

The Athabasca Oil Sands — A Regional Geological Perspective, Fort McMurray Area, Alberta, Canada

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Most of the bitumen in the Athabasca deposit is hosted within fluvial, estuarine, and marginal marine deposits of the Lower Cretaceous Wabiskaw-McMurray succession. The present study is an integration of recent outcrop and subsurface studies, mainly focused in the Fort McMurray area of northeastern Alberta. The basis of the regional geologic framework includes outcrop sections (78), detailed core descriptions (165), and a net of subsurface wire-line log sections (14), all framed within modern concepts of regional correlation and sequence-stratigraphy.

The paleogeographic evolution of the Athabasca Wabiskaw-McMurray succession includes five main phases: (1) Lower McMurray fluvial as lowstand deposits; (2) the lower part of the Upper McMurray fluvio-estuarine channel complexes which formed during early transgressive conditions; (3) the upper part of the Upper McMurray A sequences as relict bay-fill and marginal marine deposits formed during early and middle transgressive phases; (4) Wabiskaw D valley-fill developed during a relative sea-level drop at the end of McMurray time (valley-incision phase), which was backfilled during the ensuing transgression; (5) Wabiskaw D regional marine shale, deposited during widespread flooding of the main McMurray-Wabiskaw transgression; and (6) Wabiskaw C deposits formed during continued transgression or early regressive pulses.

The regional geological framework has both economic and academic significance, providing better documentation and understanding of the compartmentalization of the oil sands mainly the result of the inherent geological heterogeneity of the Wabiskaw-McMurray succession. Such regional correlation and framework will aid in predicting subsurface and surface reservoir quality and in increased understanding of marginal marine and non-marine sequence stratigraphy.

KEY WORDS: Athabasca oil sands, regional geologic, stratigraphic model.

INTRODUCTION

Recent events in the US and around the world (i.e. hurricanes in the Gulf of Mexico area, among others) show an ever-increasing need for additional energy supplies and refining capacity, with a greater reliance of North American interests on unconven-

tional energy resources. As discussed in the overview paper to this volume, one of the more strategic unconventional resources include the oil sands, which are becoming increasingly more crucial to North American needs (Hein, 2006). The largest oil-sand deposits are in Alberta, Canada, which for North America account for >95% of the in-place resources of bitumen (Hein, 2006, table 1). Remaining established reserves of Alberta's crude bitumen is estimated to be 27.66 billion cubic meters (10^9 m³), of which about 25% by area is under active development (Alberta Energy and Utilities Board, 2005a). Alberta has 15 oil-sands deposits which are

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Table 1. Stratigraphic Nomenclature and Characteristics of Different Units in the Athabasca Wabiskaw-McMurray Succession, Northeastern Alberta

A	B	C	D	E	F	G	H	I
Age	AGS stratigraphic unit ^a	RGS stratigraphic unit ^b	Gamma ray API units	Neutron porosity %	Density porosity %	Resistivity (ohm-m)	Thickness range (m)	Fissility/Fracture
		Wabiskaw BVF Sand & Shale	60 to 75	up to 45	about 30	20 to 30	5 to 40	none
Middle Albian	Wabiskaw C	Wabiskaw C Sand	60 to 90	up to 30	up to 30	<15	~0.2 to 10	none
		Wabiskaw C Mud	75 to 120	36-45	near 20	5 to 10	0.3 to 5	nonfissile
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
		Wabiskaw D Sand	20 to 30	near 36	near 33	near 100	5 to 9	prominent platy
		Wabiskaw DVF Sand & Shale	30-50, > 70 (shalier)	>30	27, but variable	<10	<0.1 to 25	platy in shale
Aptian	Upper McMurray (upper pt)	McMurray A1 Sand	about 75	>30	20 to 30	variable	0.05 to 0.4	
		McMurray A1 Mud	95 to 100	36-45	near 22	variable, >20	0.1 to 0.3	none or octagonal
		McMurray A2 Sand	about 75	>30	20 to 30	variable	0.05 to 0.4	
		McMurray A2 Mud	consistent ~120	36-45	near 22	near 10	1 to 2	none or octagonal
		McMurray B1 Sand	about 75	>30	20 to 30	variable	0.05 to 0.4	
		McMurray B1 Mud	90 to 120	near 45	20 to 30	variable	0.05 to 0.4	none or octagonal
		McMurray B2 Sand	30 to 45	>30	>30	variable	1 to 2	
		McMurray B2 Mud	90 to 120	near 45	near 22	8 to 10	1 to 2	none or octagonal
Aptian	Upper McMurray (lower pt)	McMurray C Channel or McMurray Channel	25 to 45	>30	>30	variable	~10-40+	none or octagonal
Aptian	Lower McMurray	Undifferentiated		>30	>30	variable	~10-40+	none or octagonal
Middle Barremian	pre-McMurray Sand	Not noted		>30	>30	variable	~10-40+	none or octagonal
	pre-McMurray Mud	Not noted						

Note. Surfaces as follows: TSE, transgressive surface of erosion; D, disconformity; U, unconformity (modified from Wynne and others, 1994; Hein and others, 2001; Alberta Energy and Utilities Board, 2003).

^aHein et al., 2000; Langenberg et al., 2002.

^bAlberta Energy and Utilities Board, 2003.

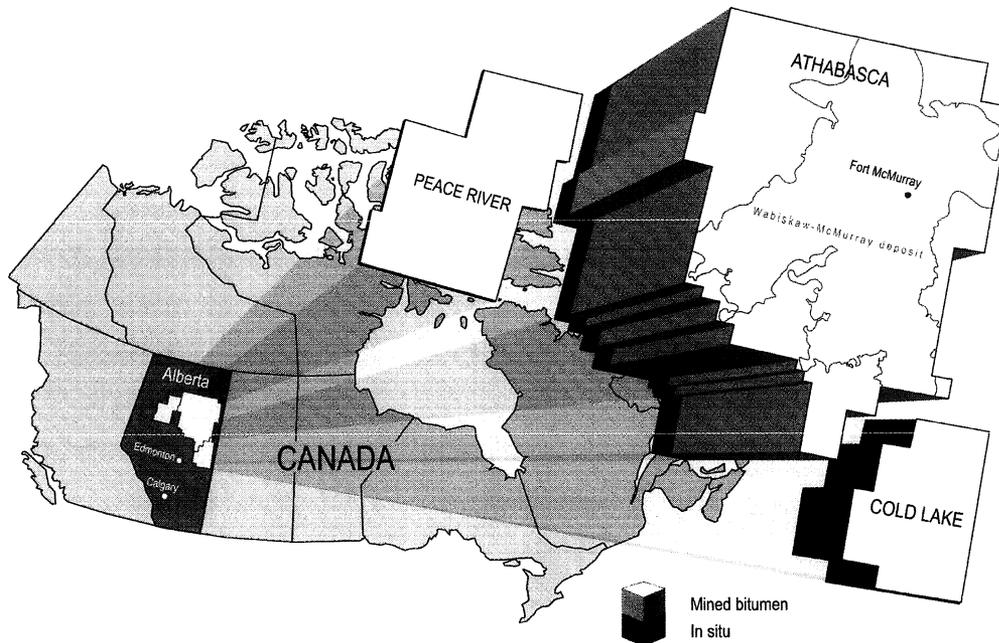


Figure 1. Location of Alberta's oil sands, with outline on surface of Athabasca block showing extent of Athabasca Wabiskaw-McMurray deposit. Height of blocks for different deposits represent relative bitumen production in 2004, *in-situ* for both Peace River ($2.5 \times 10^3 \text{ m}^3/\text{d}$) and Cold Lake ($41.4 \times 10^3 \text{ m}^3/\text{d}$); surface mining ($111.7 \times 10^3 \text{ m}^3/\text{d}$) and *in-situ* ($17.5 \times 10^3 \text{ m}^3/\text{d}$) for Athabasca (modified from Alberta Energy and Utilities Board, 2005).

grouped into three oil-sand development areas – the Athabasca, Cold Lake and Peace River, with the largest current bitumen production from Athabasca (Fig. 1). At present, the Alberta Energy and Utilities Board (EUB) is updating established reserves for each of the individual oil sands deposits.

