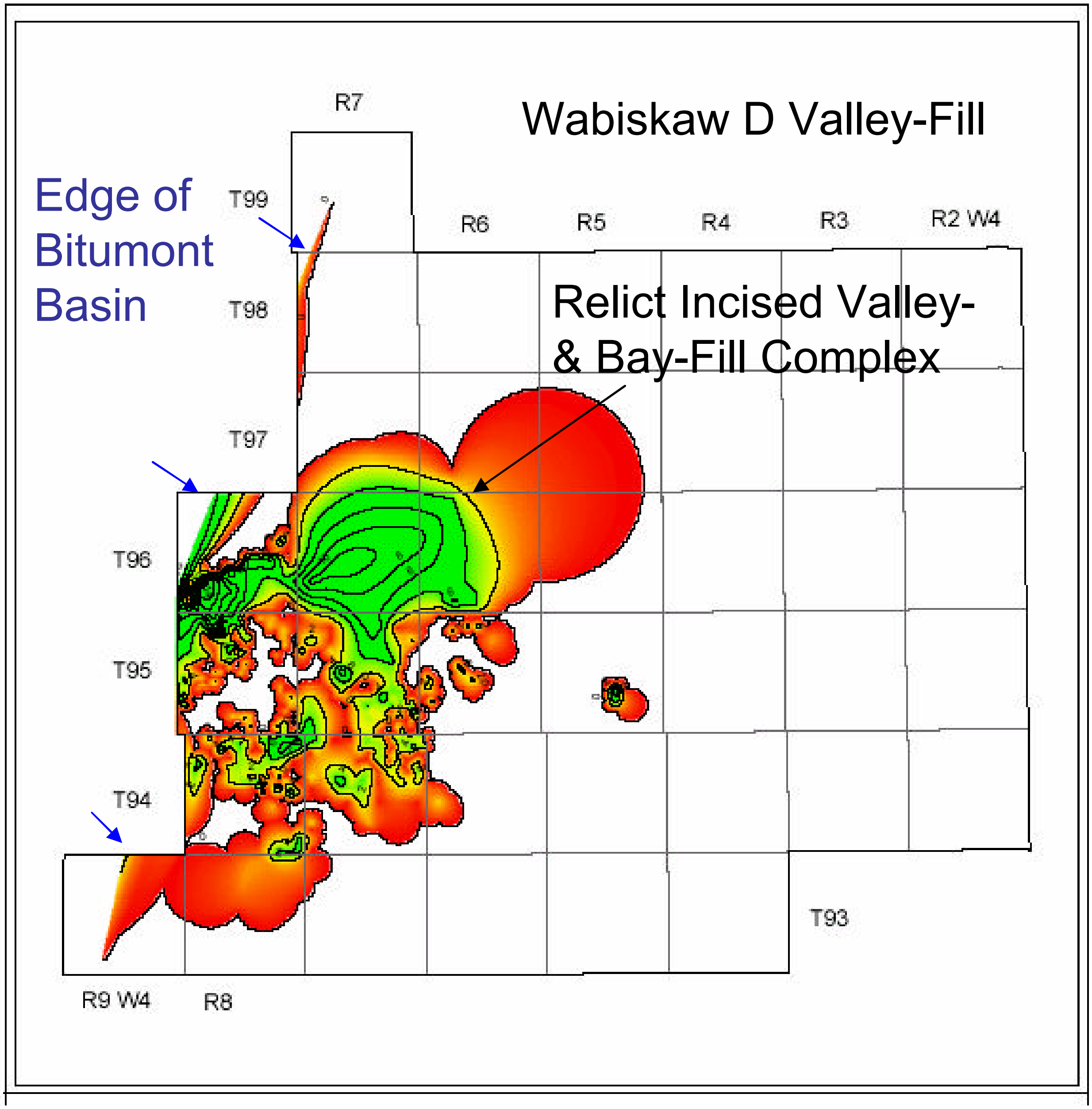

Figure 37E. Paleogeography of the Wabiskaw-McMurray in the Firebag-Sunrise area, including A) pre-McMurray topography, B) McMurray Fluvial and Estuarine Channel, C) McMurray A2, D) McMurray A1, E) Wabiskaw D Valley-Fill, F) Wabiskaw D Shale and G) Wabiskaw C units.

