EUB/AGS Earth Sciences Report 2006-06

Subsurface Geology of the Athabasca Wabiskaw-McMurray Succession: Lewis-Fort McMurray Area, Northeastern Alberta (NTS 74D/74E)

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F.J. Hein, D.K. Cotterill[1] and R. Rice[2]
[1]Parallax Resources Ltd.
[2]Formerly of Alberta Energy and Utilities Board

September 2006

ISBN 0-7785-3860-5

When using information from this publication in other publications or presentations, due acknowledgment should be given to the EUB/AGS. The following reference format is recommended:

Hein, F.J., Cotterill, D.K. and Rice, R.J. (2006): Subsurface geology of the Athabasca Wabiskaw-McMurray Succession: Lewis—Fort McMurray area, northeastern Alberta (NTS 74D/74E); Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2006-06, 59 p.

Author Address

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

Randy Rice
Suncor Energy Inc.
In Situ Operations and Technology
112 - 4th Avenue SW
Calgary, Alberta, T2P 2V5

Published September 2006 by:

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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Acknowledgments

The Alberta Geological Survey (AGS) acknowledges the following contributions to this study: Travis Hurst and Jim Lobsinger for assistance with log picks, core examination and description; Dennis Chao, MaryAnne Pinto and Shauna Miller for GIS mapping; Cal Hill and Willem C. Langenberg for critical reviews of an earlier version of this report. Production assistance and computer graphics were by Maryanne Protz and Dan Magee.

Abstract

Most of the bitumen resources in the Athabasca Wabiskaw-McMurray deposit are contained in fluvial, estuarine and marginal marine sediments of the Lower Cretaceous McMurray Formation. The subsurface of the Lewis area is characterized by picks from 1189 wells, including examination of about 50 cores, which were linked on a larger scale with the Regional Geologic Study (RGS) main and north study areas, completed by the EUB in 2003.

The informal stratigraphic nomenclature for the Lewis area includes: Lower McMurray fluvial; 'Middle'/Upper McMurray estuarine/coastal plain succession; Wabiskaw D valley fill; Wabiskaw D regional marine shale; and Wabiskaw C succession. Within the 'Middle'/Upper McMurray, further subdivision into the A1L and A2L sequences is maintained, as was done in the RGS.

The paleogeographic evolution of the Lewis area includes five main phases:

1) Lower/'Middle' McMurray fluvial/fluvio-estuarine channel and point bar complexes which formed during lowstand and early transgressive conditions;

2) 'Middle'/Upper McMurray A2L relict and reworked bay-fills, crevasse splays, fluvio-estuarine tributaries, resulted from deposition and reworking during early transgressive phases;

3) 'Middle'/Upper McMurray A1L relict and reworked bay-fills, washover deposits, and back-barrier deposits that resulted from deposition and reworking during middle transgressive phases;

4) Wabiskaw D valley fill and regional marine shale, deposited during maximum flooding of the main McMurray-Wabiskaw transgression;

5) Wabiskaw C successions, formed during waning transgressive and initial regressive phases.

1 Introduction

In July 2003 *General Bulletin (GB) 2003-28* was issued by the Alberta Energy and Utilities Board (EUB/Board) in which it announced bitumen conservation requirements for gas production from the Wabiskaw Member of the Clearwater Formation and the underlying McMurray Formation (Wabiskaw-McMurray) in the Athabasca Oil Sands Area (Figure 1a). In this *GB* the Board identified an area of concern, where it considered that associated gas production was an unacceptable risk to *in situ* bitumen recovery. The Board then conducted a *Regional Geological Study (RGS)* to identify nonassociated gas in that area (Alberta Energy and Utilities Board, 2003). This study became the basis for the Phase 3 Bitumen Conservation Hearings for the Athabasca deposit (Hein et al., 2004; Connelly et al., 2005).

In doing the *RGS* the Board focused on two subregions of the area of concern for the Athabasca deposit: the main study area (Township 67–87, Ranges 1–10W4) and the northern study area (Townships 95-97, Ranges 11-15W4). What was not examined by the Board was the subsurface area surrounding the surface mineable area and the subsurface area linking the main and northern study areas (Figure 1b). This was because there were little booked gas reserves in that area and most of the bitumen was recoverable by surface mining techniques. In order to complete an integrated assessment of the subsurface geology of the area, a joint Geology and Reserves Group (GRG) - Alberta Geological Survey (AGS) project was done in the borderlands surrounding the surface mineable area, with the aim to link the northern and main *RGS* study areas, as well as incorporating regions east of Fort McMurray. This was done to aid in updating bitumen reserves in the subsurface areas surrounding the surface mineable area (Alberta Energy and Utilities Board, 2004, 2005), including the Lewis, Sunrise and Firebag leases (Figure 2).

The present earth sciences report emphasizes the Petro-Canada Lewis Lease area and surrounding subsurface regions of the Fort McMurray area. A subsequent earth science report will focus on the Sunrise and Firebag leases, extending to the northeastern limit of the Athabasca deposit (Hein et al., in prep.).

The A1L and A2L sequences discussed in this report are younger than the A1 and A2 sequences in the *RGS* (Alberta Energy and Utilities Board, 2003), but fall in the identical stratigraphic position. As such A1L and A2L picks from the present study should not be merged with A1 and A2 picks in the *RGS*.

2 Previous Work

Previous work in the area has largely involved outcrop and subsurface studies that relied on regional mapping, along with palynological and facies analysis of outcrops and cores, well log analysis, seismic modelling, and comparisons with modern analogues (Flach, 1984; Muwais and Smith, 1990; Strobl et al., 1997; Hein et al., 2000, 2001; Flach and Hein, 2001; Hein and Dolby, 2001; Langenberg et al., 2002, 2003; Hein and Langenberg, 2003; Blakney, 2004; Brekke and Evoy, 2004; Lettley et al., 2004;). A number of field guides have been written about the geology of the oil sands in Fort McMurray area, with the most recent by Hein et al. (2001), Paulen et al. (2004), and Ranger and Gingras (2002). Crerar (2003) completed thesis work on the sedimentology and stratigraphic evolution of the Wabiskaw-McMurray succession at the Lewis property, which was augmented by palynological analysis for selected samples from that area (Sweet, 2002).

3 Regional Stratigraphy of the Wabiskaw-McMurray Succession

Typically in the past, the McMurray succession has been interpreted as fluvial for the Lower McMurray; estuarine channel and point bar for the Middle McMurray; and, coastal plain for the Upper McMurray. Although this tripartite terminology has been applied throughout the surface mineable area of the Athabasca deposit, the continued use of this stratigraphic subdivision remains controversial (cf. Hein et al., 2000, 2001; Crerar, 2003; Hein and Langenberg, 2003; Ranger and Gingras, 2003). Within the Wabiskaw-McMurray succession it is common for channels from different stratigraphic levels to cut down and remove underlying broadscale sedimentary packages (Figures 3, 4). This makes regional correlation impossible without detailed palynological or other chronostratigraphic work. In many locations, Lower McMurray fluvial deposits have been reworked into overlying 'Middle'/Upper McMurray estuarine channel successions, or completely removed such that an initial transgressive surface of erosion is interpreted to be at the top of the Lower McMurray (surface E5, Figure 6).

On a regional scale, most workers can distinguish the top of the Lower fluvial McMurray from the overlying fluvial-estuarine McMurray because of changes in lithology and facies. By contrast, there is no uniform distinction in mineralogy, lithology, facies or palynology between the 'Middle' and Upper McMurray. As succinctly stated by Keith et al (1988, p. 312): "Subdivision into the middle and upper McMurray members is especially difficult where channel sands are absent (off-channel facies in both members) or where channel sands extend to the top of the McMurray Formation (upper member absent). Therefore...only the lower portion of the McMurray Formation is differentiated." This inherent complexity of multiple incision and infill events, coupled with the dramatic north to south reduction in accommodation space for the Wabiskaw-McMurray succession (Figure 5), indicates that what is called 'Middle' McMurray to the north may not, in fact, be correlatable with what is called 'Middle' McMurray to the south.

Although a type section is not designated for the Clearwater Formation, it is clear that where sandy, the lower Wabiskaw Member of the Clearwater Formation is glauconitic, salt-and-pepper, lithic sand that unconformably overlies the McMurray Formation (Badgley, 1952). In the area where the Wabiskaw Member was first named, Badgley also noted the occurrence of 'soft black' and 'greenish grey shales,' with interbedded green/grey sands, ironstone (siderite) concretions and cemented horizons, particularly towards the base of the member. In application of Badgley's lithologic distinction between the McMurray and Wabiskaw later workers, including Carrigy (1963) and Wightman et al. (1995), cite an occurrence of a 'steel-grey' or 'blue steel-grey' shale as typical of the lowest Wabiskaw D shales. Based on palynology, the Wabiskaw D shales show a true marine affinity, compared with McMurray mudstone that is wholly brackish, and a different age (Upper McMurray is Aptian, whereas Wabiskaw D is Early Albian, Dolby in Hein et al., 2001; Hein and Dolby, 2001). All of the Wabiskaw succession is more estuarine/marine than any of the preserved McMurray Formation. The absence of any preserved nonmarine/fluvial Wabiskaw interpreted as either being due to nondeposition associated with sediment bypass, or due to removal by the ensuing transgression within Wabiskaw time.

Thus the revised, albeit still informal stratigraphy used for this report is: Lower McMurray fluvial; Upper McMurray estuarine/coastal plain succession; Wabiskaw D fluvial estuarine incised valley fill; Wabiskaw D regional marine shale; and the overlying marine Wabiskaw C .

4 Study Approach

Stratigraphic picks were made (or confirmed) on 1189 wells in the present Lewis study area and surrounding buffer zone. Major log picks were done, including identification of the major transgressive (T) and erosional (E) surfaces (Appendix 1). Confirmation of picks by examination of fifty nonconfidential core available at the Core Research Centre, with identification, digital photography and mapping of facies associations within the different stratigraphic horizons.

A single line regional approach was used on the western edge of the surface mineable area to tie in stratigraphic picks from the Lewis-Fort McMurray subsurface south to the *RGS* main study area, and northwest to the *RGS* north study area. Seven, end-to-end, north-trending sections were constructed from within the northern border of the *RGS* main area northward to Township 99 (Figure 7). Facies interpretation followed the atlas for the McMurray oil sands as developed by Hein et al. (2000) with an identification of larger-scale associations in this study.

Representative 'type' logs for the different facies associations were then constructed digitally and saved as pdf files. All picks (from logs, many confirmed by core examination) were entered into an Excel spreadsheet, which were then imported into Acculog for construction of finalized cross-sections and into ArcGIS for mapping of bounding units and stratigraphic thicknesses. The cross-sections, raster logs with facies associations and picks table are included in the CD-ROM. A schematic legend for the representative corelogs and McMurray core is given in Appendix 2; the colour legend for the interpreted facies associations on representative wire-line logs is in Appendix 3.

5 Facies Associations: Description and Interpretation

5.1 McMurray Fluvial Facies Association

The dominant facies within the fluvial facies association consists of clean, pebbly to medium-grained sands, which are massive, or crossbedded (planar-tabular and trough, Hein et al., 2000) (Figure 8). Horizontal, planar lamination and small scale ripples are less common. Rare internal mudstones are interbedded within amalgamated clean sands, with common carbonaceous debris. Bioturbation levels are very low or nil. In thicker (i.e., > 5 m) mudstone successions, the muds are carbonaceous, monotonous, and medium to light grey. Sometimes associated with these thicker mudstones are low-grade, sub-bituminous coals and organic mudstones, locally exceeding 1 m in thickness. Bioturbation occurs as root traces/casts and very rare horizontal burrows (*Planolites*). Thin paleosols may be locally preserved.

On wire-line logs, the McMurray fluvial facies association consists of sand successions, which on gamma-ray logs shows a dominantly blocky profile, commonly 5 to 10 m thick (Figure 8). For amalgamated channel-sands the blocky-profile sands may exceed 20 m in thickness. Associated mudstones are commonly < 5 metres thick, are discontinuous from well-to-well, and cannot even be correlated between wells with close spacing. For those cases in which the finer caps to individual channels are preserved, the thin mudstones and coals along with the channel sands form a distinct fining-upward log profile.

The McMurray fluvial facies association comprises two depositional end-members within a fluvial system, namely the channel and interfluve successions. The clean, crossbedded sands are interpreted as channel deposits from a braided stream complex that initially occupied the main, north-northwest trending McMurray valley during a relative base-level lowstand. Salt-dissolution subsidence maintained moderate accommodation levels as sand input kept pace with subsidence, such that the sand-rich channels were able to shift laterally back and forth, as well as aggrade within the main valley, locally preserving fine-grained overbank and interfluve sediments, which are usually not preserved in braided-channel systems. Associated mudstone, organic mudstone and peat were deposited in interfluves as overbank and marsh deposits formed on floodplains bordering the primary channels as well as on isolated bedrock highs (Figure 9). Thick coalbeds (> 1 m), with associated carbonaceous mudstones and thin paleosols, are more commonly preserved on floodplain-interfluves between principal channel fairways.

The fluvial facies association comprises the Lower McMurray Formation in the Lewis–Fort McMurray area.

5.2 McMurray Fluvio-Estuarine Facies Association

The dominant facies within the fluvio-estuarine facies association consist of clean, fine to medium-grained sands, which are massive, or mainly trough crossbedded (less commonly, planar-tabular, Hein et al., 2000) (Figure 10). Interbeds of mudstone clast breccia and internal mudstones are less common. Crossbedded sands grade up into low-angle inclined heterolithic stratified (I.H.S.) units of mudstone and sand. Sands within the I.H.S. are horizontally laminated or rippled, commonly capped by light grey mudstone interlaminae. Within the interbedded mud-and-sand sequences, bioturbation occurs as root traces/casts and, oblique, vertical and horizontal burrows (predominantly *Planolites*, less commonly *Cylindrichnus*). Thicker, capping mudstone sequences also contain rare *Gyrolithes* traces, are carbonaceous with coaly material, rarely rooted.

On wire-line logs, the McMurray fluvio-estuarine facies association consists of sand successions with a blocky profile 5 to 10 m thick. Sands at the base of fining-upward log-profiles, pass gradationally into thin alternations of sand and mud, interpreted as I.H.S., and capped by thicker mudstones (> 2 m thick). Overall fining-upward sequences range from 10 to 15 m thick. As with the fluvial facies association where thicker mudstones are preserved they form a gradational cap to the distinct fining-upward log-profile. In cases where the mudstones have been removed due to successive channeling and amalgamation of stacked facies associations, log-profiles tend to be very clean and blocky (Figure 10).

The McMurray fluvio-estuarine facies association comprises two depositional end-members within a fluvial-dominated estuarine system: the channel/point bar, and abandonment fill deposits. The clean, crossbedded sands are interpreted as meandering estuarine channel deposits that occupied the principal, north-northwest trending McMurray valley during a rising relative base-level. Salt-dissolution subsidence continued to maintain moderate accommodation levels as sand input kept pace with subsidence, such that the sand-rich channels were able to shift laterally back and forth, as well as aggrade within the main valley. The I.H.S. beds are interpreted as estuarine point bars, which are not as thick and extensively developed as those in the overlying McMurray estuarine facies association (see next section). The thicker mudstone units are interpreted as abandonment channel plugs. Single fluvio-estuarine channel deposits tend to be thicker than the underlying fluvial channel sediments, and are similar in scale to the overlying fully developed estuarine channel deposits.

The fluvio-estuarine facies association comprises the lowest part of what others have identified as the ‘Middle’ McMurray Formation in the Lewis–Fort McMurray area (Crerar, 2003).

5.3 McMurray Estuarine Facies Association

The primary features of the McMurray estuarine facies association are due to deposition within deep estuarine meandering channel and point bar complexes (Figures 11 and 12), with less preservation potential of the thinner tidal channel/tidal flat deposits (Figure 15). Through time the channel systems were replaced by localized brackish bay deposits formed near the end of McMurray time (Figures 19, 20). Preservation of these uppermost McMurray deposits was a function of the accommodation and the amount of incision along the unconformity separating the McMurray Formation from the overlying Wabiskaw Member of the Clearwater Formation (discussed in later sections). As mentioned previously, no fully marine conditions are present in the preserved sequences until Wabiskaw time, although regional mapping of prominent surfaces show that there my be more erosion than previously thought at the end of McMurray time (E10 surface, Appendix 1), with removal of any marginal marine or marine deposits. Consequently, all of the preserved McMurray succession is interpreted as largely fluvial or estuarine, with the barrier and bay fill components forming the seaward end of the brackish estuarine system.