In the Athabasca oil sands area, most of the bitumen is hosted within the Wabiskaw-McMurray succession, of which about 82% is considered to be recoverable mainly by thermal *in-situ* methods and 18% by surface mining (Alberta Energy and Utilities Board, 2005a). A bitumen-pay thickness map for the Athabasca Wabiskaw-McMurray deposit (based on lower cutoffs of 6 weight percent and 1.5 m thickness of bitumen) shows that most of the bitumen resource occurs as a north-south trend, along the eastern margin of the Athabasca oil-sands area (Fig. 2). The surface mining and *in-situ* thermal schemes are located mainly along this trend, with primary and waterflood schemes used in the subsurface of West Athabasca (Fig. 2). The surface mineable area of Athabasca comprises an area (about 37 townships, each $10 \times 10 \text{ km}$) north of Fort McMurray where the total overburden above the Athabasca Wabiskaw-McMurray deposit is $<75 \text{ m}$. Approved

schemes in Athabasca include eight surface mines, 18 *in-situ* thermal schemes (some with solvent), and 17 primary or waterflood schemes (Fig. 2) (Alberta Energy and Utilities Board, 2004). As of October, 2005, 45 major projects, totaling about \$70Cdn billion, have been completed recently, are currently under construction, or are proposed to start construction within two years (Alberta-Canada, 2005; Athabasca Oil Sands Developers, 2005; Heavy Oil Alberta Project, 2006).

PREVIOUS WORK

Since 1986 the government of Alberta has involved various departments in a concerted effort at regional characterization of the Athabasca oil sands. Much of this initial work was in association with the Alberta Oil Sands Technology and Research Authority (AOSTRA) (Wightman and others, 1995). Since the late 1990s, the Alberta Geological Survey (AGS) has continued this work, updating recent drilling, incorporating more detailed outcrop work, and getting the information about the Athabasca deposit into digital formats. This more recent AGS work has relied on facies mapping on a

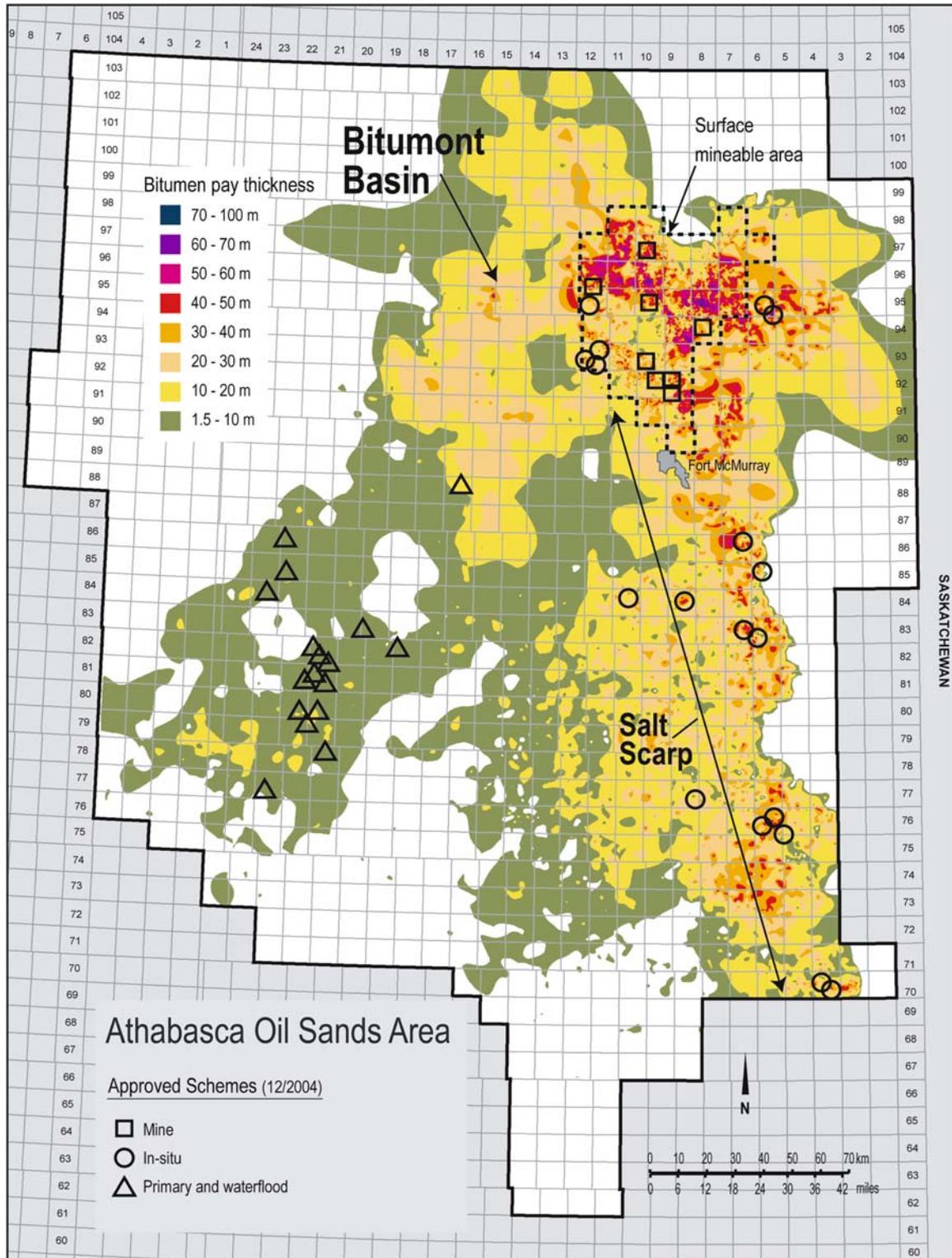


Figure 2. Bitumen pay-thickness map of Athabasca Wabiskaw-McMurray deposit, for areas with > 1.5 m of bitumen. Contour interval is 10 m. Annotations show surface mineable area (dashed line), and approved schemes including: surface mining (squares), *in-situ* thermal (circles), and primary and waterflood (triangles) (modified from Alberta Energy and Utilities Board, 2004, 2005).

regional scale, facilitated through a multidisciplinary approach involving palynological and facies analysis of outcrops and cores, well-log analysis, seismic modeling, and comparison with modern analogues (Hein and Dolby, 2001; Hein and Langenberg, 2003; Hein, Cotterill and Berhane, 2000; Hein and others, 2001; Hein, Cotterill and Rice, 2006; Hein, Cotterill, and Weiss, 2006; Langenberg and others, 2002; Langenberg, Hein, and Berhane, 2003). A number of field guides have been written about the geology of the Fort McMurray area, with emphasis on the oil sands, with the most recent by Hein and others (2001), Hein and Cotterill (2006), Paulen, Rice, and Gingras (2004), and Ranger and Gingras (2002).

From 1997 to 2005 the AGS has been involved with the EUB on issues related to bitumen conservation in the Athabasca Wabiskaw-McMurray deposit (Alberta Energy and Utilities Board, 2005a). The EUB held an inquiry and a number of gas-over-bitumen hearings to effect bitumen conservation, largely a result of the need to shut-in gas production in order to protect potentially recoverable bitumen using *in-situ* techniques (Alberta Energy and Utilities Board, 2005b). Part of this work was a regional geological study (RGS) of the Athabasca Wabiskaw-McMurray deposit (Alberta Energy and Utilities Board, 2003). The RGS focused on development of a unified stratigraphic nomenclature, regional mapping, and pooling concerns. The stratigraphic model that was developed during the RGS is discussed next.

METHODS

The present study is an integration of recent outcrop and subsurface studies, mainly focused in the Fort McMurray area of northeastern Alberta (Fig. 3). The basis of the regional geologic framework includes synthesis of detailed descriptions of outcrop (78) and cores (165), with identification of regional markers, as both major erosional (E) and transgressive (T) surfaces of erosion (Table 1). Once the surfaces were defined, and correlations were done from outcrop to core and core to wire-line logs, a net of subsurface wire-line log sections (14) were then built to describe the regional stratigraphy in three-dimensions for the Fort McMurray area. Of those 14 cross sections in the net, portions of six cross sections are discussed in this paper (Fig. 3). Stratigraphic picks and regional cross sections for the study area will be released in 2006 (Hein, Berhane, and Weiss, 2006).