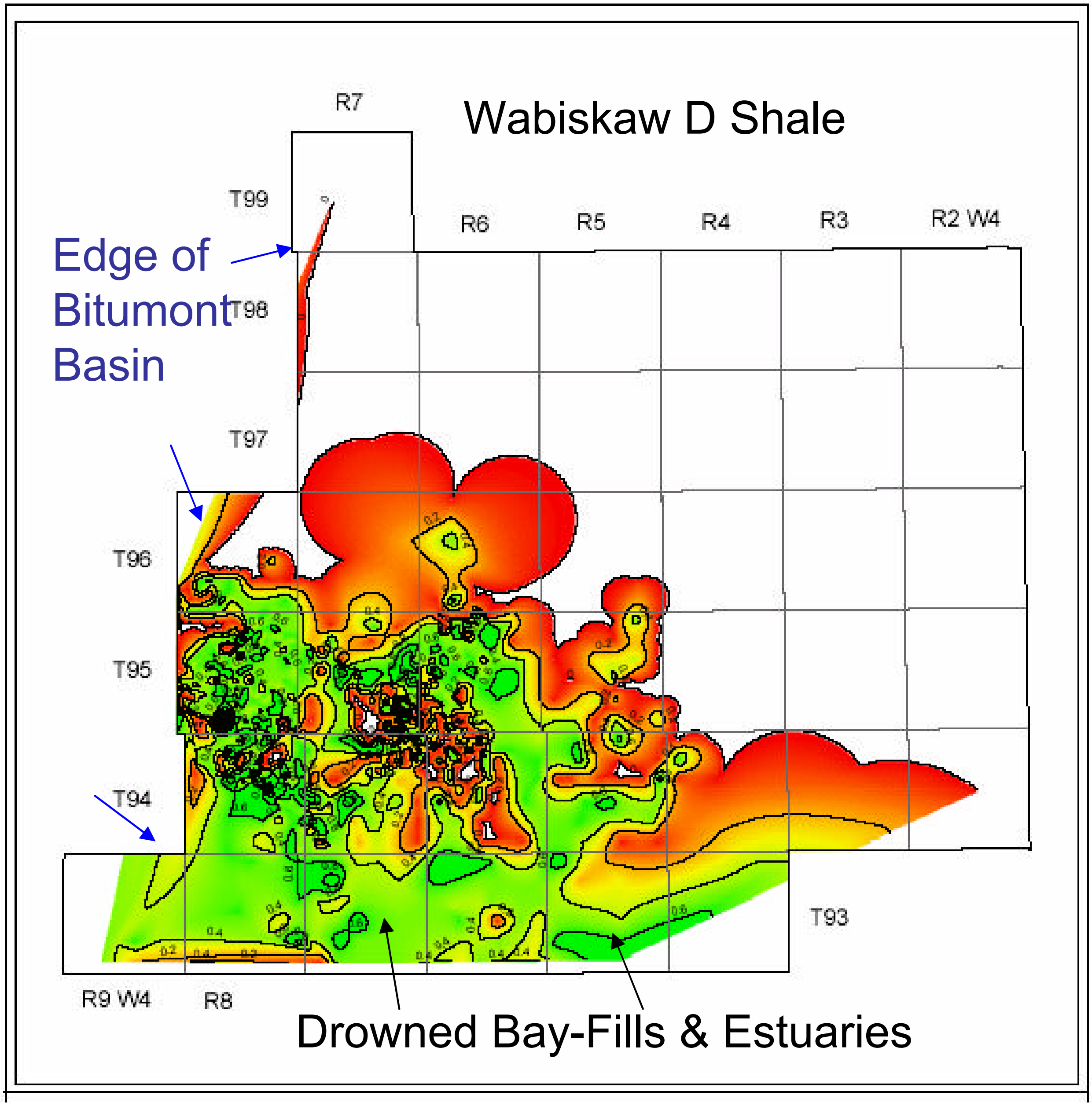

Figure 37F. Paleogeography of the Wabiskaw-McMurray in the Firebag-Sunrise area, including A) pre-McMurray topography, B) McMurray Fluvial and Estuarine Channel, C) McMurray A2, D) McMurray A1, E) Wabiskaw D Valley-Fill, F) Wabiskaw D Shale and G) Wabiskaw C units.