Channel facies within the estuarine facies association consist of clean, fine to medium-grained sands, which are predominantly crossbedded, including trough, ripple, herringbone, planar tabular, tidal couplets and tidal bundles (cf. Hein et al., 2000) (Figure 11a). The sands are usually very fine to medium-grained, less commonly medium-grained to pebbly. Sand facies are variably interbedded with and grade up into low-angle inclined heterolithic stratified (I.H.S.) units of mudstone and sand (Figure 11b), in turn, capped by thick mudstone, organic mudstone and rare coal (Figure 11b). Mudstone clast breccias are common, both interbedded within the cleaner sands and within the I.H.S. units. Bioturbation occurs as oblique, vertical and horizontal burrows (mostly *Planolites*, *Cylindrichnus* and *Gyrolithes*), less commonly as root traces.

On wire-line logs, the McMurray estuarine facies association consists of sand successions with a blocky profile, which form the base of thick, fining-upward log-profiles, ordinarily 25 to 30 metres thick where completely preserved. Incomplete sequences range from a few metres to about 15 metres thick. As with the lower fluvio-estuarine facies association where thicker mudstones are preserved they form a gradational cap to the distinct fining-upward log-profile. In cases where the mudstones have been removed due to successive channeling and amalgamation of stacked facies associations, log-profiles tend to be very clean and blocky. The McMurray estuarine facies association comprises several distinct depositional end-members within the estuarine system, including the following types of deposits: a) estuarine channel; b) estuarine point bar; c) tidal channel; d) tidal flat; e) brackish bay; and f) transgressive back barrier. These are described and interpreted separately, as follows.

a) Estuarine Channel Deposits

The McMurray estuarine channel deposits are very fine to medium-grained sand, although they may be very coarse sand or pebbly if the channels incised into and reworked older, coarser-grained fluvio-estuarine or fluvial channel sediment. Dominant crossbed types are medium to large scale trough crossbedding, with associated ripples on the toesets of the larger crossbeds (cf. Hein et al., 2000). Planar-tabular crossbeds are subordinant. Mudstone rarely occurs as laterally discontinuous (< 10 metres lateral extent) units, that may occupy paleotopographic lows. Mudstone clast breccia is common, consisting of clast or sand-matrix supported units, with both rounded and angular (or tabular) clasts, many of which are internally bioturbated. Breccia beds are commonly less than 3 metres thick, rarely attaining 5 metres in thickness. Burrowing within the estuarine channel deposits occurs chiefly within the clasts of the mudstone breccia or as reworked burrow fills, which themselves form intraclasts (mostly resedimented

Cylindrichnus burrows). The common presence of these out-of-place burrow-fills within trough crossbeds provides good evidence for repeated cut-and-fill events within the estuarine channel deposits. On gamma-ray logs, amalgamated estuarine channel deposits display a clean, blocky pattern, often separated by thin mudstone responses. Upon core examination it is apparent that many of these mudstone responses on the wire-line logs are due to the presence of mudstone intraclasts and not discrete mudstone interbeds within the estuarine channel-fills.

The transition from estuarine channel deposits to overlying estuarine point bars is marked by the following features:

- A fining in the channel sequence to be dominated by fine-grained sand (rarely medium sand size);
- An increase in the percentage of thin (≤0.05 m) mudstone interbeds;
- An increase in the degree of bioturbation, generally limited to *Planolites* and *Cylindrichnus* traces; and
- An increase in the percentage of current ripples which become dominant; with subordinate amounts of small-scale planar-tabular crossbedding., which is generally limited to the lower portion of the bar successions.

b) Estuarine Point Bar Deposits

The McMurray estuarine point bar deposits are ordinarily very fine to fine grained sand, although facies within the point bar successions can be either sand or mud-dominated. The principal feature of the estuarine point bar deposits is the common to abundant I.H.S. beds, with mudstone interbeds generally ranging from 0.03 to 0.1 metres thick (Figure 11b). The frequency and thickness of individual mudstone beds increases upsection within I.H.S. successions. Dominant crossbed types within the sands are current ripples, with common flasers and rare small-scale planar tabular crossbeds (cf. Hein et al., 2000). Rare mudstone clast breccia has both rounded and angular clasts, many of which are internally bioturbated. Breccia beds are commonly less than 0.5 metres thick, often with internal slump and load structures. Burrowing intensity is moderate to abundant, dominated by *Cylindrichnus* and *Planolites* within the mudstone interbeds of the I.H.S. successions. On gamma-ray logs, estuarine point-bar deposits display a fining-up pattern, often with serrated edges on the log profiles due to thin mudstone responses.

c) Abandonment Fill Deposits

The McMurray estuarine abandonment fill deposits usually start out as very fine to fine grained muddy sand that becomes increasingly mud-dominated upsection. Thickness of the mudstone abandonment fill varies from < 1 metre to greater than 20 metres. In some cases, the abandonment fill grades up gradually from the estuarine point bar deposits; in other cases these deposits abruptly overlie estuarine-channel sediments (Figure 11b). The frequency and thickness of individual mudstone beds increases upsection within abandonment-fill successions. Sand interbeds are crossbedded, including current ripples, with common flasers and tidal couplets. Rare mudstone clast breccia also occurs at the base of abandonment fills, associated with synsedimentary slumps and slide material.

In some cases the overall succession is fining then coarsening-upward, along with a decrease then increase in the frequency and thickness of sand interbeds, and a decrease then increase in the bioturbation intensity. These trends are thought to reflect different phases of overbank deposition within abandoned channels. Processes of overbank abandonment-fill deposition were essentially the same in areas of either the main estuarine channel or smaller tidal channel deposition. Sandy bedload deposition was through levee break through along channel margins, that debouched into interchannel overbank areas, in some cases, forming lobate, coarsening-upward crevasse splay complexes. Muddy overbank deposition was from flood flows that overtopped levees carrying mainly fine sand, silt and mud by suspension into the overbank areas, deposits of which during increasing flows are coarsening-upwards, during waning flows are fining-upward. The early abandonment phase is characterized by interbedded muddy sand and bioturbated sandy to silty mudstone. Dominant trace fossils include *Cylindrichnus*, *Planolites* and *Gyrolithes*. Late-stage abandonment phase shows light grey, massive mudstone or bedded silty mudstone, with abundant carbonaceous debris, rooting, the occassional development of paleosols, and in some cases interbedded coals. Bioturbation is rare, mostly as root traces, root casts, *Planolites* or *Gyrolithes*. On gamma-ray logs, the transition from the upper estuarine point-bar to abandonment fill deposits display a fining-up pattern, often with serrated edges on the log profiles due to thin mud bed responses and an overall decrease in grain size.

In extreme cases where there is desertion of deep channels for prolonged periods of time an anoxic abandonment phase develops. The anoxic abandonment mudstone plugs are characterized by very dark grey to black mudstone, which is massive or thick bedded, in some cases with a waxy, smooth texture. Bioturbation is absent, and on logs there is often a sharp shift on the neutron-log to the left (which can be mistaken for regional mudstones in the A and B sequences of the *RGS*, (Alberta Energy and Utilities Board, 2003) (Figure 12).

d) Tidal Channel Deposits

The McMurray tidal-channel deposits are typically thin (< 5 m thick) units of very fine to fine grained sand (Figure 13). Bases are erosional or loaded and scoured. In general, the tidal channel deposits have smaller scale bed features than the underlying main estuarine channel deposits. Dominant crossbed types are small to medium scale trough crossbedding, with a variety of ripples (current, herringbone, flaser, combined-flow) (cf. Hein et al., 2000). Planar tabular crossbeds are less common. Mudstone is common as part of flaser and tidal couplets, with in some cases a significant (> 20%) mudstone component to the tidal channel-fills. Mudstone clast breccias do occur, but are less common than in the main estuarine-channel and point-bar sequences. Tidal-channel fills may or may not contain well-developed I.H.S., and when it does occur it tends to have a greater proportion of tidal couplets and bundles, compared with the estuarine point-bar deposits. On logs the tidal-channel deposits are thin (generally < 5 m), are not as clean as the blocky, estuarine-channel sands, and show a variety of grading patterns, including fining-, coarsening-up, and blocky or ungraded (Figure 13). The tidal-channel and larger estuarine channel sediments are intimately associated both laterally and vertically with the tidal-flat sediments (Figure 15).

e) Tidal Flat Deposits

The McMurray tidal-flat deposits are normally thin units (< 5 m thick) (Figure 14). Bases are gradational, capping the larger-scale main estuarine channel deposits, or interbedded with the smaller scale tidal channels. Varying proportions of sand, mud and mixed sand and mud occur, but the mixed-flat sediments are the most common. The sand, mixed and mud-flat sediments may be adjacent to one another, or may be the only facies in a given area. For all tidal-flat deposits, the sand component is usually very fine grained and silt is common. Units consist of very thin to thinly interlaminated rippled sand and wavy, silty mudstone. Flaser bedding is very common, as are tidal couplets (cf. Hein et al., 2000).

Characteristics of the sand, mixed, and mud-flat deposits are described separately as follows.

Sand-Flats: have > 75% sand with 25% silty mudstone laminae. The chief sedimentary structures are current ripples, planar horizontal stratification and rare wave ripples. Bioturbation intensity is low to moderate, with the principal traces including *Skolithos*, *Arenicolites*, escape traces and root traces/casts. Carbonaceous debris is common.

Mixed-Flats: have between 40% and 75% thinly interlaminated sand with silty mudstone. Current ripples are common, with wavy, lenticular, and flaser bedding. Tidal couplets occur in horizontally stratified sets, and dispersed carbonaceous debris in trace amounts to moderate concentrations. Bioturbation is intense, with common traces of *Arenicolites*, *Planolites*, *Paleophycus*, *Teichichnus*, *Cylindrichnus*, and *Skolithos*. Mixed-flat deposits may be capped by organic mudstone or coal.

Mud-Flats: have > 75% mudstone with 25% very fine sand laminae, occurring as delicate, wispy interlamination and as burrow fills. The principal sedimentary structures are current ripples, wavy, lenticular and flaser bedding. Bioturbation levels are moderate to intense, with the dominant traces including *Arenicolites*, *Planolites*, *Paleophycus*, *Teichichnus*, *Cylindrichnus*, and *Skolithos*. Carbonaceous debris is common. Mud-flat deposits may be capped by organic mudstone or coal.

On logs the individual tidal flat deposits are thin (generally < 5 m), are not as clean as the blocky, tidal-channel sands, and show a variety of grading patterns, including fining, coarsening-up and blocky or ungraded (Figure 14). Coals may cap the mud and mixed-flat successions. Tidal-flat sediments interfinger with and overlie the tidal-channel and main estuarine-channel successions (Figure 15).

f) Brackish Bay Deposits

The McMurray lowermost brackish-bay deposits are moderately thick (5–10 m) units that can amalgamate forming stacked units up to 10 metres thick (Figure 16). Bases are either gradational or sharp, capping the underlying estuarine/tidal channel or tidal-flat deposits. As a rule the brackish bay deposits form well-defined coarsening-upward packages that consist of light grey silty mudstone, grading upwards into silt/very fine sand and fine sand. Mudstone at the base of the coarsening-up successions is typically 1 to 2 metres thick, nonfissile, and may have more abundant, mainly horizontal traces, (*Planolites*). As the units coarsen into the silts and sands more sedimentary structures are developed, including very thin to thinly interlaminated current and wave-rippled very fine sand, usually thinly interlaminated with wavy, dark grey mudstone. Synaeresis cracks and dispersed organic debris are common. Bioturbation intensity is generally low within the sands, predominantly small *Planolites*. The bay fills can consist of a single cleaning-upward sequence, each about 5 to 10 metres thick. Very clean, coarser sand caps to the sequences are rarely developed. Sands show low to moderate bioturbation, and where primary sedimentary structures are preserved, consist of wave ripples. Carbonaceous debris and reworked burrows may occur in the sand caps to the coarsening-up sequences.

On the gamma-ray log the brackish bay deposits have distinct and gradual cleaning-upward/coarsening-upward profile At the top of the McMurray Formation, the cleaning-upward/coarsening-upward profiles become better defined.

g) Transgressive Back Barrier Deposits

The McMurray transgressive back-barrier deposits are thin (~5 m) (Figures 17 and 18) units that are only locally preserved, due largely with the significant erosion that occurred at the top of the McMurray prior to emplacement of the Wabiskaw succession. Normally the transgressive back-barrier deposits form well-defined coarsening-upward sequences. Lithologies consist of carbonaceous mudstone that is overlain by burrowed silty/sandy mudstone, capped by laminated very fine sand and fine sand. Three main types of back-barrier transgressive units are: marsh, lagoonal, and washover sediments.

<u>Marsh sediments</u>: are usually less than 1 metre thick, comprising medium dark to very dark grey, mottled mudstone. The base of the marsh sediments is usually abrupt, generally overlying estuarine/tidal channel or tidal flat deposits. Within the marsh sediments the percentage of carbonaceous material is variable. Mottling is pedogenic, largely due to rooting.

<u>Lagoonal sediments</u>: are normally less than 1.5 metres thick, consisting of light to medium grey, silty/sandy mudstone, with the sand component increasing towards the north. The lagoonal sediments commonly gradationally overlie the marsh sediments. Bioturbation within the lagoonal package is intense, with high concentrations of small *Teichichnus* (a key trace fossil identifier of the lagoonal units) and small *Planolites* silt/sand-filled burrows.

<u>Washover sediments</u>: consist of laminated, very thin bedded, very fine and fine sand that rarely exceeds 4 metres in thickness. The base of the washover sediment package is abrupt and erosional, ordinarily overlying back-barrier lagoonal/ brackish-bay or estuarine channel deposits. Internally the washover sand is horizontally or planar laminated, with low-angle truncations. Intraclasts consists of reworked burrow fills and carbonaceous debris is common. Bioturbation intensity is low to nil, and consists mostly of vertical *Skolithos* or escape burrows.

The channel/point bar and abandonment fill deposits of the estuarine facies association comprise the bulk of what Crerar (2003) identified as 'Middle' McMurray Formation in the Lewis–Fort McMurray area. Associated, tidal channel/tidal flat, brackish bay and transgressive back-barrier deposits belong to Crerar's (2003) Upper McMurray in the area.

5.4 Wabiskaw D Incised Valley Fill (DVF) Deposits

The Wabiskaw D incised valley fill (DVF) deposits range in thickness from < 1 metre to 10 metres. The base of the DVF is always erosional or loaded and scoured., although a basal lag is usually absent. The sand component of the DVF is typically an immature litharenite, except in those cases where the DVF consists of reworked quartzose McMurray sediment. Shale interlaminations are typically dark, steel-grey blue, with a marked fissility, and sharp discordant edges. Trace fossils within the DVF include principally *Bergaugeria*, *Asterosoma*, and *Thalassinoides*.

The DVF is sand or shale-dominated, or a mixed sand-and-shale succession (Figure 21), as follows.

<u>Sand-dominated DVF</u>: has very little shale content (generally < 5%). The principal crossbed types are small to medium scale trough crossbedding, with a variety of ripples (current, flaser). Planar tabular crossbedding is less common. In cases where the sandy DVF reworked underlying quartz-dominated McMurray channel-sediment, it is very difficult in either core or logs to distinguish the two. The shale interbeds occur as thin, wavy interlaminations within the sand crossbeds. Shale-clast breccias are rare.

Shale-dominated DVF: has very little sand content (generally < 5%), and is rare, typically occurring at the base of the DVF succession. The shaly base of the DVF cleans-upward/coarsens-upward into the more characteristic sand-dominated or mixed sand-and-shale DVF.