STRATIGRAPHIC NOMENCLATURE

The stratigraphic nomenclature for the Athabasca Wabiskaw-McMurray deposit mainly is informal and has evolved through time. Historically, the McMurray has been divided into 'Lower, Middle, and Upper.' This simple scheme may be valid on a small scale, but when extended to a broader scale may no longer apply. This relates to the results of large-scale correlations and mapping, with the recognition that successions termed 'Middle' and 'Upper' are related intimately and represent the same systems-tract on a regional scale. Consequently, many regional workers (Keith and others, 1988; Hein and Langenberg, 2003) have advocated abandonment of the term 'Middle,' with only distinction of Lower vs. Upper McMurray. In general, this has not been followed by industry, who working at a small 1/4-township or section scale, do not face problems of regional correlation. Here the Lower fluvial is distinguished from the overlying Upper estuarine and coastal plain complexes. The lower part of what we term Upper McMurray includes what industry workers have termed typically 'Middle McMurray.'

In this paper an approach is used that recognizes both the importance of the various transgressive (T) and erosive (E) surfaces (Table 1) as well as the lithofacies within the different successions. This scheme builds upon the previous AGS work since 1986 (Wynne and others, 1994), as well as incorporating the more recent 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/marginal marine successions; Wabiskaw D estuarine incised valley-fill; Wabiskaw D regional marine shale; and Wabiskaw C marine succession. Further subdivision of the marginal marine Upper McMurray is into the following sequences (in descending order): A1, A2, B1, and B2. Note the McMurray B1 and B2 are absent in the study area, but occur in the subsurface to the south (Fig. 4; Table 1).

In some of the regulatory work by the Alberta government channel deposits of the Lower, 'Middle' or Upper McMurray are considered together, designated as McMurray Channel (or as McMurray C Channel if the B1 or B2 are present, cf. Alberta Energy and Utilities Board, 2003). In other more detailed geologic studies, especially where seismic is available, individual channels and channel complexes are mapped separately within the McMurray

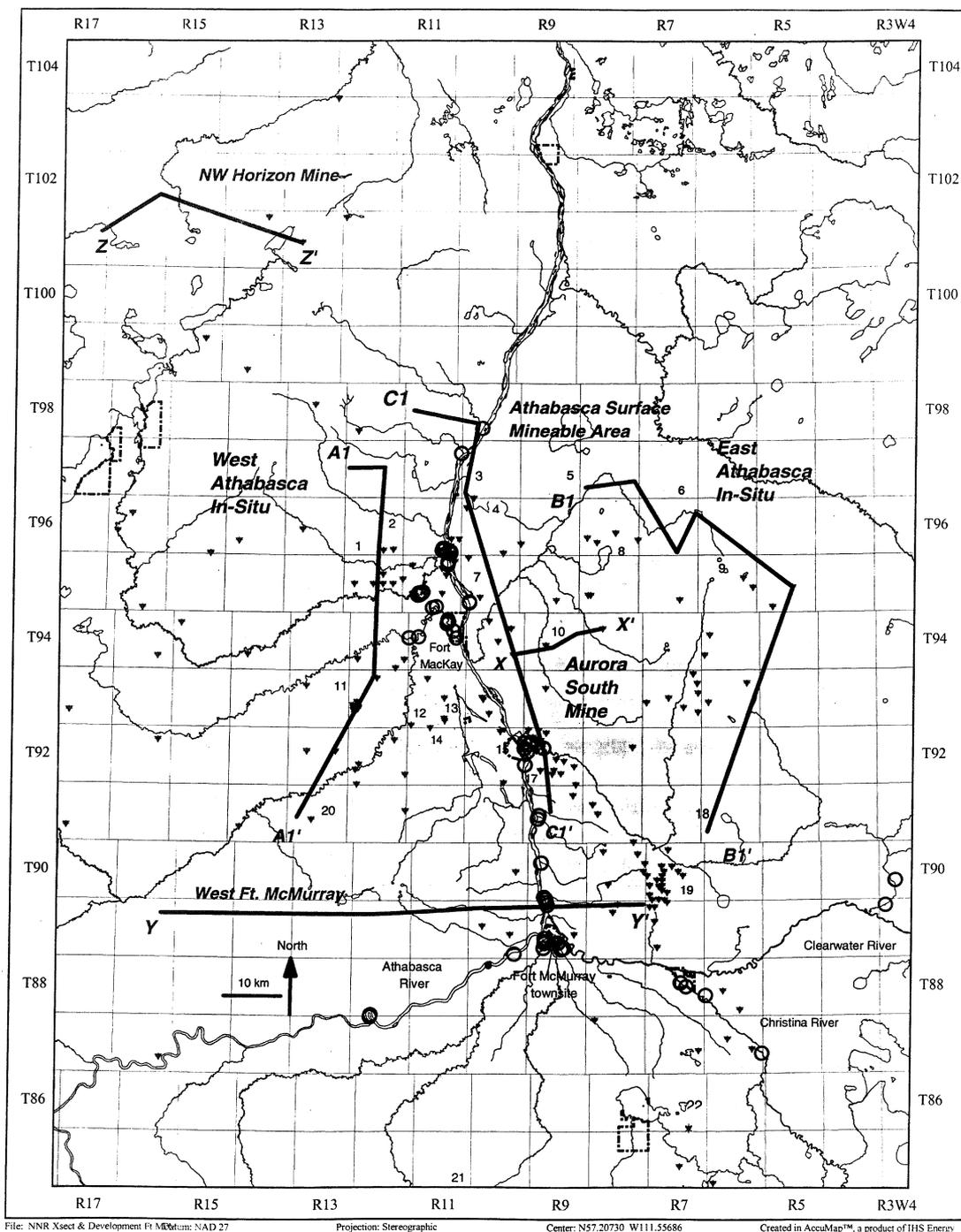


Figure 3. Location of study area near Fort McMurray, showing oil-sand development in area (numbered), outcrop (dots) and core (triangles) control, lines of sections with bolded portions showing those discussed in text. Oil-sand development in the Fort McMurray, Alberta, area include: (1) Joslyn Creek In-Situ; (2) Horizon Mine; (3) Fort Hills Mine; (4) Aurora North Mine; (5) Jackpine In-Situ; (6) Sunrise In-Situ; (7) Muskeg River Mine; (8) Kearl Lake Mine; (9) Firebag In-Situ; (10) Aurora South Mine; (11) Dover UTF In-Situ; (12) Syncrude North Mine; (13) Mildred Lake Facilities; (14) Syncrude Base Mine; (15) Suncor Main Mine; (16) Steepbank Mine; (17) Millenium Mine; (18) Lewis In-Situ; (19) Clarke Creek In-Situ; (20) MacKay River In-Situ; (21) Hangingstone In-Situ; (22) Gregoire Lake In-Situ.

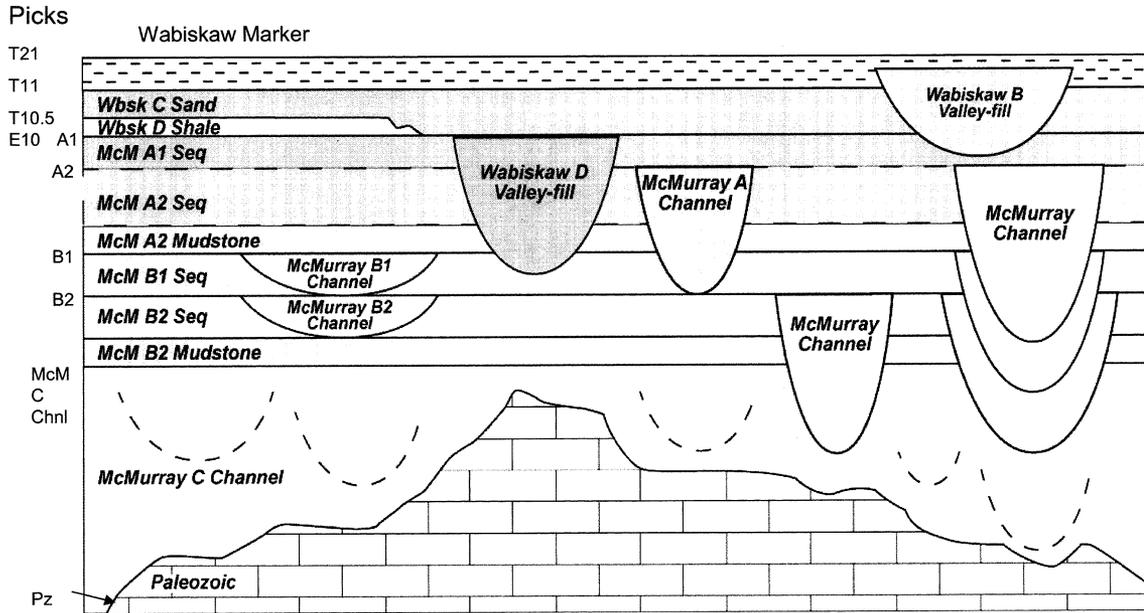


Figure 4. Stratigraphic model for Athabasca Wabiskaw-McMurray deposit, showing AGS and RGS picks, with Wabiskaw Marker (T21) as datum at top, and schematic showing geometric relationships between different stratal units. Note McMurray B1 and B2 sequences do not occur in present study in surface mineable area, but are only mapped in subsurface area to south (modified from Wynne and others, 1994; Hein and others, 2001; Alberta Energy and Utilities Board, 2003).

or Wabiskaw successions (cf. Langenberg and others, 2002; Langenberg, Hein, and Berhane, 2003; Paulsson and others, 1994; Zhang and others, 2002; Zhang, Youn, and Doan, 2005).