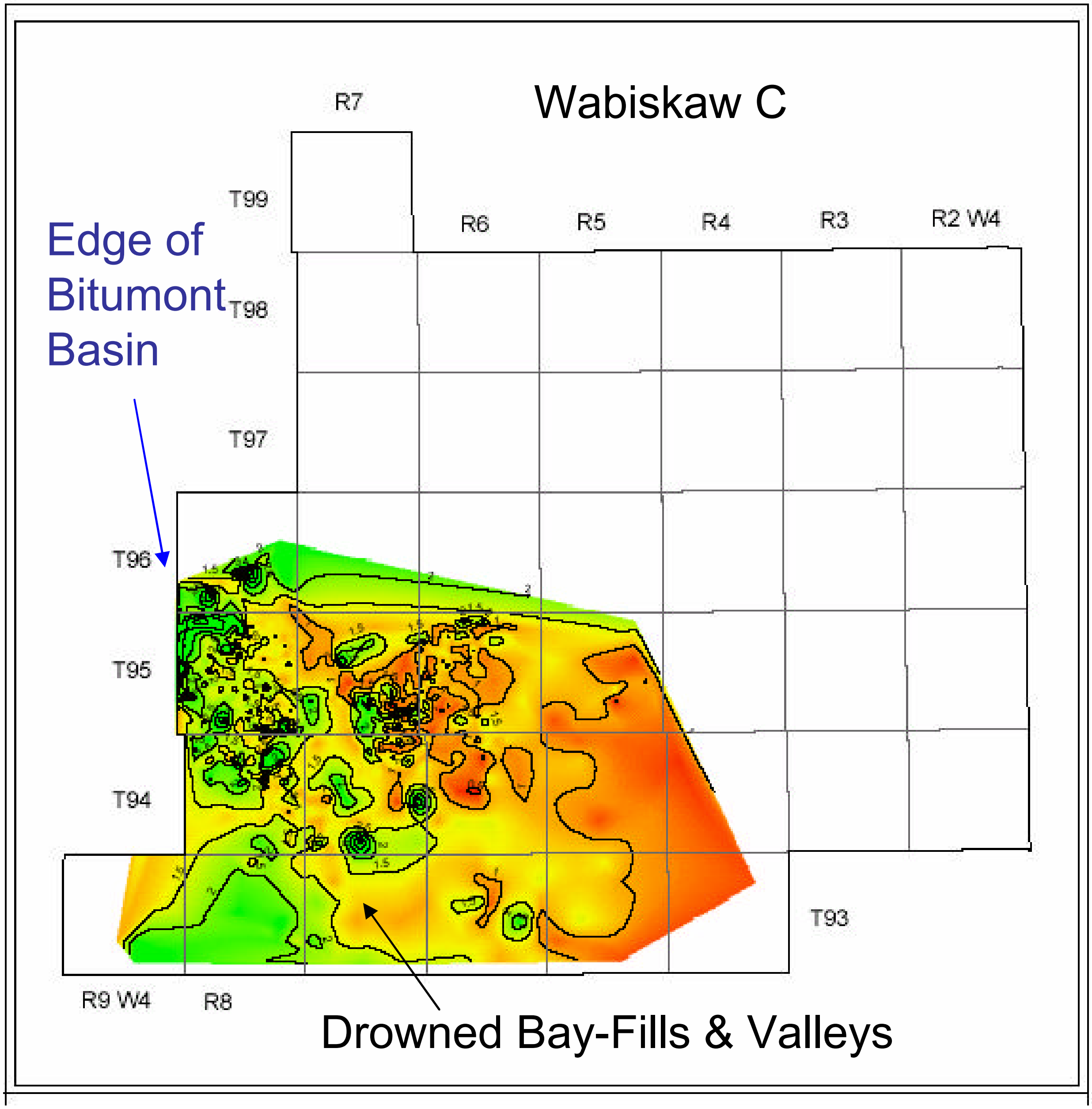

Figure 37G. Paleogeography of the Wabiskaw-McMurray in the Firebag-Sunrise area, including A) pre-McMurray topography, B) McMurray Fluvial and Estuarine Channel, C) McMurray A2, D) McMurray A1, E) Wabiskaw D Valley-Fill, F) Wabiskaw D Shale and G) Wabiskaw C units.