Mixed Sand-and-Shale DVF: is the most common occurrence in the DVF, and typically has 20% to 40% shale component. The shale component is distinct and rarely changes character throughout the study area, and lithologically appears similar to the regional Wabiskaw D shale that caps the DVF (where present). In cases where the shale component of the mixed DVF is about 50%, it is very difficult in core or on logs to distinguish the mixed DVF from the regional Wabiskaw D shale.

On logs where the DVF is shaly at the base, and this shale greater than 5 metres in thickness, the DVF typically displays a cleaning-up/coarsening-up profile on the gamma-ray log. Sand-dominated DVF has a blocky appearance on logs. The shale component of the DVF typically registers a sharp deflection to the left on the neutron logs, a response that is not exhibited on the density logs. On gamma-ray logs, the Wabiskaw DVF usually reads 30 to 50 API units (> 70 API units where shalier) (Table 1). Neutron porosity logs are generally > 30%, with density porosity readings variable, averaging about 27%, and shallow resistivity < 10 ohm-m (Figure 21) (cf. Alberta Energy and Utilities Board, 2003).

5.5 Wabiskaw D Shale (D Sh) Deposits

The Wabiskaw D shale (D Sh) is commonly < 1 metre thick (0, where completely eroded, to a maximum of about 2 m) (Figure 22). The base of the D shale is erosional where it sits unconformably above the McMurray succession (overlying the E10 surface, Appendix 1). In other cases the Wabiskaw D shale caps the DVF succession, and in these cases it may have a gradational base with the underlying units. As with the underlying DVF, the Wabiskaw D shale is variable. It is not pure shale, but rather shale to sandy shale. The sand component of the D shale is typically an immature litharenite, by definition comprising < 50% of the unit (In units with 50% or more of sand, these are identified as DVF). The shale is identical to the shaly component of the DVF, typically dark, steel grey-blue with a pronounced fissility. The sands within the Wabiskaw D shale occur as thin interbeds or interlaminae, or may be admixed into the shale through bioturbation. Trace fossils within the D shale include principally small *Planolites*. Glauconite is present within the D shale, where burrowing brings it down along with sand from the overlying Wabiskaw C succession. Where the burrows originate from the overlying Wabiskaw C unit, the traces within the D shale include *Diplocriterion*, *Asterosoma*, *Thalassinoides*, and *Skolithos*. Locally, extensive vertical burrowing occurs at the Wabiskaw D/C contact, and in these cases, this is interpreted as representing *Glossifungites* surfaces.

Distinctive welllog characteristics of the Wabiskaw D shale include a low resistivity and a sharp deflection to the left on the neutron log (with no deflection on the density log). The responses have been noted even in cases where the Wabiskaw D shale is very thin (i.e., 7 cm). On gamma-ray logs, the Wabiskaw D shale usually reads 75 to 90 API (Table 1). Neutron porosity logs are generally > 30% to > 45% with density porosity readings variable, averaging about 27%. The shallow resistivity is < 10 ohm-m, commonly around 2 ohm-m (Figure 22) (cf. Alberta Energy and Utilities Board, 2003).

5.6 Wabiskaw C Deposits

The base of the Wabiskaw C is erosional where it sits unconformably above the Wabiskaw D or McMurray successions (overlying the T10.5 or E10 surfaces, Appendix 1). The Wabiskaw C succession varies in thickness from < 0.1 metres (confirmed in core) to 5 metres thick. The sand component of the Wabiskaw C is typically a glauconitic, immature litharenite, by definition comprising > 50% of the unit

(In units with 50% or more of mudstone, these are identified as Wabiskaw C mudstone). Sands within the Wabiskaw C succession occur as distinct beds, as thin interbeds or interlaminae, burrow-fills, or caps of well-defined cleaning-up/coarsening-up sequences. The Wabiskaw C mudstone is a sandy mudstone, which ranges from 0.3 to 0.5 metres in thickness, and can occur at the base of the Wabiskaw C or be interbedded within the sand sequences. The Wabiskaw C mudstone is distinctive from the underlying Wabiskaw D shale, consisting of a light to medium green-grey, nonfissile, unbioturbated to highly bioturbated, glauconitic and lithic sandy mud. The degree of bioturbation within the Wabiskaw C sand and upper or medial mudstone is moderate to heavily burrowed, with much of the primary stratification rarely preserved. In cases where the mudstone occurs at the base of the succession it may be unburrowed or highly bioturbated. Trace fossils within the Wabiskaw C sands and mudstone include *Diplocriterion*, *Asterosoma*, *Thalassinoides*, and *Skolithos*. Robust vertical burrow assemblages often penetrate deep into the underlying Wabiskaw D shale, Wabiskaw D valley fill or McMurray succession. This extensive vertical burrowing at the lower Wabiskaw C contact is interpreted as a *Glossifungites* (firm-ground) surface, and locally may be cemented (usually siderite).

Within the study area the Wabiskaw C succession is a glauconitic, litharenite, variable both in terms of thickness and proportions of sand and mud. In some cases one sand is present; in other cases, two sands with a sandy mudstone between them; and, at other locations, a sandy mud grades up into sand, or two muddy sands occur (Figure 23). The lower Wabiskaw C sand is commonly absent, and if the internal mudstone is absent, it is very difficult to differentiate between the upper and lower Wabiskaw sand. Where preserved, the top of the upper sand has a siderite-cemented, *Glossifungites* facies developed.

Distinctive well-log characteristics of the Wabiskaw C sand include a gamma-ray of 60 to 90 API units, and density and neutron porosities up to 30% (Table 1). Spontaneous potential log responses are variable, both weak and strong. The shallow resistivity values are usually less than 15 ohm-m. Because the Wabiskaw C sands are immature litharenites (i.e., density is higher than the McMurray quartz sand), there tends to be separation of the neutron and density porosity curves. Gamma-ray curves are typically funnel shaped, with the upper values generally between 20 and 30 API units, density porosity about 33%, and neutron porosity near 36%. In clean sands that are saturated with bitumen, the resistivity values are near 100 ohm-m. Typical log signatures for the Wabiskaw C mudstones are a gamma-ray between 75 to 100 API units, density porosity near 20%, and resistivity values between 5 and 10 ohm-m (Figure 23) (cf. Alberta Energy and Utilities Board, 2003).

6 Stratigraphic Units: Descriptions, Mapping and Interpretations

The datum used in the study area is the T21 marker that occurs at the top of the Wabiskaw Member of the Clearwater Formation (Appendix 1). Structure maps for the T21 and the sub-Cretaceous unconformity are given in Figures 24 and 25, with a total isopach map (T21 – Paleozoic) in Figure 26. Isopach and structure maps of the top of the various stratigraphic units discussed below are in Figures 26 to 37, with digital versions of all maps included on the CD.

Different mappable stratigraphic units within the Wabiskaw-McMurray succession are present in the Lewis area, including McMurray Channel, McMurray A2L sequence, McMurray A1L sequence, Wabiskaw D Valley fill, Wabiskaw D Shale, and Wabiskaw C (Figure 4). In constrast with the subsurface areas to the south examined during the RGS (Alberta Energy and Utilities Board, 2003), in the Lewis study area, the McMurray B1, McMurray B2, McMurray A Channel, and Wabiskaw B Valley fill do not occur, and are interpreted to be absent largely due to nondeposition. Because of the absence of the McMurray B sequences, only McMurray Channel is recognized (i.e., McMurray C Channel is not identified). The main characteristics of the different units summarized in Table 1.

Table 1. Characteristics of stratigraphic units in the Wabiskaw-McMurray Succession

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.		

McMurray Channel includes the various channel/point-bar, overbank, and associated abandonment fill/tidal channel and tidal flat successions of different facies associations, including: the Lower McMurray fluvial facies association, the initial ‘Middle’/Upper McMurray fluvio-estuarine facies association, and the bulk of the ‘Middle’/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 channeled successions and generally identifiethe main bitumen reservoirs within the study area.

The isopach map of the McMurray Channel deposits (Figure 27) shows that the channel sediments generally align with the main structural lows along the sub-Cretaceous unconformity. An irregular pattern occurs in the Lewis-Fort McMurray area, largely reflective of irregularities on the unconformity surface (Figure 24). Channel deposits along the main valleys commonly reach 40 m, locally in excess of 80 m. The thickest deposits occur in Townships 87 and 88, Ranges 7 to 9W4; Townships 91 and 92, Range 7W4; Township 91, Range 5W4; and, Township 93, Range 2W4. In the tributary valleys, located in the southeastern and western portions of the study area, the channel deposits are commonly 50 m thick, ranging up to about 80 m in thickness.

The McMurray A2L isopach map (Figure 28) shows that these sediments generally align with the underlying channel deposits along the channel trends in Township 91, Ranges 7 to 9W4; Township 93, Ranges 7 to 8W4; Township 91, Range 5W4; and, Township 93, Range 4W4. Elsewhere, thickened deposits of the McMurray A2L do not correlate with the underlying McMurray Channel. The McMurray A2L sequence commonly reaches 2 metres, locally greater than 7 metres. The thickest deposits occur in Township 91, Ranges 7 to 9W4 and in Township 88, Range 6W4.

McMurray A1L includes a mixture of tidal channel/tidal flat, and transgressive back-barrier successions that overlie the McMurray A2L sequence. The McMurray A1L sequence is the second mappable coarsening-upwards/cleaning-upwards unit in the area. The isopach map of the McMurray A1L deposits (Figure 29) shows that these sediments do not generally align with the trends in the underlying McMurray A2L succession. The McMurray A1L sequence commonly reaches 3 metres, locally greater than 6 metres. The thickest deposits occur in Township 90, Ranges 7 to 9W4; Township 87 and 88, Ranges 7 and 8W4; and, Township 93, Ranges 5 to 7W4.

Wabiskaw D Valley fill and Wabiskaw D Shale are combined for mapping purposes. This is due to two reasons. The first is that the distribution of points for the Wabiskaw D Valley fill is quite restricted in the study area, mainly occurring as two lines, one from Township 93, Range 7W4 to Township 93, Range 9W4, and the other in Township 87, Range 6W4. This makes mapping difficult with linear distributions and so few control points. The second reason concerns identification of the presence and thickness of the Wabiskaw D shale. Recent core reviews of the Wabiskaw D shale and Wabiskaw D valley fill show that it is impossible to reliably identify Wabiskaw D shale from associated units on the basis of logs alone (Connelly et al., 2005; Nexen, 2005). Furthermore, Bagdan et al. (2005) indicate that diagenetic effects further complicate the distinction of the Wabiskaw D shale. Hence, due to the absence of extensive core review (and reliance on logs in some areas) as well as the sparcity of data, in the present discussion Wabiskaw D units are combined.

The isopach map of the Wabiskaw D deposits shows that the Wabiskaw D crosscut trends in the underlying McMurray Channel, A1L and A2L deposits (Figure 30). The Wabiskaw D sequence averages < 1 metre thick, as regional background shale deposits, with the greater thickness (> 7 m) occurring in areas of incised main or tributary valley fill deposition. In Township 87 Range 6W4 a Wabiskaw D valley fill cuts obliquely to a north trend in the underlying McMurray Channel. In Township 91, Ranges 7 to 9W4, thickened deposits in the McMurray Channel succession align generally north, whereas the thicker Wabiskaw D valley fill is oriented east.

Wabiskaw C sequence includes the various muddy, shaly and sandy, immature litharenites that unconformably overlie the McMurray and Wabiskaw D successions. 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). As previously discussed (Section 5.5), the Wabiskaw C is variable in the study area, consisting of differing proportions of mudstone/shale and sand, arranged in single or multiple coarsening/cleaning-upwards successions. The base of the Wabiskaw C is marked by a transgressive surface of erosion, 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 a regional marine shale.

The isopach map of the Wabiskaw C deposits (Figure 31) shows that the units cross cut trends in the underlying Wabiskaw D or McMurray deposits. The Wabiskaw C commonly reaches 3 metres in the west and southwest part of the study area, thinning to generally < 1.5 metres to the north-northeast. As shown by the isopach of the Wabiskaw T21 Marker–Wabiskaw C thickness variation is consistent with more widely spaced contours in the Lewis-Fort McMurray subsurface study area and a more dramatic change northeast of Range 7W4. The thickest deposits occur in Townships 87 to 90, Ranges 7 to 9W4 and in Township 88, Range 6W4 (Figure 31).

The thickness of the interval from the top of the Wabiskaw C to T21 Marker shows a similar pattern to the Wabiskaw C isopach, being thinner to the north, and thicker to the southwest (Figure 32). This is interpreted as being a result of younger Wabiskaw deposits draping over the Wabiskaw C.

7 Wabiskaw-McMurray Depositional Model: Subsurface Lewis-Fort McMurray

The Lower McMurray deposits represent a fluvial low-stand systems tract of braided bar and channel complexes, largely infilling lows on the sub-Cretaceous unconformity (Figures 6, 9 and 38). With transgression, some of the Lower McMurray fluvial succession was eroded and reworked into fluvial-estuarine channel and point bar complexes of the initial ‘Middle’/Upper McMurray succession (Figures 6 and 12). Through time, with continued overall transgression, paleotopographic features became blanketed, and by late Upper McMurray time more nearshore coastal plain conditions prevailed (Figures 6, 15, 19 and 20). By time of deposition of the top of the Wabiskaw Member conditions were fully marine. 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 valley that meandered across the study area (Figure 39a), branching and rejoining with smaller tributaries, and eventually debouching into areas of increased accommodation along the southern margins of the Bitumont Basin. Interfluve sedimentation was prominent along the eastern and northeastern parts of the study area. The central and western part of the study area has a very complex isopach pattern, interpreted to be largely a result of amalgamation of smaller tributary channels (Figure 39a). Mapping of individual channel sequences is very difficult if not impossible.

At Time 2, during middle to late transgressive phases, the McMurray A2L sequences were deposited; however, much of this stratigraphy is not present due to either nondeposition or nonpreservation, associated with younger erosional events (Figure 39b). The isopach pattern of the McMurray A2L 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 northern 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. Two other thickened areas of A1L deposition in the central and southwest study areas may be reworked tributary-fill within drowned valleys in areas of less accommodation (Figures 39b compared with Figure 39a).

At Time 3, during late transgressive phases, the McMurray A1L sequences were deposited. Although more stratigraphy is preserved compared with the underlying A2L sequence, large portions in the southeast part of the study area are not represented in the stratigraphy due either to nondeposition or erosion (Figure 39c). Here, the isopach pattern of the McMurray A1L with zero-edges is somewhat complex and patchy, but more trends are apparent compared with the underlying McMurray A2L succession. A band of thickened A1L units occur at the northern limit of the study area. Compared with the underlying A2L sequences, the A1L pattern is more lobate and elongated to the south. These likely represent a transgressive, coarsening-up washover deposits deposited behind and inferred barrier complex located north/northwest of the study area. Linear thickened A1L units in the central study area may be remnant transgressive barrier deposits. A final thickened pattern at the southern area is lobate, extending towards the north/northwest (Figure 39c).

At the end of McMurray time a significant relative drop in seal level occurred, removing much of the more marine McMurray succession and creating several large incised valleys. At Time 4, during maximum transgressive phases, the Wabiskaw D sequences were deposited, with the Wabiskaw D Shale representing the maximum flooding surface. Although the data are sparce for mapping (see previous discussion), several possible trends may occur within the Wabsiskaw D. The isopach map of the Wabiskaw D succession shows mainly blanket deposition across the study area, with two channel fairways, one, a remnant tributary fill, in the central part and the second main channel in the southeastern corner of the study area (Figure 39d). The southern Wabiskaw D valley fill also shows a secondary tributary remnant west of the edge of the main valley fill.

At Time 5, during waning transgressive and beginning regressive phases, the Wabiskaw C sand was deposited. The isopach map of the Wabiskaw C succession shows mainly irregular, blanket deposition across the study area, with thickened areas, representing marine bar complexes (Figure 39e).

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 Lewis-Fort McMurray subsurface area.
- Mappable stratigraphic units in the study area include: McMurray Channel, McMurray A2L sequence, McMurray A1L sequence, Wabiskaw D Valley fill and D Shale, and the Wabiskaw C.
- Contrasting with the *RGS*, in the Lewis-Fort McMurray 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).