OIL-SAND RESERVOIR GEOLOGY

The Lower McMurray fluvial succession is preserved mainly along lows on the sub-Cretaceous unconformity, and contains mostly bottom water, although some developments, such as the Joslyn Creek *in-situ* project (Fig. 3), are targeting bitumen in Lower McMurray braided river-sand reservoirs. Such reservoirs comprise sand-dominated, channel-and-bar complexes, have high porosities and permeability (locally averaging 8.6 darcies, from 12 to 13 darcies), high interconnectivity, and lack internal barriers or baffles (Flach and Hein, 2001). Such sheet-sands may be interconnected along the bases of main paleovalleys fills; outside main valley trends, basal sands are more localized. These were deposited during Lower McMurray low-stand conditions.

The overlying Upper McMurray succession is a transgressive systems tract that contains some of the richest bitumen reservoirs within the Athabasca de-

posit, hosted mainly within amalgamated or stacked estuarine channel-and-point bar complexes. These reservoirs include thick (up to 58-m) estuarine channel sands with no laterally extensive shale breaks. Such examples occur in the lower part of the Steepbank Mine, the Amphitheatre outcrop section near Fort MacKay (about 65 km northwest of Fort McMurray), and in both outcrop and subsurface at the northern limit of the surface mineable area (Figs. 2 and 3). Other areas show estuarine channel - lateral accretion point bar sands, with well defined, shallow-dipping, mud interbeds (inclined heterolithic stratification, IHS), that fine-upwards into point-bar top, crevasse-splay and floodplain deposits. The lateral-accretion geometry of the fluvio-estuarine point bars is seen in outcrop, interpreted in the subsurface by seismic and confirmed with dip meter logs (Langenberg and others, 2002; Langenberg, Hein, and Berhane, 2003; Strobl and others, 1997a, 1997b).

The Upper McMurray amalgamated estuarine meandering channel-and-point bar complexes have somewhat lower porosity, locally averaging 6.5 darcies (Flach and Hein, 2001), and reduced permeability and interconnectivity, compared with the Lower McMurray fluvial sheet sands. Mudstone occurs as intraclast breccias within channels and on

point-bars, as IHS, and as thick but discontinuous fill of abandoned channels. In all cases, these muds are interpreted as baffles (and not barriers) to subsurface *in-situ* steam or fluid flow. Notable areas where there have been successful pilot and commercial schemes within the Upper McMurray where there are mudstone baffles include: the Dover UTF, MacKay River, Hangingstone (Fig. 3), and Christina Lake (~170 km south of Fort McMurray) (Strobl and others, 1997a, 1997b; Zhang, Youn, and Doan, 2005). Mudstone breccias and IHS beds also occur in many of the mines, including the Steepbank, Syncrude North, and Millenium mines (Fig. 3), but again such muds do not cause significant problems to surface-mining operations.

Where preserved, the topmost Upper McMurray consists of stacked coarsening-upward parasequences of mud (generally ≤ 1 m) into clean sand (usually ≤ 5 m) (the A1, A2, sequences, Fig. 4). Locally, for example in outcrops near the Joslyn *in-situ* project (Fig. 3), parasequence sediments are thin, but locally extensive, and are interpreted as crevasse splay sheet-sands and tidal flat sediments. Such deposits may locally be good, thin, small-scale bitumen reservoirs, encased within otherwise nonproductive fine-grained and coaly coastal plain successions (Flach and Hein, 2001; Hein and others, 2001). Elsewhere, in the subsurface, such coarsening-up parasequences have been mapped regionally, and locally may provide barriers to connectivity between bitumen-reservoirs and overlying top gas and/or water reservoirs (cf. Alberta Energy and Utilities Board, 2003, 2005b). Amalgamated estuarine channel sands (McMurray Channel, Fig. 4) form good, thick bitumen reservoirs high upsection in the Athabasca Wabiskaw-McMurray deposit. Elsewhere, with the thinner parasequences and more laterally continuous mudstones, the higher portions of the Upper McMurray are not targets for *in-situ* bitumen recovery. In the surface mining area the bitumen within the parasequence sands may be recovered by surface mining or stripped off with the overburden (if uneconomic).

REGIONAL CROSS SECTIONS: DESCRIPTION AND INTERPRETATION

The stratigraphic relationships of the Wabiskaw and McMurray units are shown in a series of regional cross sections, portions of which are shown in summary from in Figures 5–10. The datum selected for the sections is the T21 “Wabiskaw Marker” — a

distinctive, low-resistivity mudstone that defines the top of the Wabiskaw Member (Clearwater Formation). This mudstone is usually <5 m thick, on logs tends to have a high neutron porosity and in core shows a platy fissility and black color (Wynne and others, 1994). The most prominent stratigraphic surfaces are the sub-Cretaceous unconformity (Pz) and the unconformity at the contact between the McMurray and Wabiskaw (E10, usually sitting on McMurray A1/A2 or McMurray Channel). Other evident stratigraphic surfaces occur as: T 11, top of Wabiskaw C; T10.5 Top of Wabiskaw D; A1, A2, McMurray Channel, and where preserved and recognizable, the E05 at the contact between the Lower and Upper McMurray units (Fig. 4, Table 1). Ages of the stratigraphic units in this study are based on an integration of regional correlation and palynology (Table 1) (Hein and Dolby, 2001).

Surface Mineable Area

North-South Trends

A regional north-south longitudinal section through the main valley trend of the Athabasca bitumen deposit in the surface mineable area shows a rapid thickening in reservoir sands from Eymundson Creek, at the northern limit of the outcrop belt (T98, R11W4) to the Fort Hills Mine and Steepbank Mine (T97, R10W4 to T92, R9W4), with thinning again to the south towards the Millenium Mine (T91, R9W4) (Figs. 3 and 5). These trends within McMurray reservoirs largely reflect topography along the sub-Cretaceous unconformity, whereas the overlying Wabiskaw D valley-fill has trends that do not reflect the sub-Cretaceous unconformity surface (Fig. 5). Local bitumen reservoirs exceed 50 meters in thickness, with good saturations, particularly lower down in the McMurray succession and within the Wabiskaw D valley-fill. There is discontinuous preservation of the Wabiskaw D valley-fill in the Millenium Mine area (AA/02-21-091-09W4). The more regional marine Wabiskaw C succession generally is preserved throughout much of the area (Fig. 5).

East-West Trends

Northwest of the surface mineable area (Figs. 3 and 6) overburden generally exceeds 75 m and bitumen saturations are variable. For example,