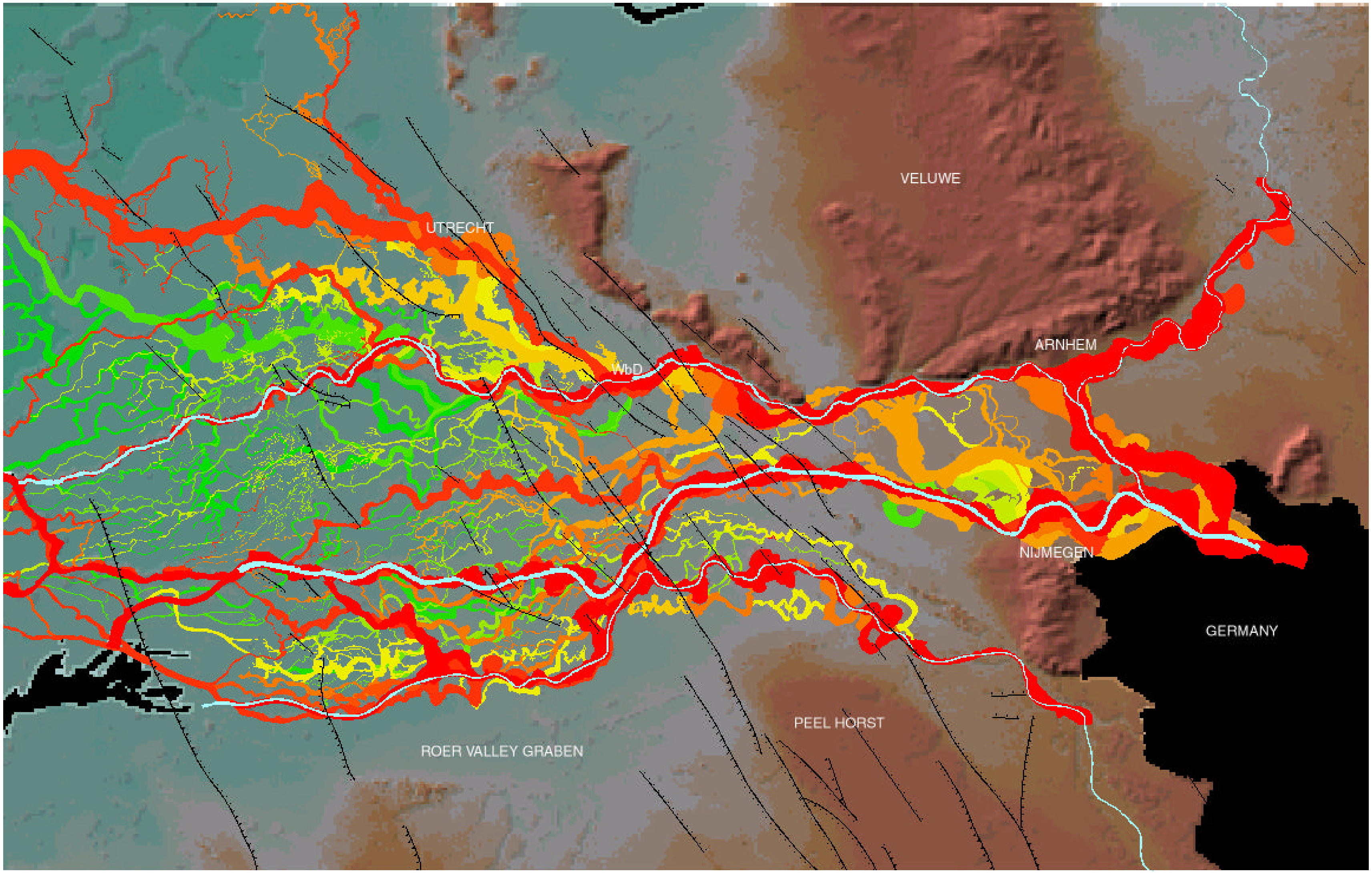

Figure 38. Late-Weichselian and Holocene palaeogeography of the Rhine-Meuse delta, The Netherlands, channel belts: youngest (red), intermediate (yellow), and oldest (green) (modified from Berendensen and Stouthamer, 2001).