9 Recommendations for Future Work

Although the present 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:

- Addition of the ongoing subsurface work in Townships 94 and north, including examination of core to confirm the Wabiskaw D shale presence and thickness.
- Reconciliation of different stratigraphic picks used by the *RGS*, the GRG, the AGS, and other schemes in the public domain.
- Bringing together results of the present subsurface study with outcrop work in the Fort McMurray area.
- Incorporation of previous regional palynological work with the stratigraphic framework to develop a regional chronostratigraphic/sequence stratigraphic framework for the Athabasca Wabiskaw-McMurray deposit.

10 Conclusions

In the Lewis–Fort McMurray area, using the typical 'industry' terminology,

- The Fluvial Facies Association comprises the Lower McMurray Formation;
- The Fluvio-Estuarine Facies Association includes the basal 'Middle'/Upper McMurray;
- The channel/point bar and abandonment fill deposits of the Estuarine Facies Association consist of the overlying 'Middle'/Upper McMurray;
- The tidal channel/tidal flat, brackish bay and transgressive back-barrier deposits of the Estuarine Facies Association belong to the Upper McMurray.

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 in the Lewis-Fort McMurray area, largely reflective of irregularities on this unconformity surface.
- McMurray A2L deposits coincidently align with the underlying channel deposits along the channel trends in Township 91, Ranges 7 to 9W4; Township 93, Ranges 7 to 8W4; Township 91, Range 5W4; and, Township 93, Range 4W4. Elsewhere, thickened deposits of the McMurray A2L do not correlate with the underlying McMurray Channel deposits.
- The top of the Wabiskaw C to T21 Marker shows a similar pattern to the Wabiskaw C isopach, being thinner to the west-southwest, and thicker to the northeast, largely a result of younger Wabiskaw deposits draping over the pre-existing Wabiskaw C.

Surfaces separating the different stratigraphic units are erosional, including major erosional unconformities with significant relief, and transgressive surfaces of erosion, with less relief. Generally relief on these surfaces decreases upsection, with the topmost Wabiskaw Marker T21 surface showing the least relief, interpreted as representing minor erosion associated with transgression of the Clearwater Sea into the area.

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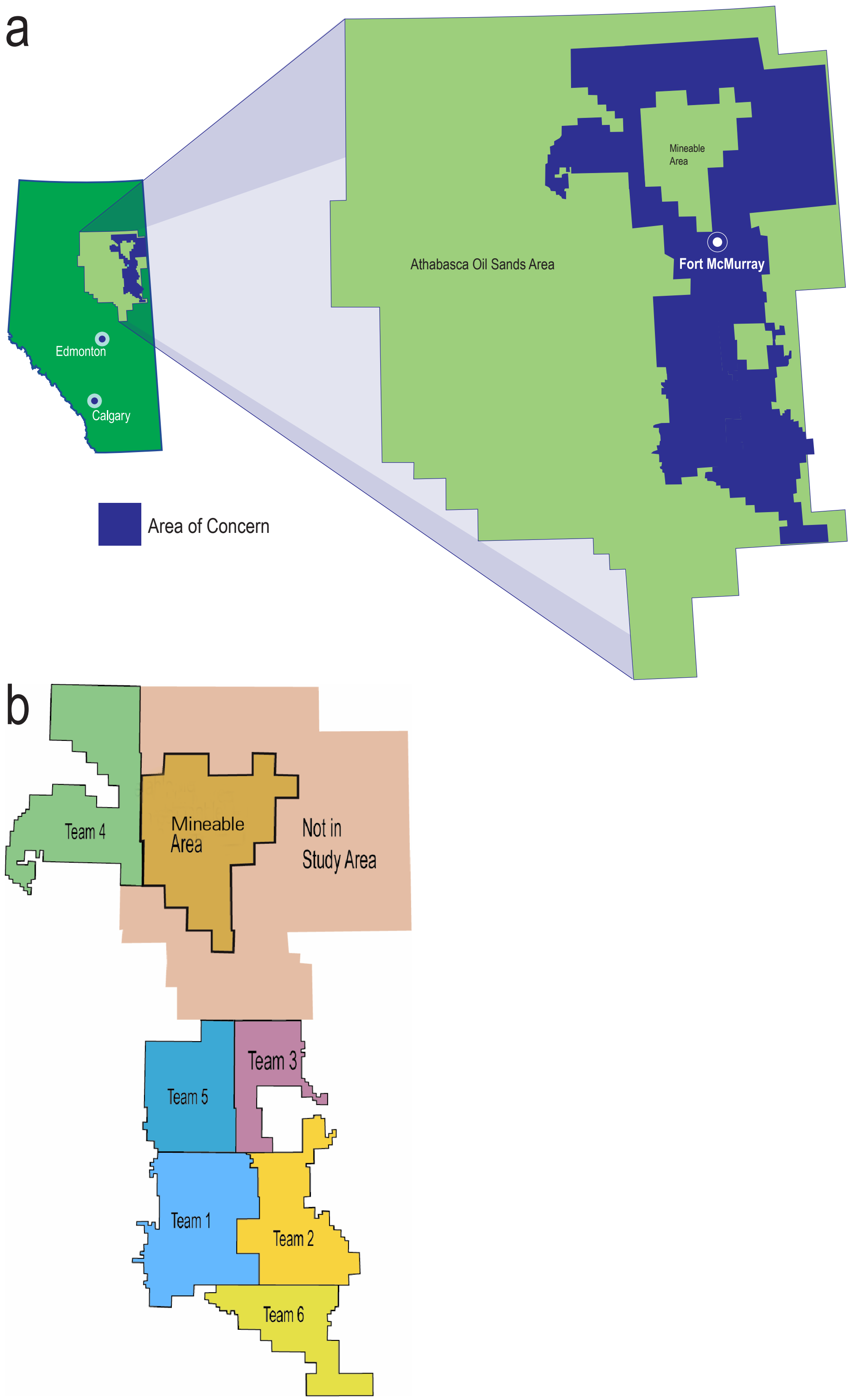


Figure 1a. Wabiskaw-McMurray Athabasca oil sands area, showing the area of concern by the Board concerning gas and bitumen co-production issues, and the surface mineable area (SMA, from Alberta Energy and Utilities Board, 2003). Figure 1b. Study area covered in the Regional Geological Study (RGS) by the Alberta Energy and Utilities Board (2003).

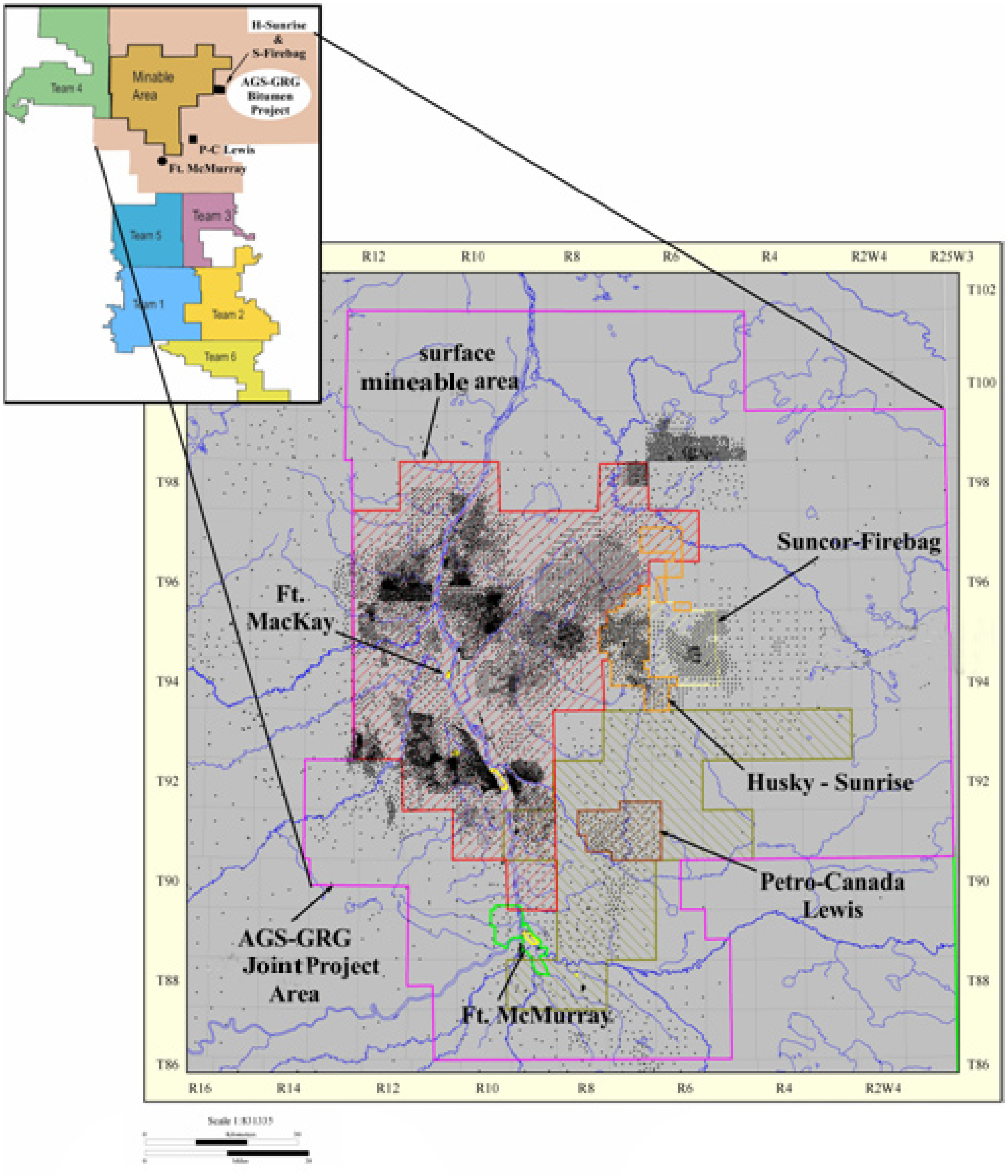


Figure 2. Study area showing location of main leases, including Sunrise, Lewis and Firebag, the surface mineable area, and the AGS-GRG joint project area.

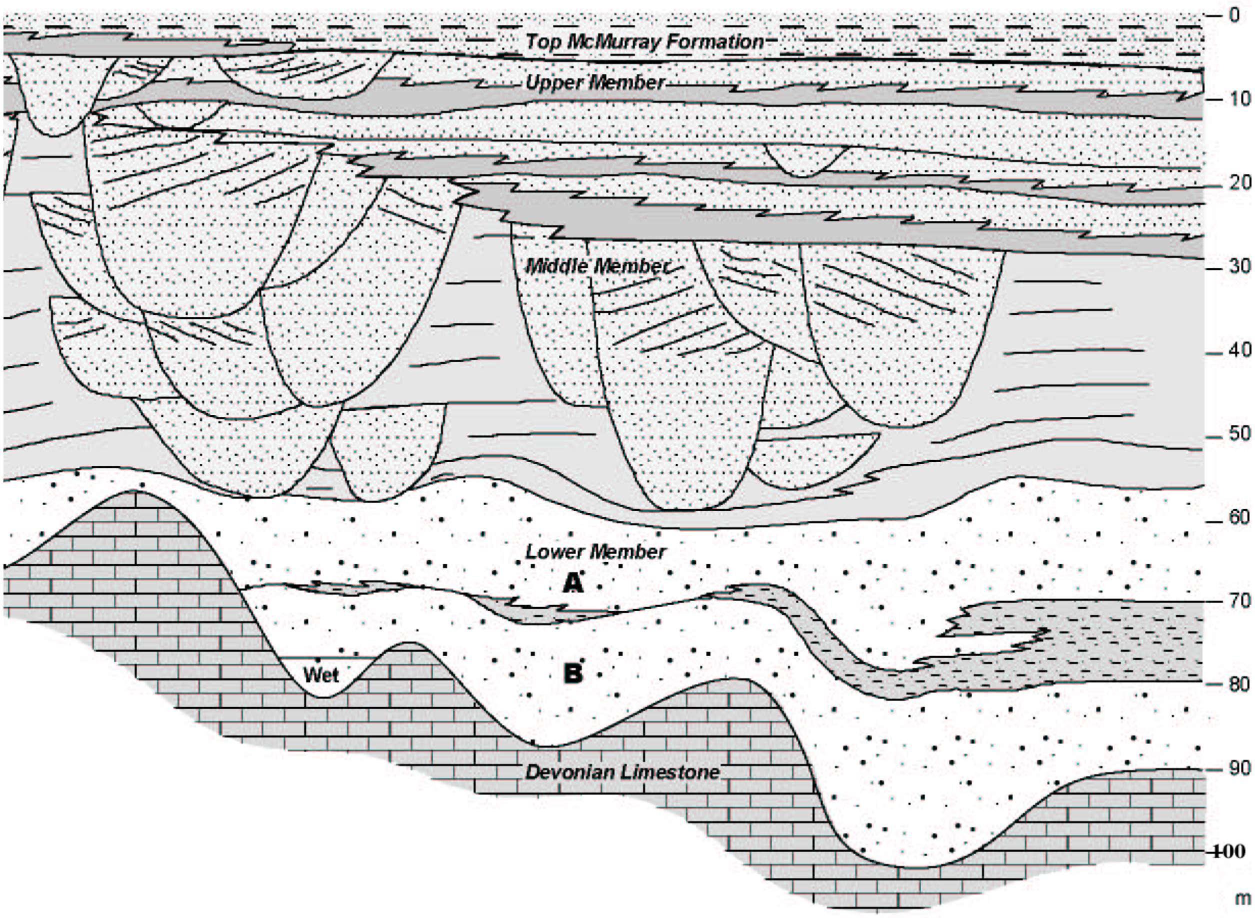


Figure 3. Schematic sketch illustrative of the informal Lower, 'Middle', and Upper McMurray Formation as seen in outcrops in the Fort McMurray area (Figure 2, Hein and Langenberg,2003)

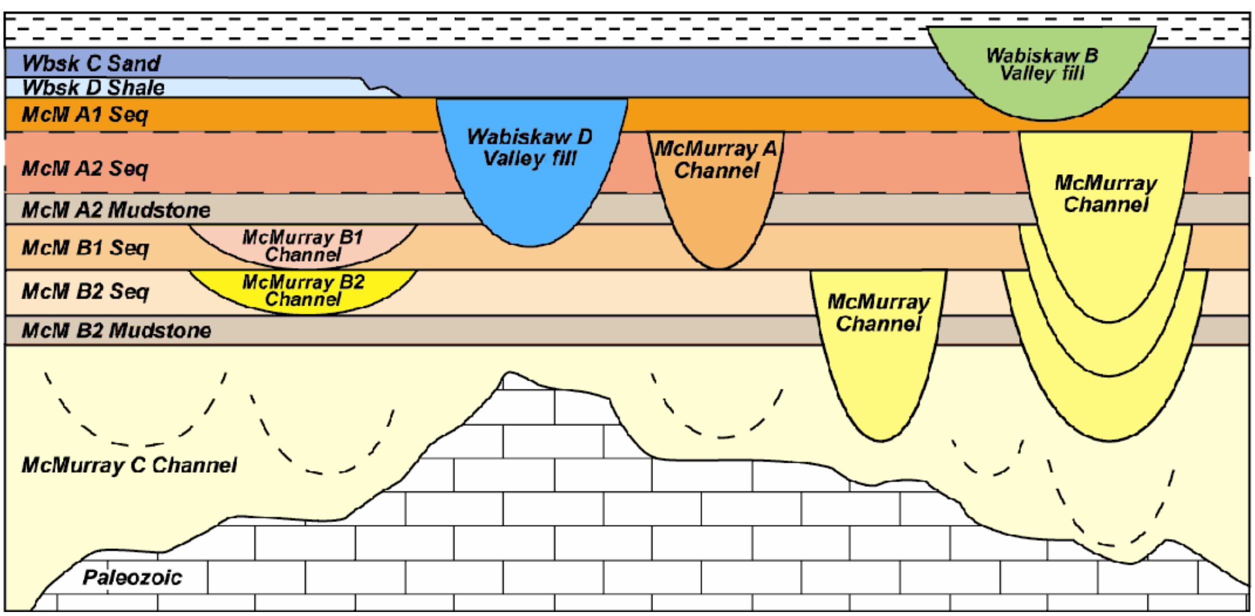


Figure 4. Schematic stratigraphic model for the Athabasca Wabiskaw-McMurray deposit as developed in the Regional Geological Study (RGS) (from Alberta Energy and Utilities Board, 2003a).