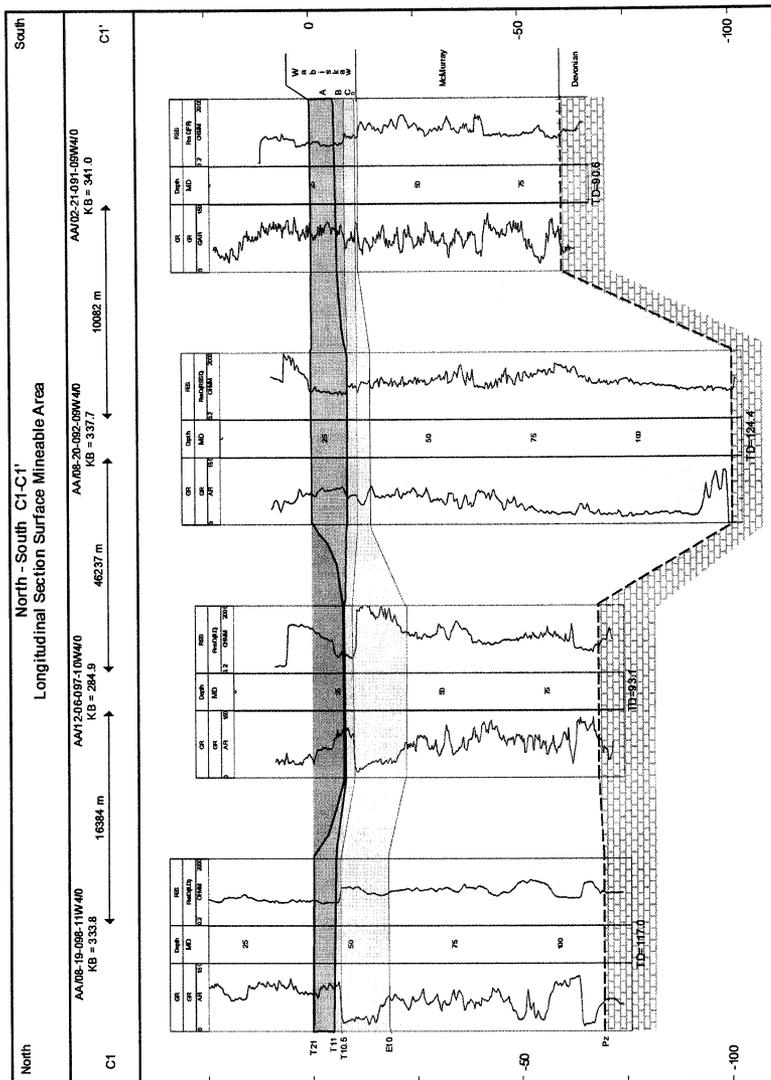


Figure 5. Regional longitudinal north-south section through surface mineable area, showing prominent markers and LAS-files of gamma-ray and resistivity wire-line logs (see Fig. 3 for section location, with stratigraphic units and markers shown in Fig. 4 and Table 1).

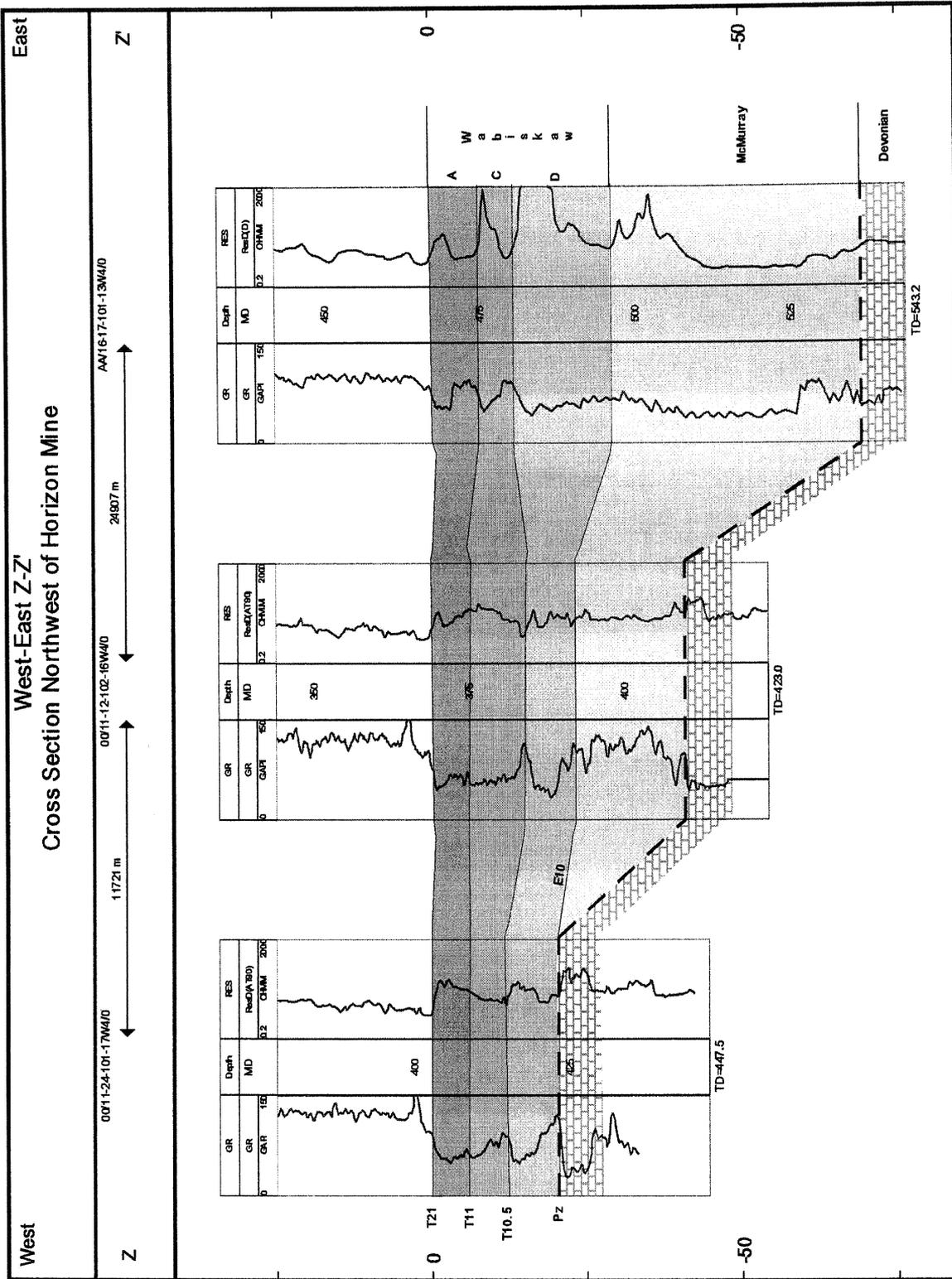


Figure 6. Regional west-east cross section northwest of Horizon Mine, showing prominent markers and LAS-files of gamma-ray and resistivity wire-line logs (see Fig. 3 for section location, with stratigraphic units and markers shown in Fig. 4 and Table 1).