9 Recommendations for Future Work

Although this study serves as one of the first links in joining different studies into a comprehensive stratigraphic framework for the Athabasca deposit, some outstanding issues remain to be resolved, including

- Ongoing subsurface facies analysis throughout the study area as more recently drilled core becomes non-confidential.

Addition of the ongoing subsurface facies analysis should be done throughout the study area as more recently drilled core becomes non-confidential. This is needed to test the proposed facies models from this initial work, and to see if some of the exceptional facies found in this area, such as the delta front, tidal flat and tidal channel sediments, show more defined regional facies patterns. Currently, there are high levels of exploration drilling in this area, with up to 150 new wells being cored in the central and eastern parts of the Firebag-Sunrise study area. Other high levels of drilling activity are currently being done on similar-aged oil sands of northwestern Saskatchewan. Eventually, as this information becomes public, there should be a reassessment of the Firebag-Sunrise area with facies mapping of new core, tied into unconformity maps.

- Structural influences associated with salt dissolution

Previous work by Darrell Cotterill on contract to the EUB has shown that structural influences associated with salt-dissolution tectonics extend from the base of the McMurray to top of the Mannville. In some townships there is up to 30 m of structural relief on some of the major correlation surfaces, including the top of the Wabiskaw C and the Wabiskaw Marker (T21), among others. To date, aside from this confidential report to the EUB, there has not been a township-scale focused assessment of the structural influences of salt-dissolution tectonics on the stratigraphy and pooling within the Wabiskaw-McMurray in the Athabasca deposit. Furthermore, the salt tectonics itself may reflect basement control. The role of structure is clearly important, and is known to exist, due to thickened stratigraphy, faults on sections and preliminary mapping. The role of structure is critical to understand pooling in the area, as well as to show where local sealing shales/mudstones may be breached by faults.

10 Conclusions

In the Firebag-Sunrise area, regional isopach maps show the following trends

- McMurray Channel deposits generally align with the main structural lows along the sub-Cretaceous unconformity, with the irregular pattern largely reflective of irregularities on this unconformity surface.
- McMurray A2 deposits do not seem to correlate with the underlying topography on the sub-Cretaceous unconformity or to thick development of the McMurray Channel units, with main preservation along the southern margin of the Bitumont Basin.
- McMurray A1 shows two thickened trends, one along the southern edge of the Bitumont Basin, and the second that likely relates to flooded bays and estuaries along the eastern margin of the Bitumont Basin.
- Wabiskaw D units (both Wabiskaw D valley-fill and Wabiskaw D shale) crosscut trends in the underlying McMurray Channel, A1 and A2 deposits.

- Wabiskaw C deposits crosscut trends in the underlying Wabiskaw D or McMurray deposits.
- The individual facies percentages for what may be units associated with deltaic complexes are much more prevalent in the Firebag-Sunrise area. At the present scale of resolution of core and wireline log density, it is impossible to map these units in sufficient detail in the central and eastern part of the study area. With more recent drilling, and eventual release of this confidential data into the public domain, refined mapping of facies and their associations will help in the identification and refinement of facies models along the eastern margin of the Bitumont Basin.

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Appendix 1. Definition of Stratigraphic Markers ('picks') with Quality Codes (modified from Wynne et al., 1994 and Hein et al., 2000).*

Pick	Type of Surface	Description	Quality Code**
T21	Transgressive	Wabiskaw Marker Top Wabiskaw Mbr. 'A'	Good–Very Good
T15	Transgressive	Top Wabiskaw Mbr. 'B'	Good–Very Good
E14	Major Erosion	Wabiskaw Internal Incision	Good–Very Good
T11	Transgressive	Base First Regional Marine Shale in the Clearwater Fm. Top Wabiskaw Mbr. 'C'	Very Good–Excellent
T10.5	Transgressive	Top Wabiskaw Mbr. 'D' Incised Valley-Fill Deposit	Excellent–Very Good
E10	Disconformity/ Unconformity	Top Upper McMurray Fm.	Excellent–Very Good Major Erosion Surface
E5	Disconformity/ Unconformity	Top Lower McMurray Fm. Major Erosion Surface	Variable Very Poor–Fair
Sub-Cret. (Pal.)	Unconformity	Base of McMurray Fm. Major Erosion Surface	Variable Very Good–Excellent (However this is sometimes difficult to pick in areas of significant clastic karst-infill, or where marl is above the sub-Cretaceous unconformity.)