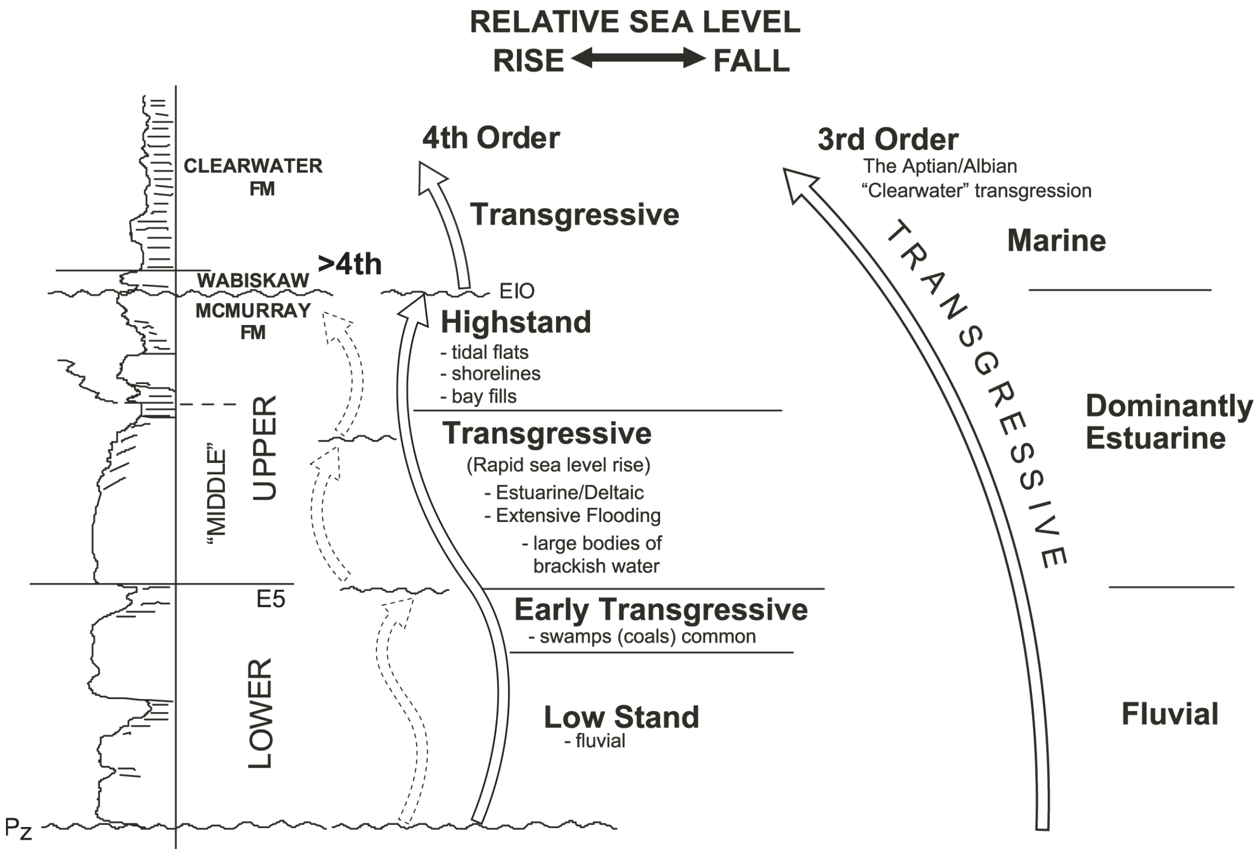


Figure 5. Sequence stratigraphy for the Wabiskaw-McMurray Athabasca deposit, (Figure 2 from Flach and Hein, 2001; published in Hein and Langenberg, 2003).

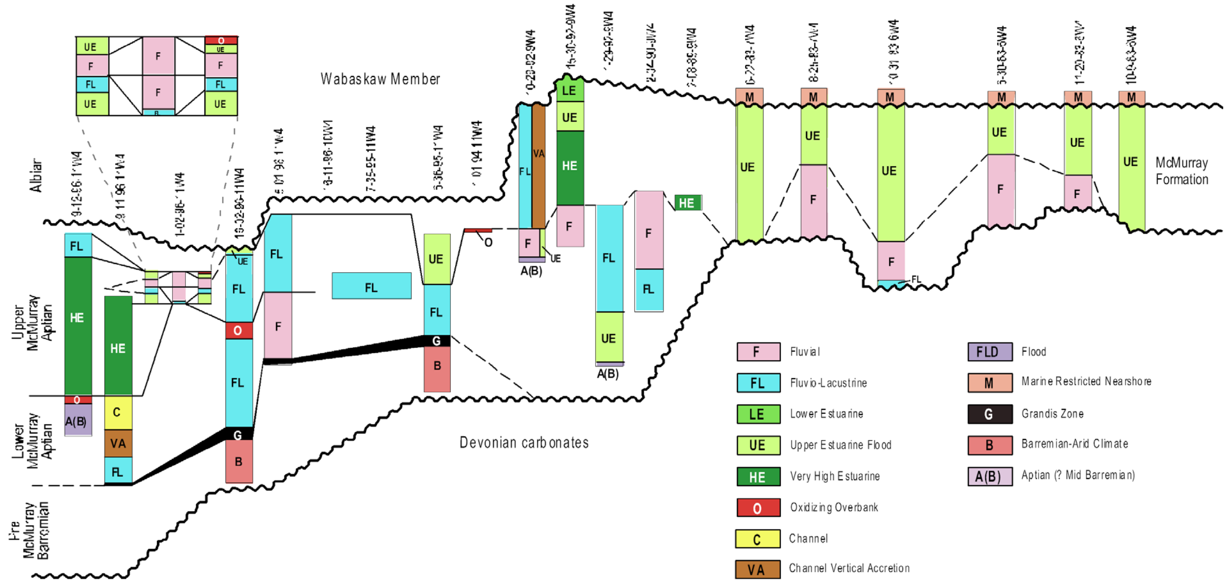


Figure 6. Schematic regional north (left) to south (right) section of the McMurray Formation showing rapid thinning of the formation, concomitant with a rapid reduction in accommodation space, (Figure 10, Hein, Langenberg, et. al. 2001).

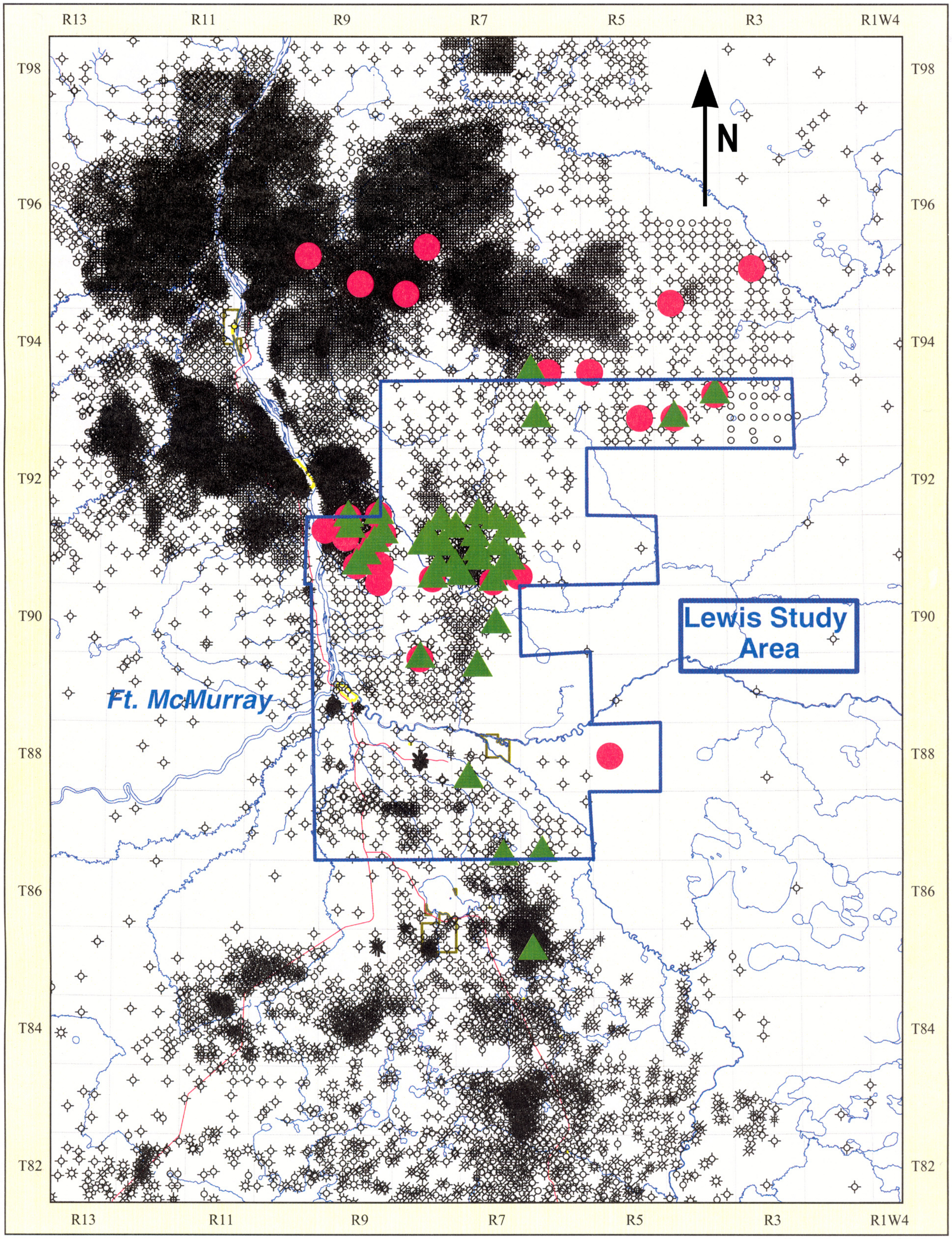


Figure 7. Map of the Lewis Ft. McMurray study area, with well control (small symbols) and surface drainage. Large red dots show the locations of wells for which there are interpreted logs with facies associations, and green triangles indicate core for which there are digital photos included on the accompaning CD.

McMurray – Fluvial Facies Association

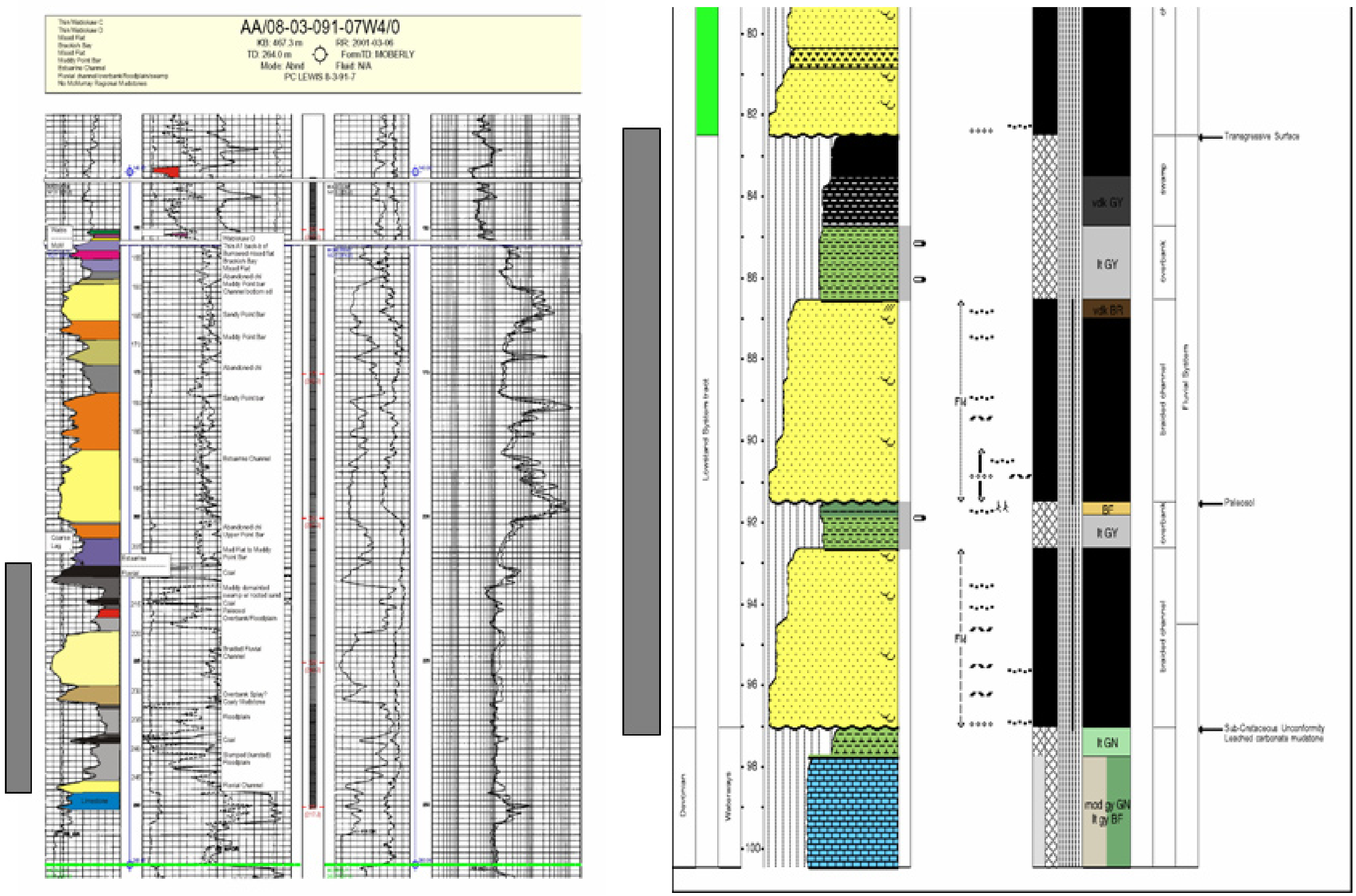


Figure 8. Representative wire-line logs and schematic corelog for the McMurray fluvial facies association, AA/08-03-091-07W4 well, Lewis-Fort McMurray area.

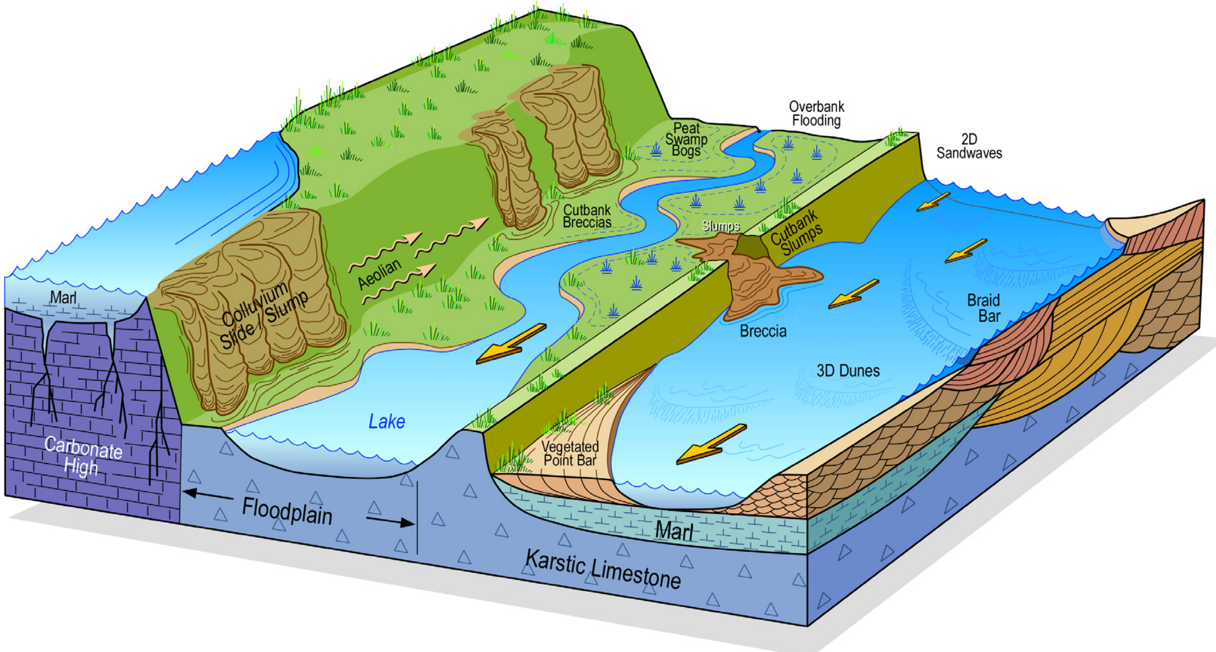


Figure 9. Schematic facies model for the McMurray fluvial facies association (Lower McMurray Formation), Athabasca Oil Sands deposit, northeast Alberta , (Figure 82, Hein, Cotterill and Berhane, 2000).