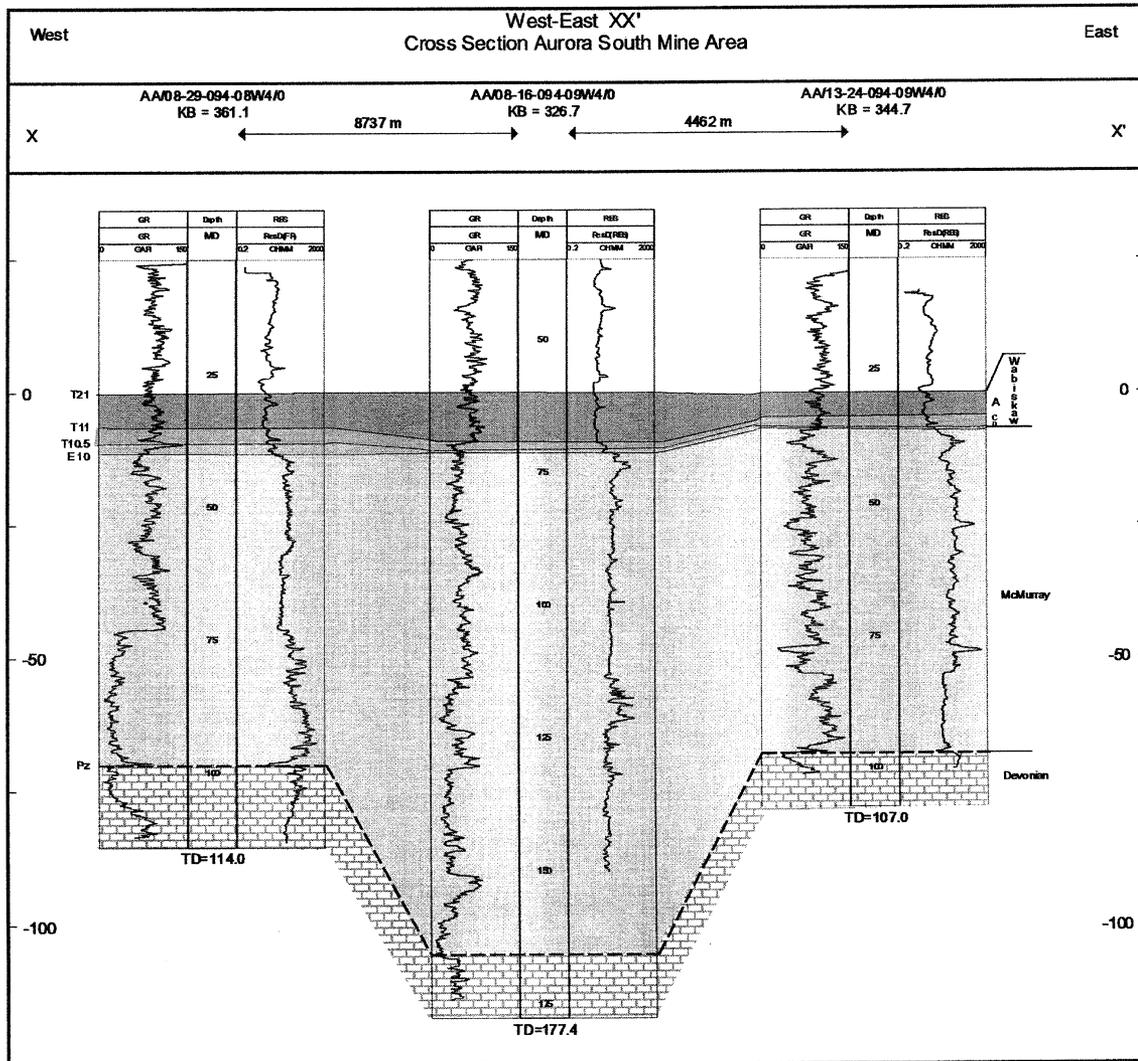


Figure 7. Regional west-east cross section in Aurora South Mine area, showing prominent markers and LAS-files of gamma-ray and resistivity wire-line logs (see Fig. 3 for section location, with stratigraphic units and markers shown in Fig. 4 and Table 1).

in the upper part of the McMurray channel succession in the AA/16-17-101-13W4 well, bitumen is more common at the top where sands alternate with thin mud beds; but below that within the main channel deposit the reservoir sands are mainly water-wet (Fig. 6, east side). Generally the Wabiskaw D changes from a regional coarsening up sequence in the west (00/11-24-101-17W4 well) that changes laterally to coarsening-then-fining upward succession in the middle of the cross section (00/11-12-102-16W4 well), eventually thickening to a blocky incised valley-fill sequence to the east (AA/16-17-101-13W4, confirmed in core) (Fig. 6). These trends reflect increased accommodation space

because of deposition within a paleolow structure. The overlying regional marine Wabiskaw A and Wabiskaw C successions generally blanket the area.

In the central part of the surface mineable area, near the Aurora South Mine area, rapid thickening of the McMurray reservoir sands is interpreted to be the result of influence of bedrock topography (Fig. 7). The paleotopography likely developed by downdropping associated with regional salt-dissolution and collapse during sedimentation of the Wabiskaw-McMurray succession. Younger subsidence also occurred near the end of Wabiskaw time as shown by thickened Wabiskaw A units between

the T21 and T11 markers in the AA/08-16-94-9W4 well (Fig. 7).

Southwest of the surface mineable area overburden generally exceeds 75 m, and bitumen saturation is variable, generally absent both over bedrock highs (i.e. >200 m depth in the AA/10-26-089-16W4 well, Fig. 8) and/or within paleotopographic lows where the McMurray channel succession is muddier. Other McMurray channel successions that consist of stacked channel sands fining up into sand-and-muddy point bar successions show some bitumen saturation within sandier portions (i.e. 190–200 m depth in the AA/10-26-089-16W4 well) (Fig. 8). In general, the Wabiskaw-McMurray succession is relatively thin (20–30 m thick) where it drapes over bedrock highs, thickening into the main valley 40–50 m within paleotopographic lows (AA/09-36-089-08W4) (Fig. 8). Most noticeable in this area is erosion of the T21 Wabiskaw Marker to the west (AA/10-26-089-16W4), where it is replaced by the younger Clearwater sands beneath the T31 marker.

In-Situ Area

West Athabasca North-South Trends

In the West Athabasca area, from north to south, there is a rapid thickening, then gradual thinning of the Wabiskaw-McMurray succession, reflecting mainly the topography on the sub-Cretaceous unconformity (Fig. 9). Although the Wabiskaw D succession was not noted in the Dover River UTF and McKay River *in-situ* project sites (Fig. 3), wells and outcrops in the surrounding area show an upper Wabiskaw D valley-fill succession that is superimposed upon and replaces thinning McMurray sequences (i.e. in the AA/01-33-093-12W4 and AA/11-17-091-13W4 wells, Fig. 9). Bitumen saturations are moderate to high, particularly in lower parts of the McMurray channel and in lower parts of the Wabiskaw D valley-fill successions. In some areas Wabiskaw D valley-fill overlies stacked McMurray Channel successions (AA/3-23-097-12W4, Fig. 9). In shalier zones and in channel sands to the north, bitumen saturation is more sporadic, largely interbedded with water reservoirs.

East Athabasca North-South Trends

In the East Athabasca *in-situ* area, there is a rapid northward-thickening of the Wabiskaw-

McMurray succession, again reflective of increased accommodation because of deepening of the sub-Cretaceous unconformity (Fig. 10). Thin remnants of the Wabiskaw D are preserved, and the succession is capped by northward-thinning Wabiskaw C and northward-thickening Wabiskaw A/B marine units (between the T21 and T11 markers). Bitumen saturation within reservoir sands is moderate to high, particularly in lower parts of the McMurray channel succession (i.e. in the AA/10-15-095-05W4 and AA/07-07-091-06W4 wells, Fig. 10). Local basal water zones occur along flanks of the paleotopographic low in bedrock (i.e. >240 m depth in the AA/07-07-091-06W4 well, Fig. 10).

SEQUENCE STRATIGRAPHIC FRAMEWORK

The Wabiskaw-McMurray succession in northeastern Alberta has numerous stratal disconformities and unconformities (the T and E surfaces), which formed as a response to increases or decreases in relative base level. Some of these surfaces occur at lithostratigraphic boundaries (Pz, E05, E10, T10.5), whereas others reflect sequence boundaries that are mainly a result of the interplay between sea-level rise within the overall McMurray-Wabiskaw transgression and accommodation space associated to salt-dissolution tectonics during sedimentation (Table 1, Fig. 11).

The most obvious unconformities are at the base and top of the McMurray Formation (Pz and E10). Paleotopography on the lower sub-Cretaceous unconformity had a great influence on paleodrainage and preservation of successions within the McMurray. The best preservation of the Lower McMurray fluvial successions is along lows in the unconformity, where basal water zones also may lie beneath the bitumen reservoirs. The Lower McMurray is a braided river fluvial low-stand deposit at the base, which is capped (where preserved) by early transgressive coal deposits. At the top of the Lower McMurray is a major surface of erosion (E05). Following this was a period of rapid sea level rise, associated with extensive flooding of estuaries and overbank areas, with the creation of large bodies of brackish water bays.

The lower phases of Upper McMurray deposition comprise the main meandering, deep estuarine channel and point bar deposits that host some of the most important bitumen reservoirs within