* Abbreviations: Group, Grp.; Formation, Fm.; Member, Mbr.

** Quality Codes are relative: Excellent to Very Good, can be picked on all wireline logs and seismic; Poor to Very Poor, need to be confirmed by outcrops or core, difficult to pick on wireline logs, somewhat easier to pick on seismic.

Appendix 2. List of Wells with Annotated Digital Photos and/or Annotated Logs Included on CD. (Note: Under the legend heading, EUB refers to the coloured patterns with stripes; AGS refers to the coloured patterns without stripes for the annotated logs.)

Well Location	Log (.jpg)	Legend	# Photos
AA/10-17-093-04W4	1	EUB	19
AA/12-25-093-04W4	1	EUB	4
AA/10-14-093-05W4	1	EUB	7
AA/10-27-094-04W4	0	AGS	1
00/09-04-094-05W4	0	AGS	1
AA/11-06-094-05W4	3	EUB	0
AA/10-16-094-05W4	0	AGS	2
00/10-19-094-05W4	0	AGS	1
AA/10-21-094-05W4	0	AGS	2
00/10-22-094-05W4	0	AGS	1
AA/10-30-094-05W4	0	AGS	1
AA/10-04-094-06W4	2	EUB	0
00/12-05-094-06W4	0	AGS	12
AA/10-06-094-06W4	2	EUB	0
AA/14-19-094-06W4	1	EUB	0
AA/10-25-094-06W4	1	EUB	0
AA/10-31-094-06W4	1	EUB	0
AA/02-33-094-06W4	1	AGS	0
AA/14-35-094-06W4	1	EUB	0
AA/10-12-094-07W4	0	AGS	3
AA/01-13-094-07W4	0	AGS	2
00/04-20-094-07W4	0	AGS	2
AA/04-24-094-07W4	0	AGS	1
AA/14-28-094-07W4	0	AGS	1
AA/16-28-094-07W4	0	AGS	2
AA/13-32-094-07W4	0	EUB	8
AA/03-35-094-07W4	0	EUB	14
AA/16-35-094-07W4	0	AGS	2
AA/10-21-095-03W4	1	EUB	6
AA/10-28-095-03W4	0	AGS	1
AA/09-31-095-03W4	0	AGS	2
AA/10-05-095-04W4	1	EUB	11
AA/10-11-095-04W4	0	AGS	3

Well Location	Log (.jpg)	Legend	# Photos
AA/10-12-095-04W4	0	AGS	2
AA/10-13-95-04w4	0	AGS	1
AA/10-23-095-04w4	0	AGS	3
AA/10-24-095-04w4	0	AGS	1
AA/10-25-095-04w4	0	AGS	1
00/10-31-095-04W4	0	AGS	2
AA/10-07-095-05W4	1	EUB	1
AA/10-15-095-05W4	0	AGS	1
AA/10-18-095-04W4	0	AGS	1
AA/04-19-095-05W4	0	AGS	2
00/10-20-095-05W4	1	EUB	8
AA/14-20-095-05W4	0	AGS	2
AA/10-26-095-05W4	0	AGS	3
AA/10-30-095-05W4	1	EUB	2
AA/16-32-095-05W4	0	AGS	1
AA/06-34-095-05W4	0	EUB	1
AA/06-35-095-05W4	0	AGS	2
AA/10-06-095-06W4	2	EUB	0
AA/10-07-095-06W4	2	EUB	0
AA/10-10-095-06W4	1	EUB	0
AA/10-14-095-06W4	1	EUB	4
AA/10-23-095-06W4	1	EUB	0
AA/04-30-095-06W4	1	EUB	0
AA/07-32-095-06W4	1	EUB	12
AA/08-01-095-07W4	0	EUB	8
AA/12-03-095-07W4	0	EUB	9
AA/05-05-095-07W4	0	EUB	18
AA/13-09-095-07W4	0	AGS	11
AA/11-11-095-07W4	0	EUB	11
AA/13-11-095-07W4	0	AGS	0
AA/11-13-095-07W4	1	EUB	10
AA/13-15-095-07W4	1	EUB	0
AA/14-17-095-07W4	0	AGS	22
AA/03-19-095-07W4	1	EUB	0
AA/06-21-095-07W4	1	EUB	0
AA/03-23-095-07W4	1	EUB	0
AA/03-25-095-07W4	1	EUB	0
AA/03-27-095-07W4	1	EUB	0