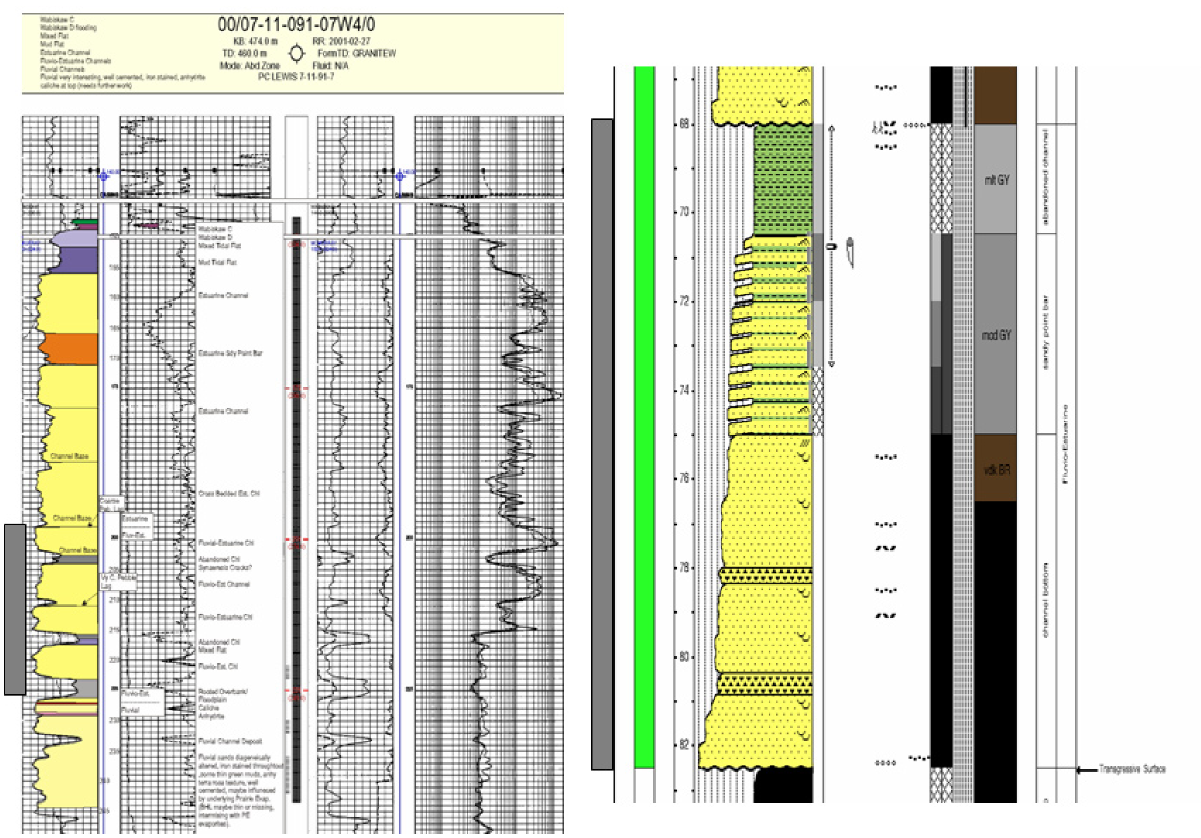


Figure 10. Representative wire-line logs and schematic corelog for the McMurray fluvio-estuarine facies association, 00/07-11-091-07W4 well, Lewis-Fort McMurray area.

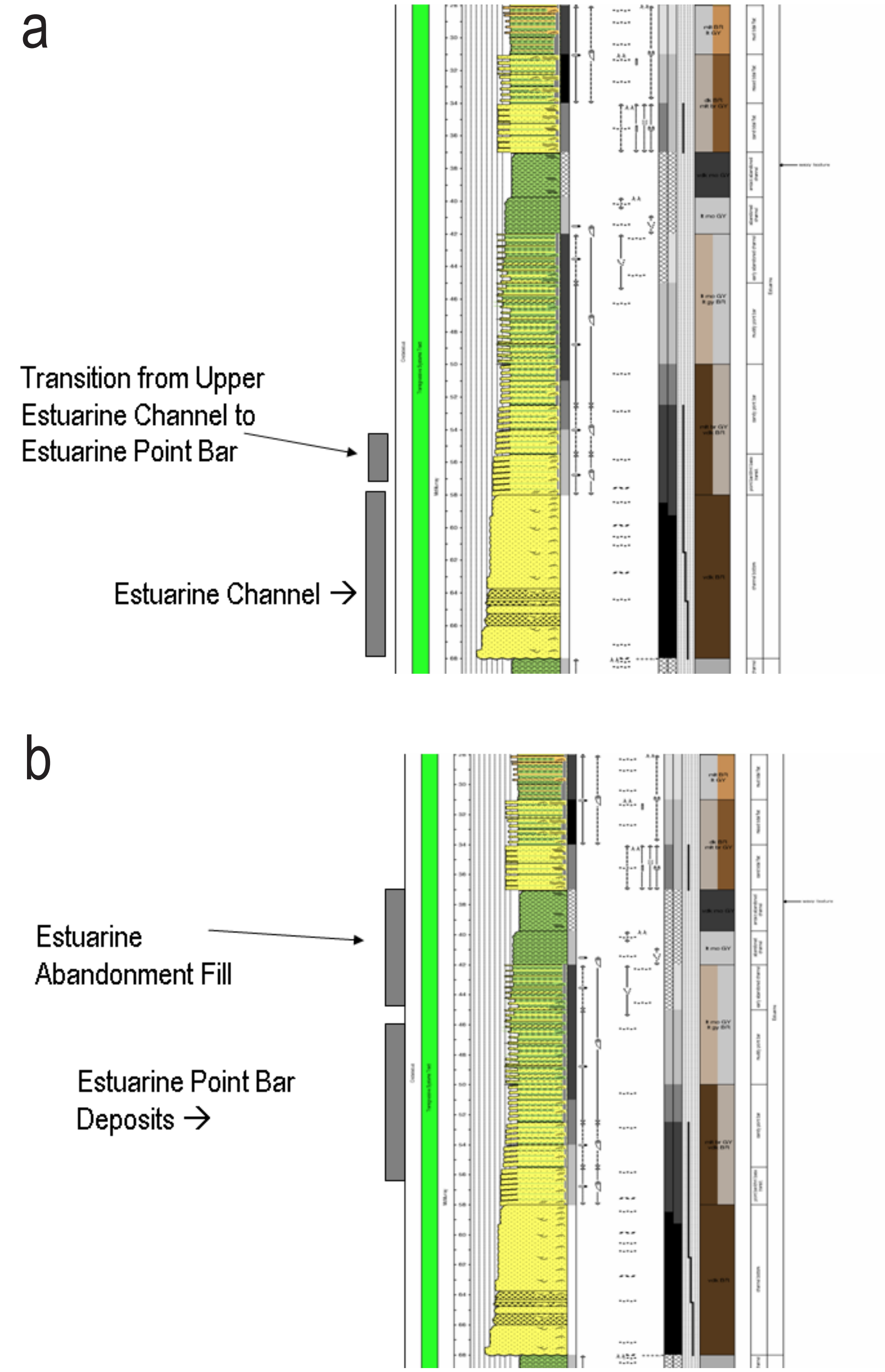


Figure 11. Schematic corelogs for the McMurray estuarine facies association: a) channel transition, b) point bar and abandonment fills, Lewis-Fort McMurray area.

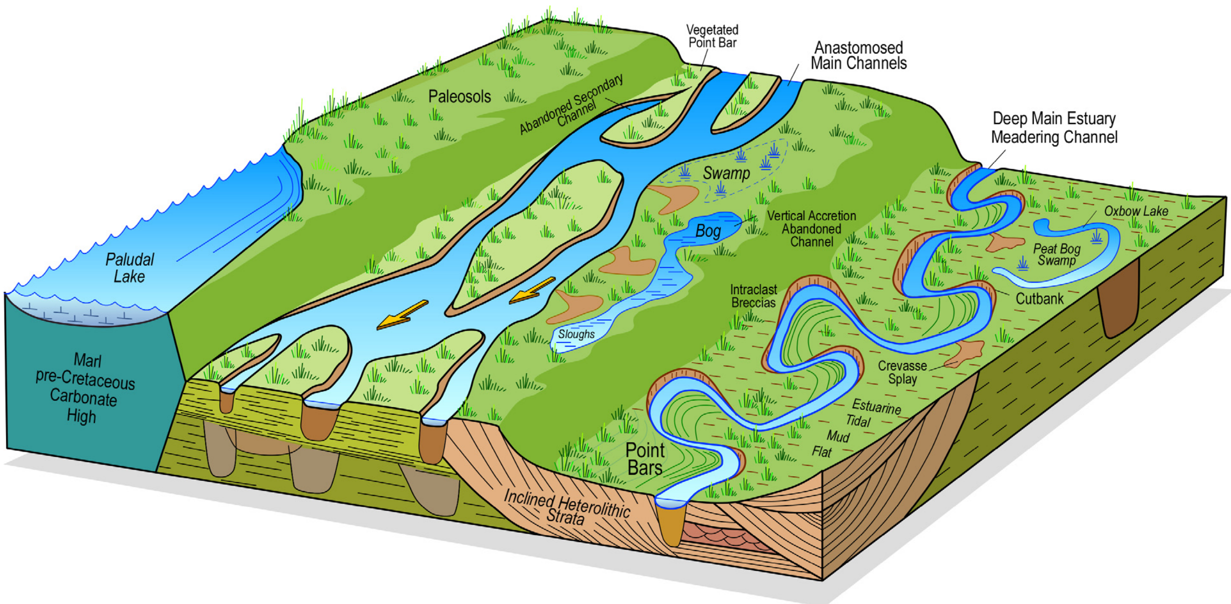


Figure 12. Schematic facies model for the McMurray estuarine facies association, channel, point bar, abandonment fill and overbank deposits ('Middle'/Upper McMurray Formation), Athabasca Oil Sands deposit, northeast Alberta, (Figure 83, Hein, Cotterill and Berhane, 2000).

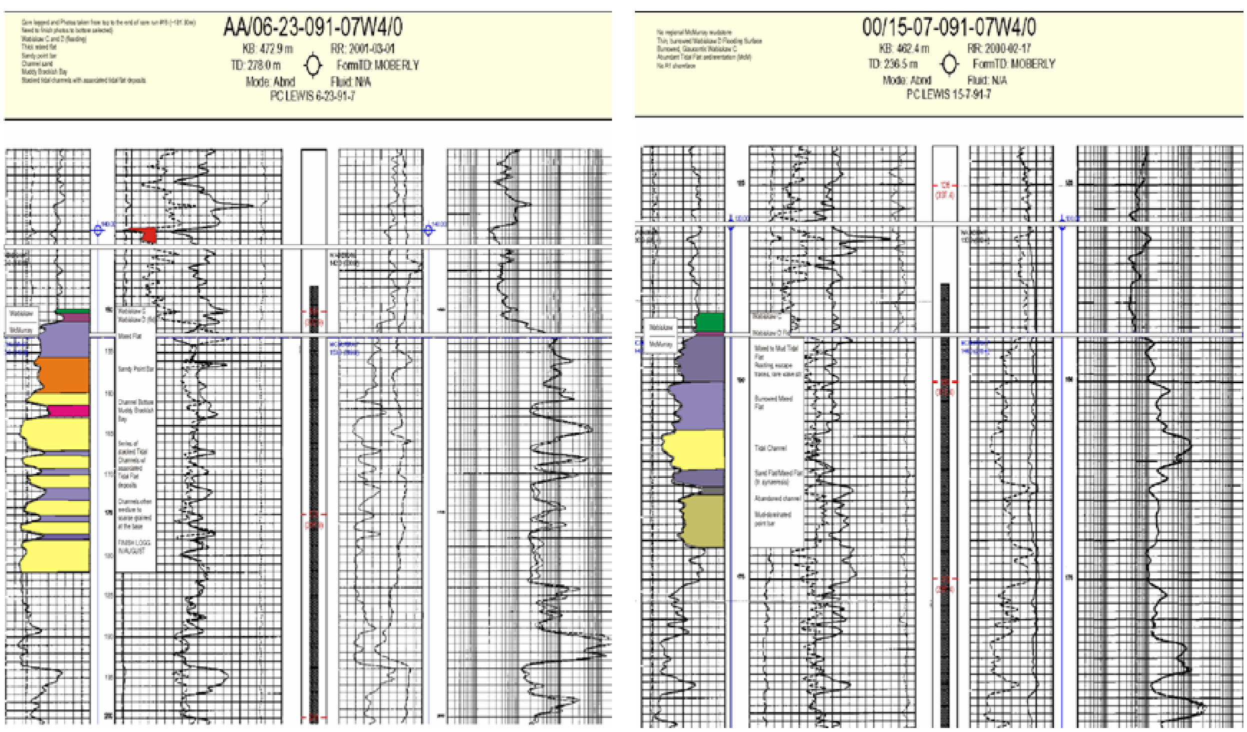


Figure 13. Representative wire-line logs for the McMurray estuarine facies association, tidal channel deposits, AA/06-23-091-07W4 well, 00/15-07-091-07W4 well, Lewis-Fort McMurray area.

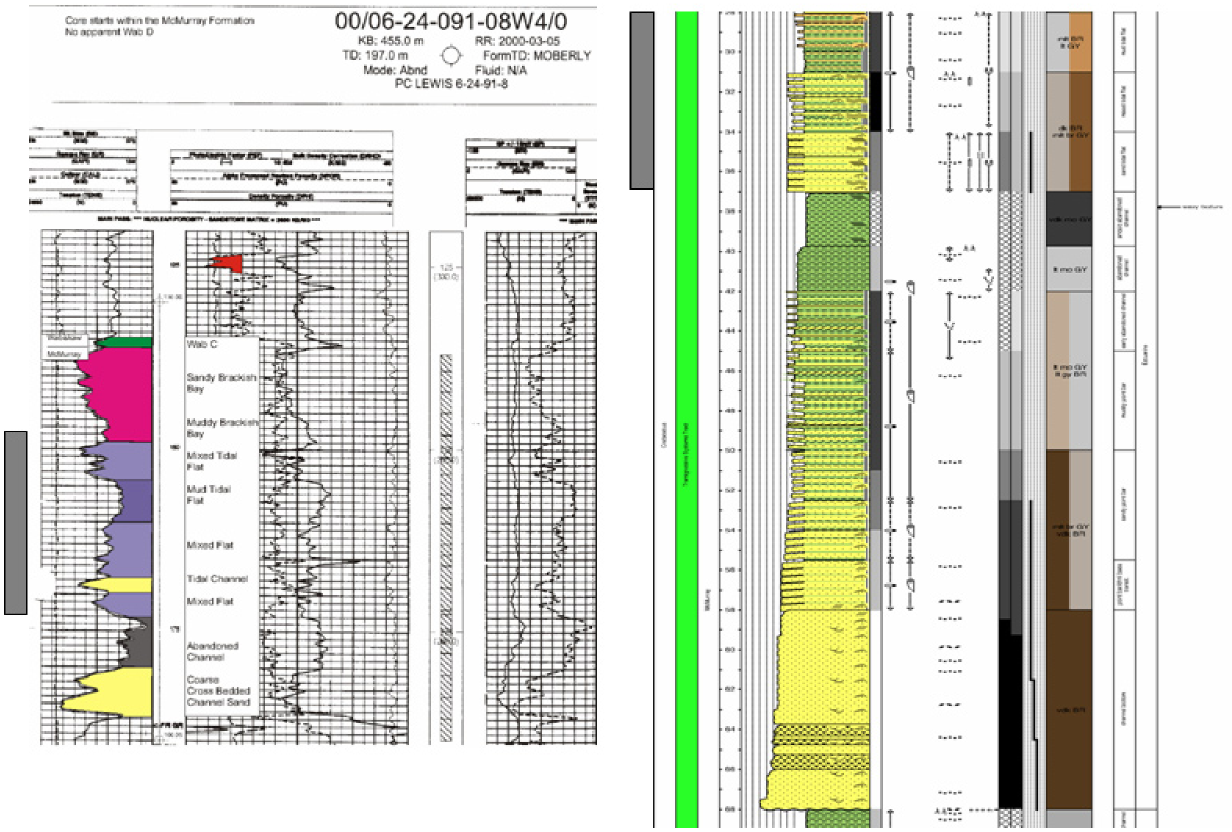


Figure 14. Representative wire-line logs and schematic corelog for the McMurray estuarine facies association, tidal flat deposits, 00/06-24-091-08W4 well, Lewis-Fort McMurray area.