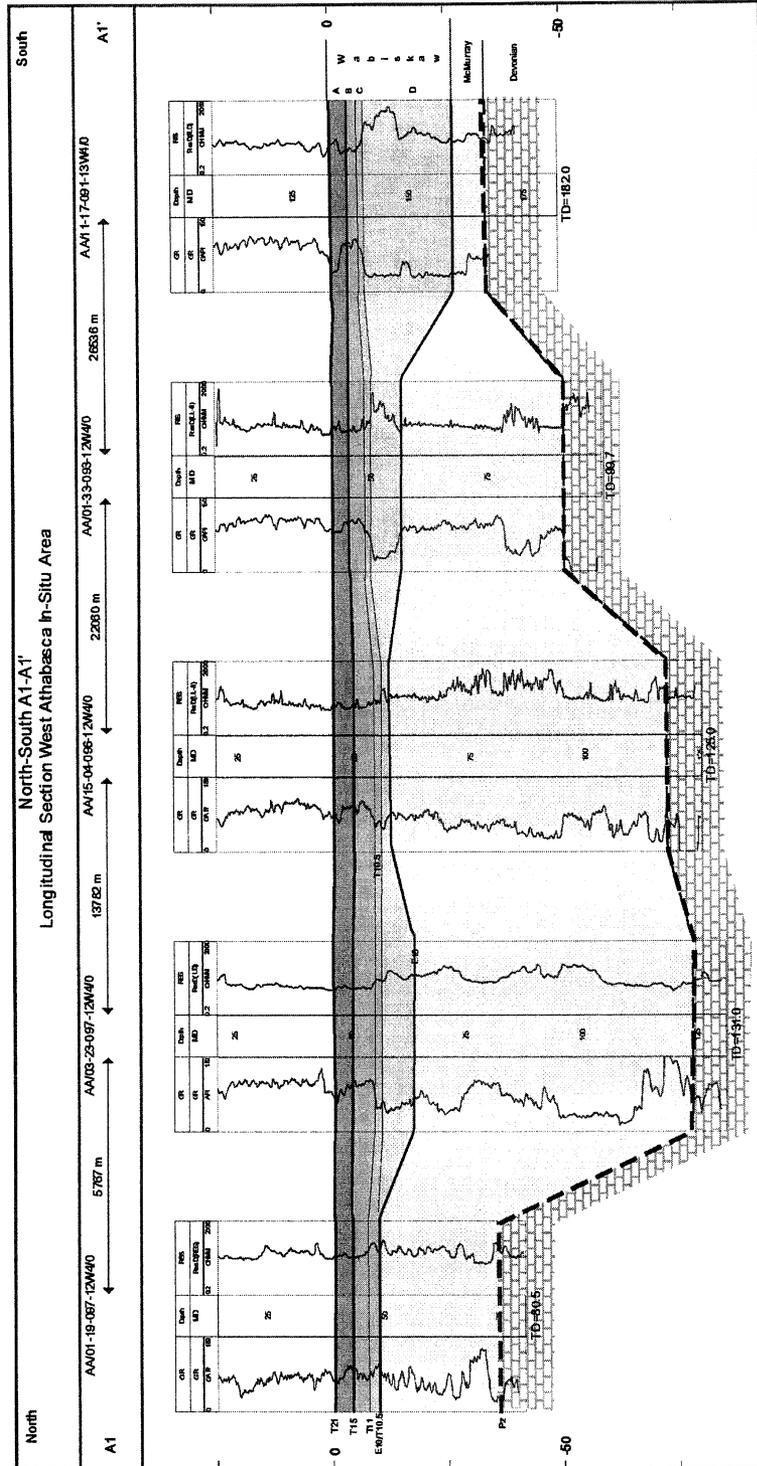


Figure 9. Regional north-south longitudinal section in West Athabasca in-situ area, showing prominent markers and LAS-files of gamma-ray and resistivity wire-line logs (see Fig. 3 for section location, with stratigraphic units and markers shown in Fig. 4 and Table 1).

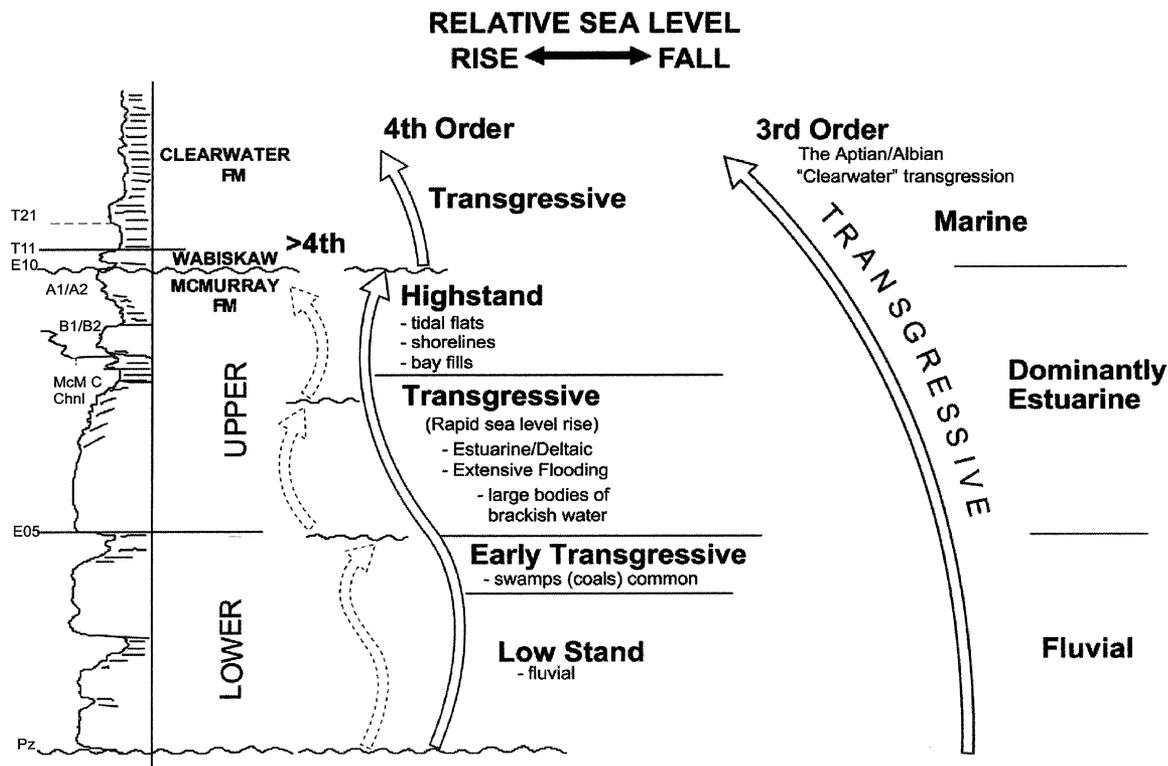


Figure 11. Sequence stratigraphy of Athabasca Wabiskaw-McMurray succession drawn from geology of McMurray Formation in Joslyn Creek *in-situ* area (modified from Flach and Hein, 2001).

the McMurray Formation. Estuarine channel systems are marked by extreme lateral heterogeneity, although none of the mudstone beds (as abandonment channel fills, IHS or floodplain deposits) are persistent for any significant distance, and would be mere baffles as opposed to true barriers to *in-situ* thermal operations. With increased transgression, through time, the Upper McMurray channel-and-point bar sedimentation became replaced by overbank, vertical accretion sedimentation in off channel areas and floodplain swamps. Within the topmost Upper McMurray high stand conditions prevailed with development of extensive tidal flats, local brackish bay, back-barrier, and deeper bay-fill deposits. This is evident by the presence of more extensive, and laterally continuous mudstones at the base of the coarsening-up parasequences (A1, A2). In situations of down cutting, where the basal mudstones to the parasequences are removed, bitumen reservoirs may be in contact with overlying water or gas reservoirs. Such top water or top gas may be potential thief zones to bitumen recovery for *in-situ* thermal SAGD-operations. Continued transgression

locally resulted in significant removal of underlying parasequences prior to emplacement of Wabiskaw D valley-fill. The Wabiskaw D valley-fill is capped by the regional Wabiskaw D shale, the base of which is at the T10.5 surface. The T10.5 is interpreted as a transgressive surface of erosion associated with the maximum flooding event within the overall Wabiskaw-McMurray transgression.

CONCLUDING REMARKS

The bitumen area of the Athabasca Wabiskaw-McMurray deposit in northeastern Alberta is characterized by complex stratigraphic relationships, numerous erosional surfaces, as unconformities, transgressive surfaces of erosion, and internal erosional surfaces that result in widely varying facies distributions and reservoir characteristics. The base of the Athabasca Wabiskaw-McMurray succession represents a major unconformity, with deep fluvial incision and the formation of a large north-south valley. Distribution of basal water and lower bitumen

reservoirs are controlled mainly by relief along the sub-Cretaceous unconformity. A multistory succession of fluvial → fluvio-estuarine → estuarine/brackish bay-fill/coastal plain → marine is recorded in the overall Wabiskaw-McMurray transgression, with the maximum flooding surface marked by the Wabiskaw D shale, near the top of the Wabiskaw Member.

History of deposition is related to relative base-level changes, because of a complex interplay between ensuing relative sea level rise (overall transgression) coupled with forced regressions, because of >4th order cycles reflecting influences of salt-dissolution tectonics and local base-level drop within the main north-south valley trend. Compartmentalization of reservoirs depends both upon salt-dissolution tectonics as well as preservation of mudstone caps. The occurrence of laterally continuous mudstones to break up the reservoirs are dependent upon magnitude and type of erosion associated with the various sequence boundaries and other stratal surfaces. Without good and closely spaced core and wire-line log control it would be impossible to recognize many of the stratigraphic relationships documented in this paper. This regional geologic framework has both economic and academic significance, providing better documentation and understanding of the compartmentalization of the oil-sand reservoirs, mainly the result of the inherent complexity of the Athabasca Wabiskaw-McMurray deposit.