Well Location	Log (.jpg)	Legend	# Photos
AA/11-29-095-07W4	1	EUB	0
AA/09-33-095-07W4	1	EUB	0
AA/03-35-095-07W4	1	EUB	0
AA/03-36-095-07W4	1	EUB	0
AB/09-09-095-08W4	1	EUB	12
AA/10-35-095-08W4	1	EUB	8
AA/08-14-095-09W4	1	EUB	4
AB/14-30-095-09W4	1	EUB	8
AA/10-07-096-06W4	0	AGS	14
AA/10-02-096-07W4	0	AGS	2
AA/11-03-096-07W4	0	EUB	0
AA/10-16-097-06W4	0	AGS	8
AA/10-28-097-06W4	0	AGS	23
AB/05-12-099-06W4	0	AGS	13
Total 88 Wells	38 (logs)		339 (photos)

Appendix 3. ArcGIS Mapping Specifications

ArcGIS mapping of the isopach and structure maps was done by Dennis Chao, MaryAnne Pinto and Shauna Miller, using the following procedures and specifications.

1. All shapefiles and grids are stored in the sub-folder Map on the CD.
2. ArcGIS 8.3 was used to create Map.mxd where all gridding and contouring was done.
3. In Map.mxd, pick locations of different units were designated as subsets of the allpick u12n27 layer, which was created from the following folders: 'denis.xls' and 'bulleyes corrections.xls.' These data were combined into a single Excel table, called all_picks.xls (on CD), which was then converted to allpick_u12n27 shapefile. In this preliminary set of data there were a number of 0 values in the shapefile, which represent the NIL value in the Excel spreadsheets, and these 0 values were not used for gridding. Eventually these values should be converted to -999.
4. A natural neighbour was used to grid, with the cell size at 250 m.
5. The naming convention is as follows: feature_unitname theme, such as 'gr_mcma1_th', stands for net thickness grid of McMurray A1 sequence; 'cl_mcma1_th' is the McMurray A1 thickness grid clipped with study boundary; and 'c_mcma1_th' is the contours shapefile based on clipped McMurray A1 thickness grid. Theme 'elv' stands for elevation/structure. Unitname 'mcmch' stands for McMurray Channel; 'dvalno' is Wabiskaw D Valley-Fill north portion; 'dvalso' is Wabiskaw D Valley-Fill south portion.
6. Two PDFs were created (isopach thickness and structural contours) for each unit. They are Arch 'E' size (36 x 48 inch).
7. The projection is UTM 12, NAD 27.
8. To get the zero edges on the different units, a value of -0.5 was assigned to zero values; the maps were then regridded and recontoured, using the same grid and contour intervals as above. The zero contour line was then plotted in bold on the Arch 'E' size (36 x 48 inch) maps. Original data contour patterns with posting of control points were kept, with the 'zero' edge contour line serving as the mask to eliminate zones with nil values.
9. Large maps (~ 1:85 000; Arch 'E' size, 36 x 48 inch) maps were then replotted with the zero-contour edge for each unit.
10. Small scale versions of the maps (~ 1:300 000, size 11 x 17 inch) were included as foldout to the report.
11. Digital versions of all maps are included on the CD.

Appendix 4. AGS Core Logging Legend - Gas/Bitumen North

Appendix 5. EUB Core Logging Legend Bitumen Project