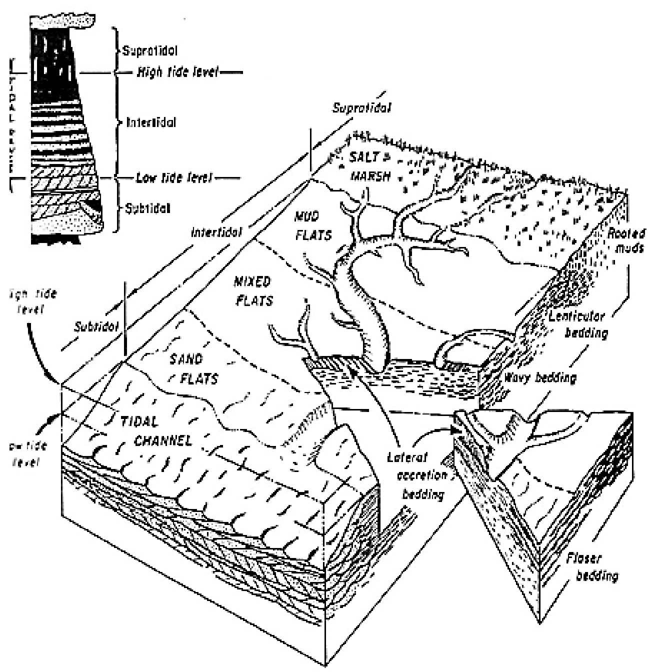


Figure 15. Facies model for the McMurray estuarine facies association, tidal channel and tidal flat deposits (Figure 12, Dalrymple, 1992).

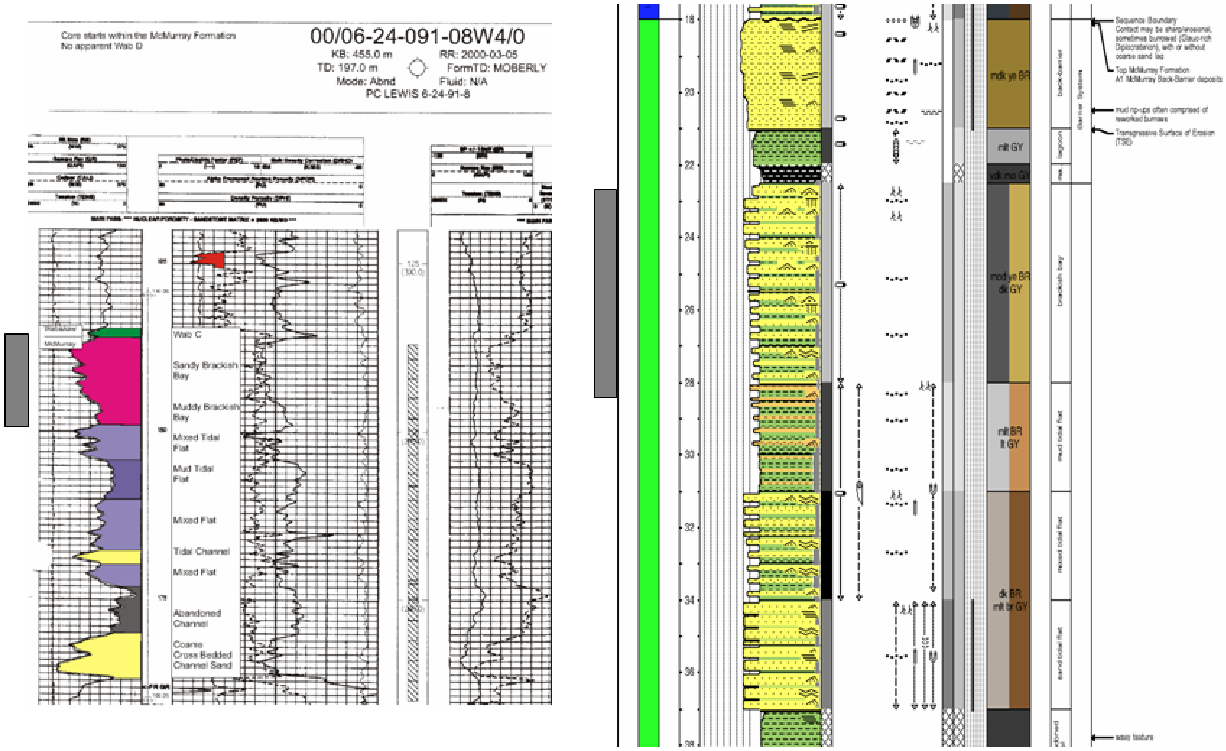


Figure 16. Representative wire-line logs and schematic corelog for the McMurray estuarine facies association, brackish bay deposits, 00/06-24-091-08W4 well, Lewis-Fort McMurray area.

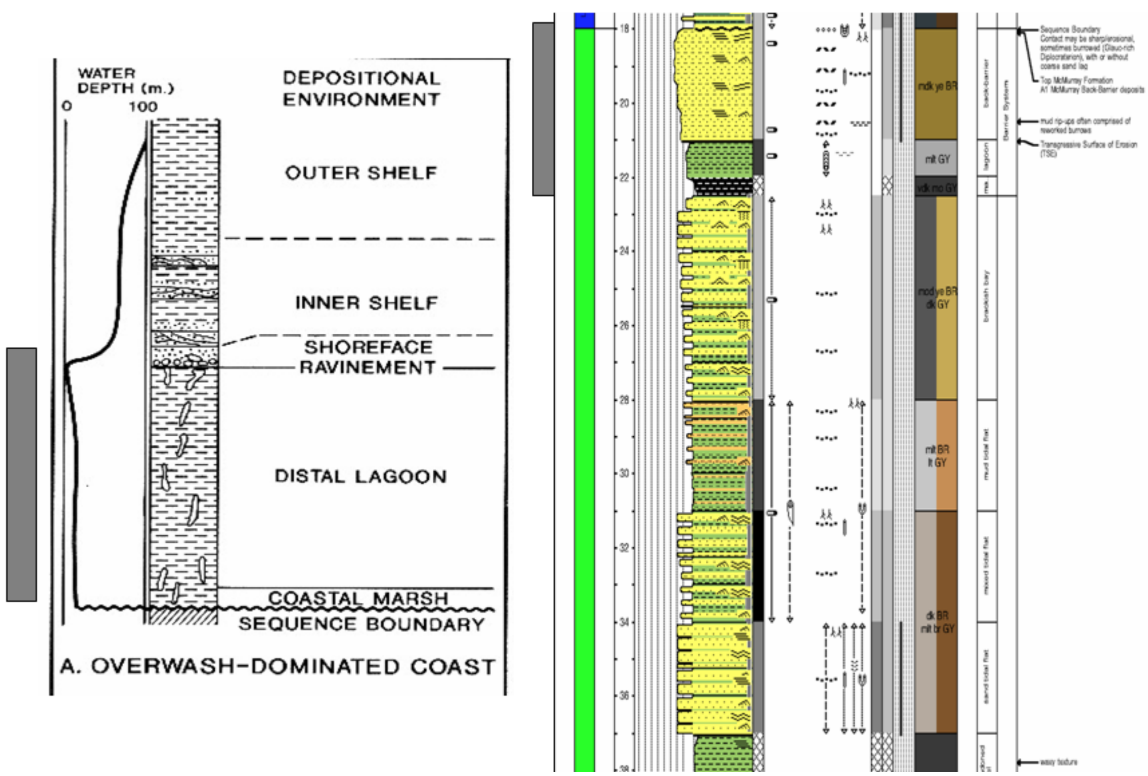


Figure 17. Schematic corelogs (left) for the McMurray Estuarine Facies Association, back barrier deposits, Lewis-Fort McMurray area, compared with a schematic log right, (Figure 15, Reinson 1984, 1992).

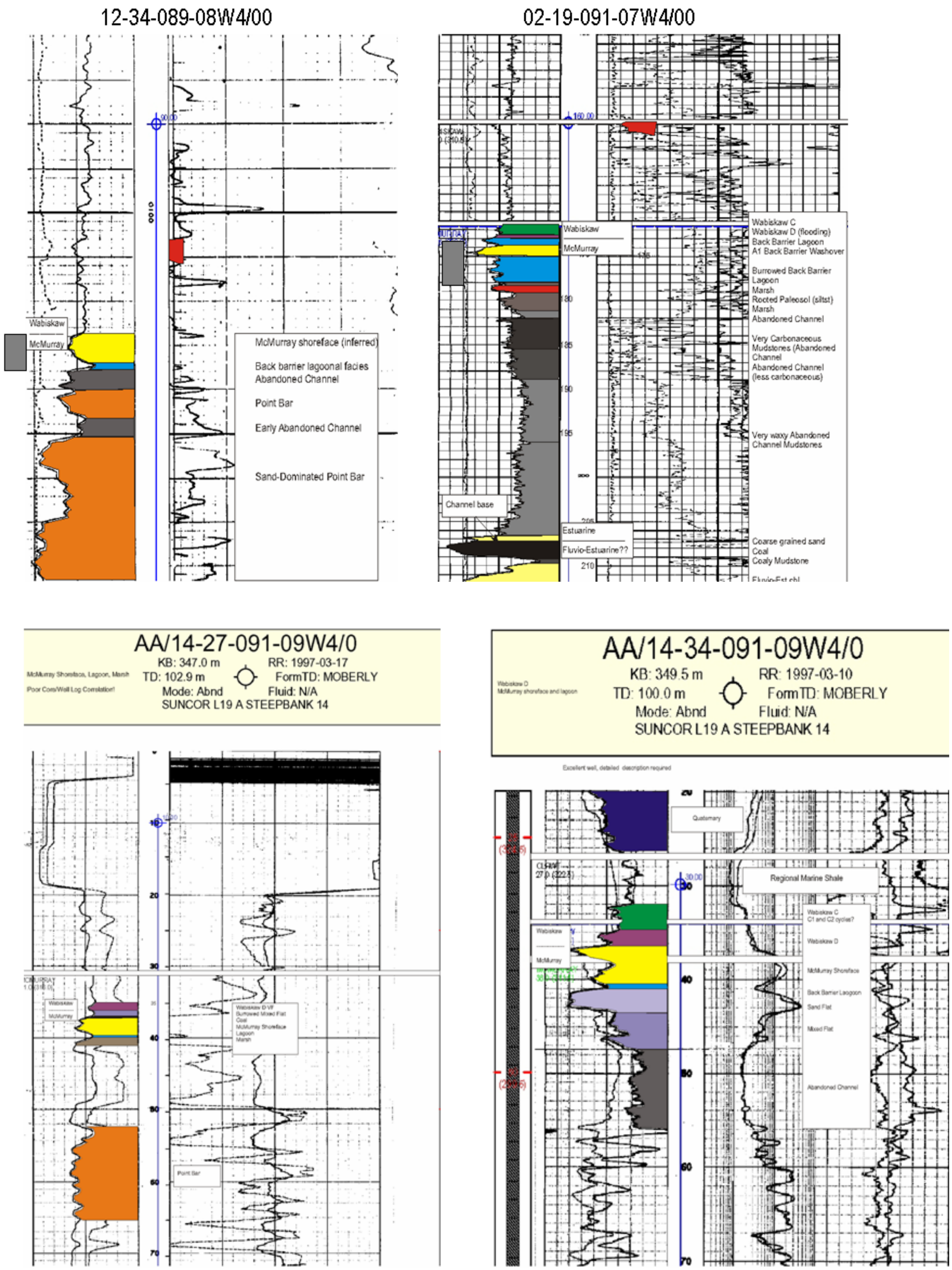


Figure 18. Representative wire-line logs for the McMurray estuarine facies association, transgressive back barrier deposits, 00/12-34-089-08W4 well, 00/02-19-091-07W4 well, AA/14-27-091-09W4 well, AA/14-34-091-09W4 well, Lewis-Fort McMurray area.

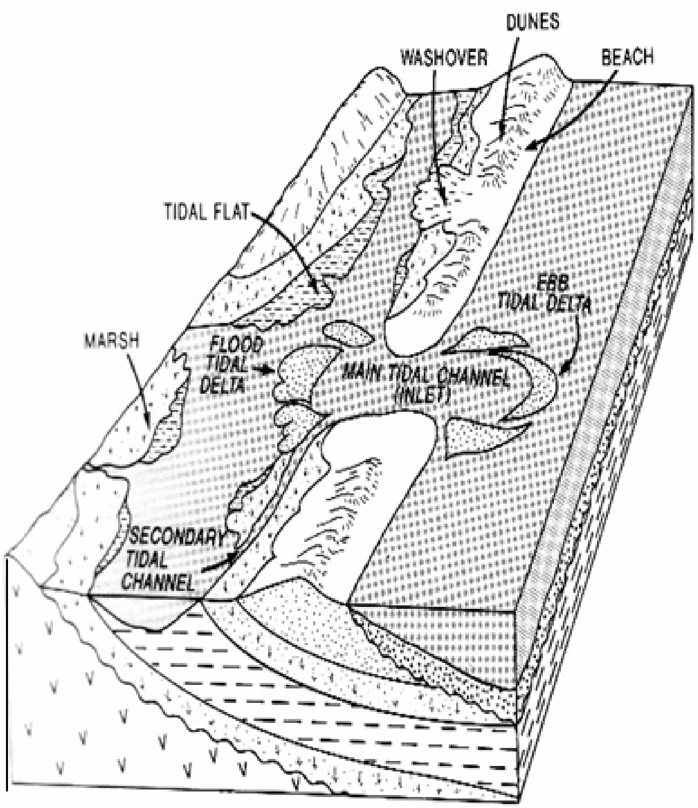


Figure 19. Depositional model for the McMurray estuarine facies association, back barrier deposits, (Figure 3, Reinson 1984, 1992).