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REFERENCES

- Alberta-Canada, 2005, Inventory of major Alberta projects summary and inventory of Alberta regional projects, oil, gas and oil sands, Alberta Economic Development: <http://alberta-canada.com/statpub/albertaConstructionOProjects/mp0510.cfm>.
- Alberta Energy and Utilities Board, 2003, Athabasca Wabiskaw-McMurray regional geological study: Rep. 2003-A, 188 p. (CD-ROM).
- Alberta Energy and Utilities Board, 2004, Active oil sands schemes map: Statistical Series, ST-44, one map-sheet (December 2004).
- Alberta Energy and Utilities Board, 2005a, Alberta's reserves 2004 and supply demand outlook 2005–2014: Statistical Series, ST98-2005, p. 1–1 to A-29.
- Alberta Energy and Utilities Board, 2005b, Phase 3 Final proceeding under bitumen conservation requirements in the Athabasca Wabiskaw-McMurray: Decision 2005-122, 32 p.
- Athabasca Oil Sands Developers, 2005, Publications and information, project list and update, oil sands lease maps: <http://www.oilsands.cc/publications/projects.asp>.
- Flach, P. D., and Hein, F. J., 2001, Outcrop-core correlation of channel and non-channel facies, McMurray Formation, Fort MacKay area, NE Alberta: Rock the Foundation Conf., Proc. Can. Soc. Petroleum Geologists (Calgary), p. 132–133.
- Heavy Oil Alberta Project (HOAP), 2006, Unlocking 176 billion barrels: the energy of alberta innovation, Guidebook and Directory to Alberta's Heavy Oil Industry, June Warren Publishing Ltd., 150 p., in press. www.junewarren.com
- Hein, F. J., 2006, Oil sands and heavy oil in North America: an overview and summary, Natural Resources Research, V.15, no.2, this volume.
- Hein, F. J., and Cotterill, D. K., 2006, Field Guide: Regional sedimentology and processes of deposition of the Athabasca oil sands, NE Alberta: Alberta Energy and Utilities Board/Alberta Geological Survey, GeoNote 2006, 167p. (CD-ROM), in press.
- Hein, F. J., and Dolby, G., 2001, Regional lithostratigraphy, biostratigraphy and facies models, Athabasca oil sands deposit, northeast Alberta: Ann. Conv. Proc. Rock the Foundation (Calgary), Can. Soc. Petroleum Geologists, 3 p.
- Hein, F. J., and Langenberg, C. W., 2003, Reply to discussion of seismic modeling of fluvial-estuarine deposits in the Athabasca oil sands using ray-tracing techniques, Steepbank River area, northeastern Alberta: Bull. Can. Petroleum Geology, v. 51, no. 3, p. 354–366.
- Hein, F. J., Cotterill, D. K., and Berhane, H., 2000, An atlas of lithofacies of the McMurray Formation, Athabasca oil sands deposit, northeastern Alberta: surface and subsurface: Alberta Energy and Utilities Board/Alberta Geol. Survey, Earth Sciences Rep. 2000-07, 216 p. (CD-ROM).
- Hein, F. J., Cotterill, D. K., and Rice, R., 2006, Subsurface geology of the Athabasca Wabiskaw-McMurray succession: Lewis - Fort McMurray area, northeastern Alberta (NTS 74D/14): Alberta Energy and Utilities Board/Alberta Geol. Survey, Earth Sciences Rep. 2006, 61 p.(CD-ROM), in press.
- Hein, F. J., Cotterill, D. K., and Weiss, J., 2006, Subsurface geology of the Athabasca Wabiskaw-McMurray succession: Sunrise-Firebag area, northeastern Alberta (NTS 74D/14): Alberta Energy and Utilities Board/Alberta Geol. Survey, Earth Sciences Rep. 2006, 107p.(CD-ROM), in press.
- Hein, F. J., Langenberg, C. W., Kidston, C., Berhane, H., Berezniuk, T., and Cotterill, D. K., 2001, A comprehensive field guide for facies characterization of the Athabasca oil sands, northeast Alberta (with maps, air photos, and detailed descriptions of seventy-eight outcrop sections): Alberta

- Energy and Utilities Board/Alberta Geol. Survey, Spec. Rep. 13, 335 p. (CD-ROM).
- Keith, D. A. W., Wightman, D. M., Pemberton, S. G., MacGillivray, J. R., Berezniuk, T., and Berhane, H., 1988, Sedimentology of the McMurray Formation and Wabiskaw Member (Clearwater Formation), Lower Cretaceous, in the central region of the Athabasca oil sands area, northeastern Alberta, *in* James, D. P. and Leckie, D. A., eds., Sequences stratigraphy, sedimentology: surface and subsurface: Can. Soc. Petroleum Geologists, Mem. 15, p. 309–324.
- Langenberg, C. W., Hein, F. J., Lawton, D., and Cunningham, J., 2002, Seismic modeling of fluvial-estuarine deposits in the Athabasca oil sands using ray-tracing techniques, Steepbank River area, northeastern Alberta: *Bull. Canadian Petroleum Geology*, v. 50, No. 1, p. 178–204.
- Langenberg, C. W., Hein, F. J., and Berhane, H., 2003, Three-dimensional geometry of fluvial-estuarine oil-sand deposits of the Clarke Creek area (NTS 74D), northeastern Alberta: Alberta Energy and Utilities Board, Alberta Geological Survey, Earth Sciences Rep. 2001-06, 44 p. (CD-ROM).
- Paulen, R., Rice, R., and Gingras, M., 2004, Geology of the Fort McMurray area, northeast Alberta: *Edmonton Geol. Society (Edmonton)*, 67 p.
- Paulsson, B. N. P., Meredith, J. A., Wang, Z., and Fairborn, J. W., 1994, The Steepbank crosswell seismic project: Reservoir definition and evaluation of steam flood technology in Alberta tar sands: *The Leading Edge*, v. 13, no. 7, p. 737–747.
- Ranger, M., and Gingras, M., 2002, Geology of the Athabasca oil sands: Field Guide and Overview, @ 2001, 2002, Michael J. Ranger, Murray K. Gingras, 134 p.
- Ranger, M. J., and Pemberton, S. G., 1997, Elements of a stratigraphic framework for the McMurray Formation in south Athabasca area, Alberta, *in* Pemberton, S.G. and James, D. P., eds., Petroleum geology of the Cretaceous Mannville Group, Western Canada: Can. Soc. Petroleum Geologists, Mem. 18, p. 263–291.
- Strobl, R. S., Muwais, W. K., Wightman, D. M., Cotterill, D. K., and Yuan, L-P., 1997a, Geological modeling of McMurray Formation reservoirs based on outcrop and subsurface analogues, *in* Pemberton, S. G. and James, D. P., eds., Petroleum geology of the Cretaceous Mannville Group, Western Canada: Can. Soc. Petroleum Geologists, Mem. 18, p. 292–311.
- Strobl, R. S., Muwais, W. K., Wightman, D. M., Cotterill, D. K., and Yuan, L-P., 1997b, Application of outcrop analogues and detailed reservoir characterization to the AOSTRA underground test facility, McMurray Formation, northeastern Alberta, *in* Pemberton, S. G. and James, D. P., eds., Petroleum geology of the Cretaceous Mannville Group, Western Canada: Can. Soc. Petroleum Geologists, Mem. 18, p. 375–391.
- Wightman, D. M., Attalla, M. N., Wynne, D. A., Strobl, R. S., Berhane, H., Cotterill, D. K., and Berezniuk, T., 1995, Alberta energy: AOSTRA Tech. Publ. Series 10, 220 p.
- Wynne, D. A., Attalla, M., Berhane, H., Brulotte, M., Cotterill, D.K., Strobl, R., and Wightman, D. M., 1994, Athabasca oil sands database: McMurray/Wabiskaw Deposit: Alberta Energy and Utilities Board/Alberta Geological Survey, Open File Rep. 1994–14, 44 p.
- Zhang, W., Youn, S., and Doan, Q., 2005, Understanding reservoir architectures and steam chamber growth at Christina Lake, Alberta, by using 4D seismic and crosswell seismic imaging: *Proc. SPE Intern. Thermal Operations and Heavy Oil Symposium*, (Calgary, Alberta), SPE/PS-CIM/CHOA 87808, 9 p.
- Zhang, W., Li, G., Cody, J., and Meyer, J., 2002, Understanding reservoir architectures at Christina Lake, Alberta, with crosswell seismic imaging: *Recorder*, v. 27, no. 5, p. 33–36.