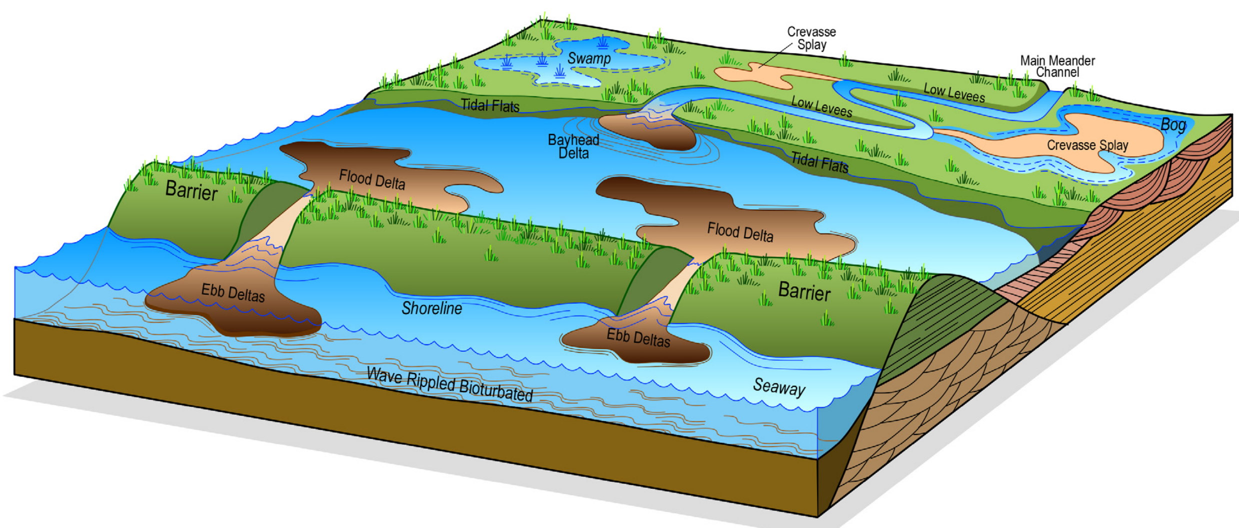


Figure 20. Schematic facies model for the McMurray estuarine facies association, tidal channel, tidal flat, barrier and back barrier deposits, (Upper McMurray Formation), Athabasca oil sands deposit, northeast Alberta (Figure 84, Hein et al.,

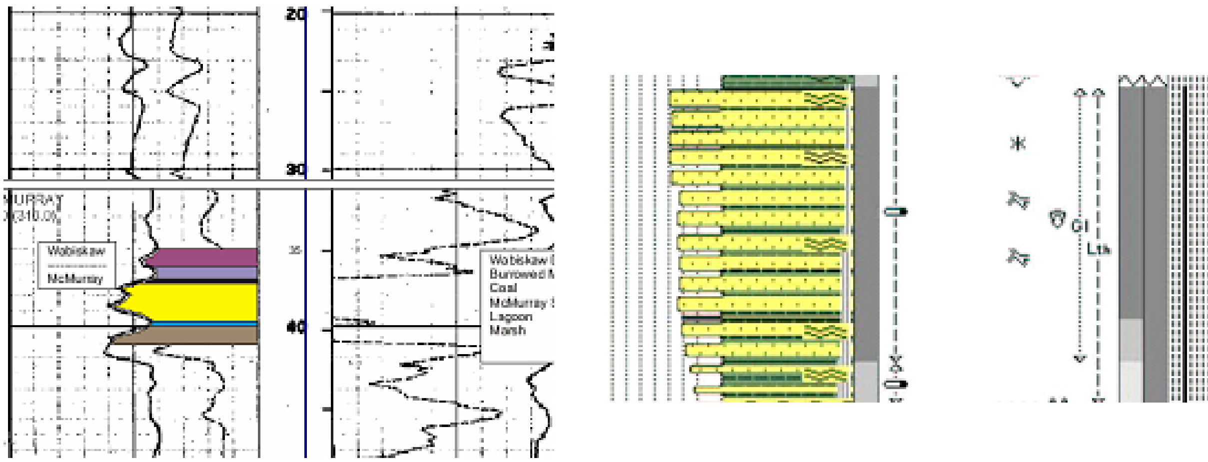


Figure 21. Representative wire-line logs and schematic core-log for the Wabiskaw D incised valley-fill, AA/10-24-091-09W4 well, subsurface Lewis-Fort McMurray area.

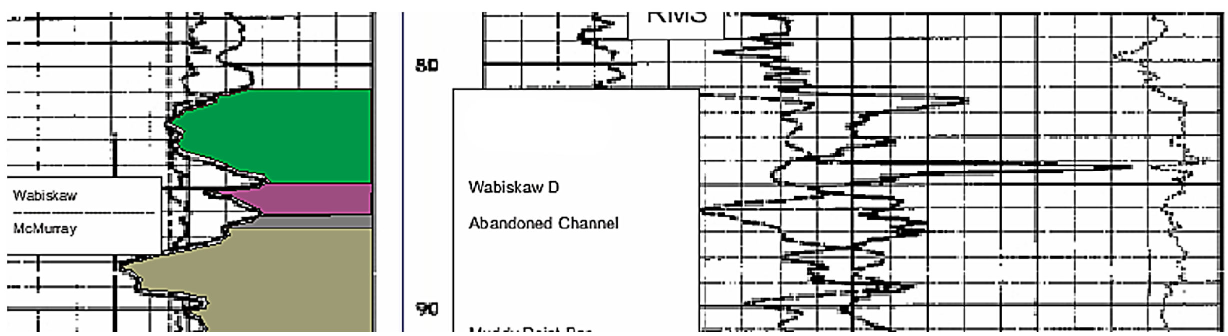


Figure 22. Representative wire-line logs for the Wabiskaw D shale, facies association AA/12-07-091-08W4 well, Lewis-Fort McMurray area.

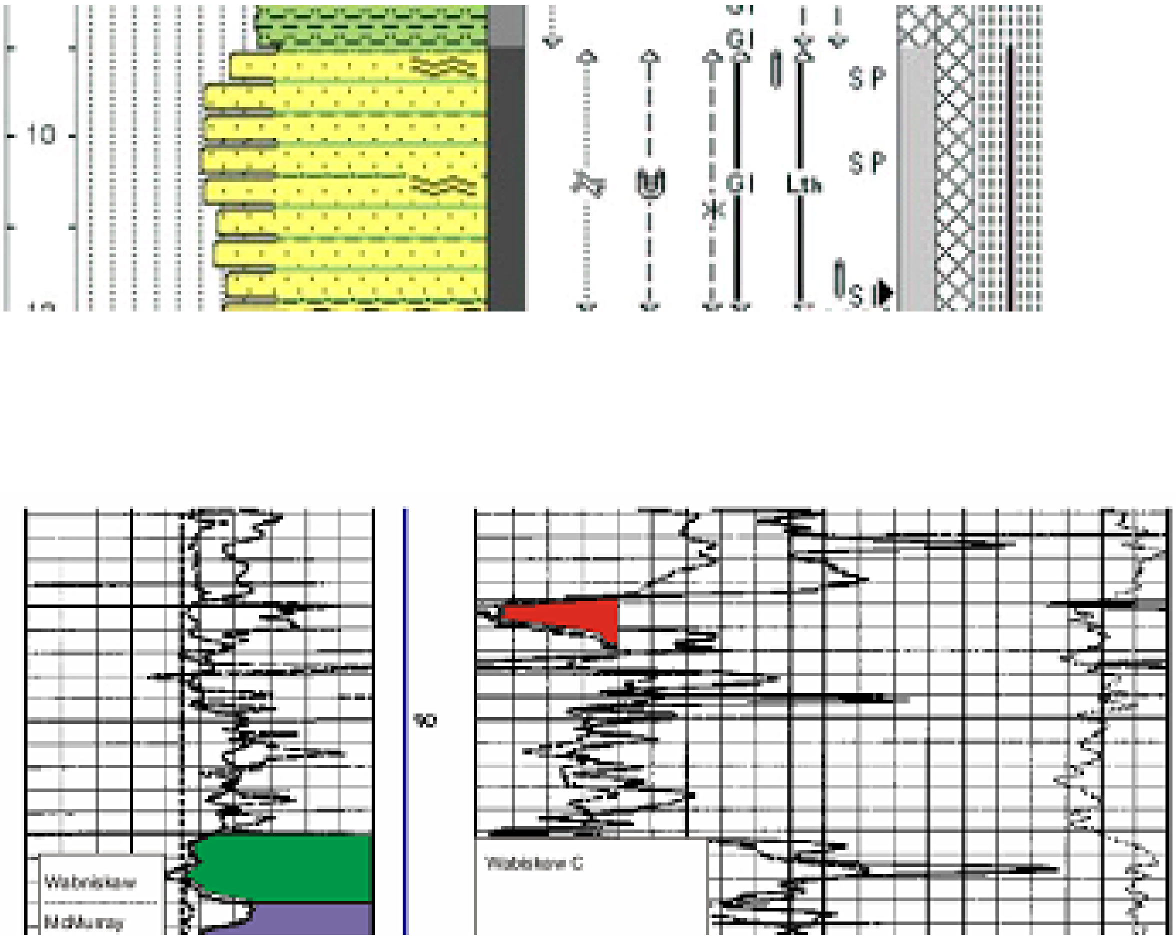


Figure 23. Schematic corelog (upper) and representative wire-line logs (lower) for the Wabiskaw C, AA/08-01-091-14W4 well, Lewis-Fort McMurray area.

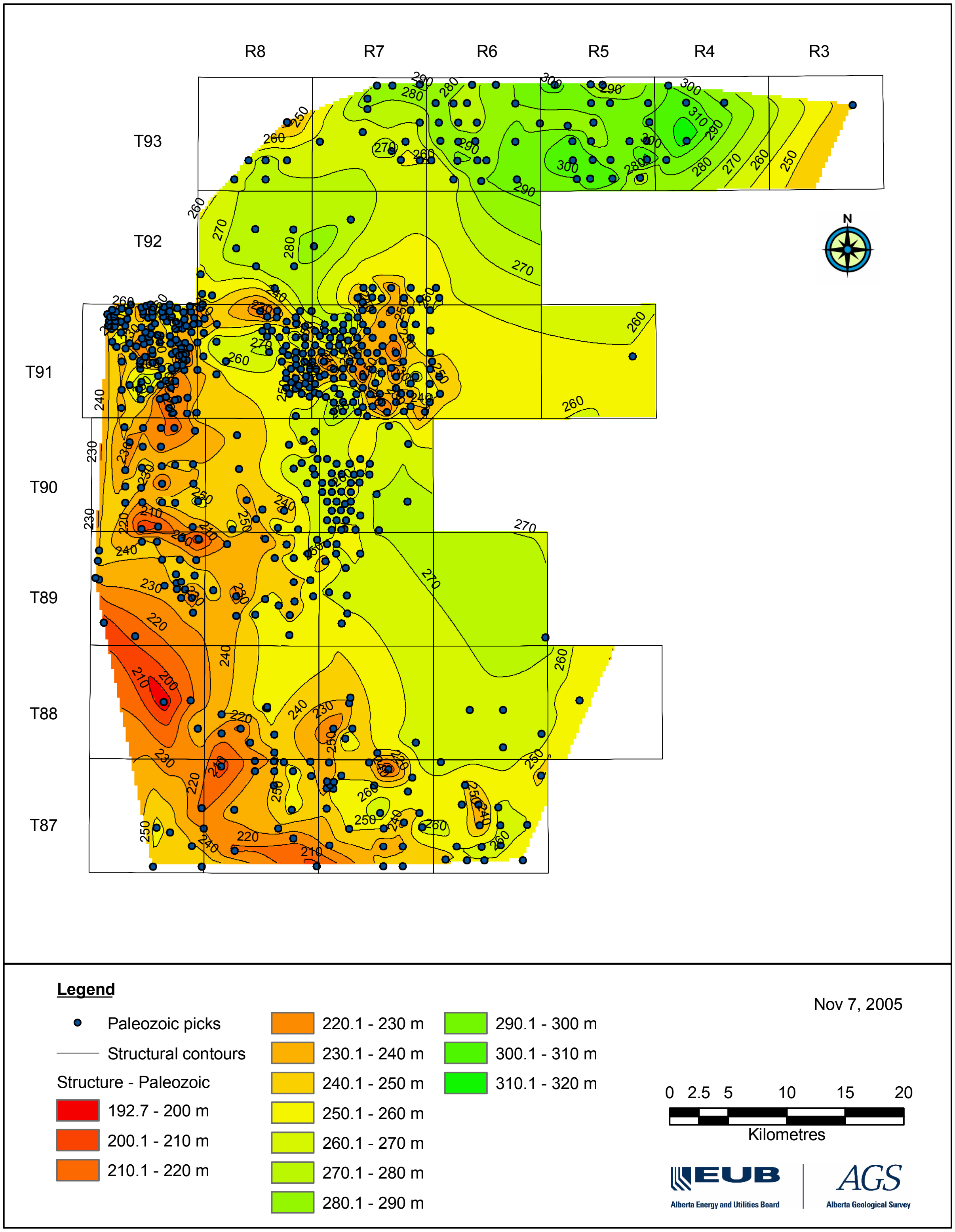


Figure 24. Sub-Cretaceous unconformity structure map (symbols show Paleozoic well penetrations).

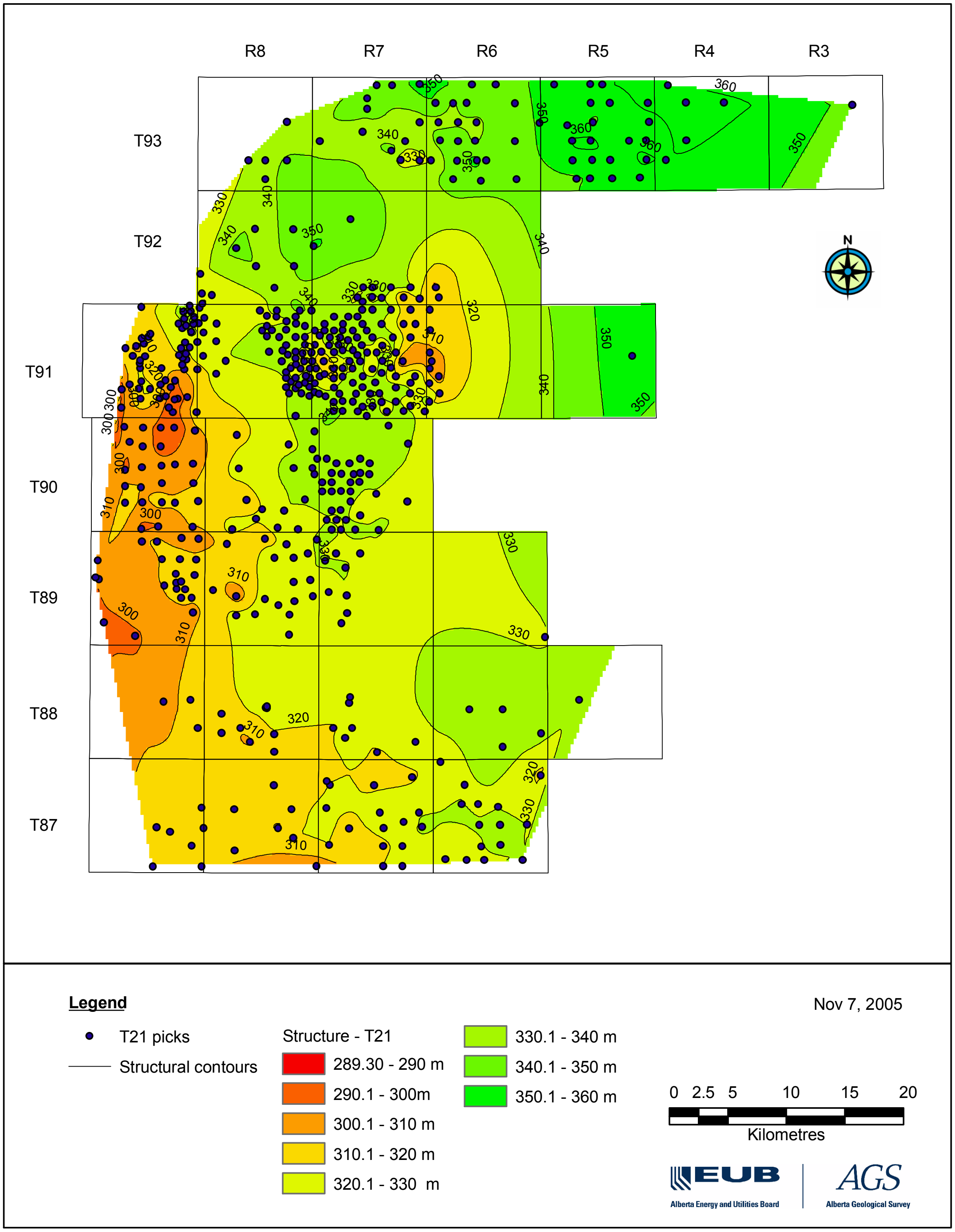


Figure 25. T21 structure map (symbols show T21 well penetrations).

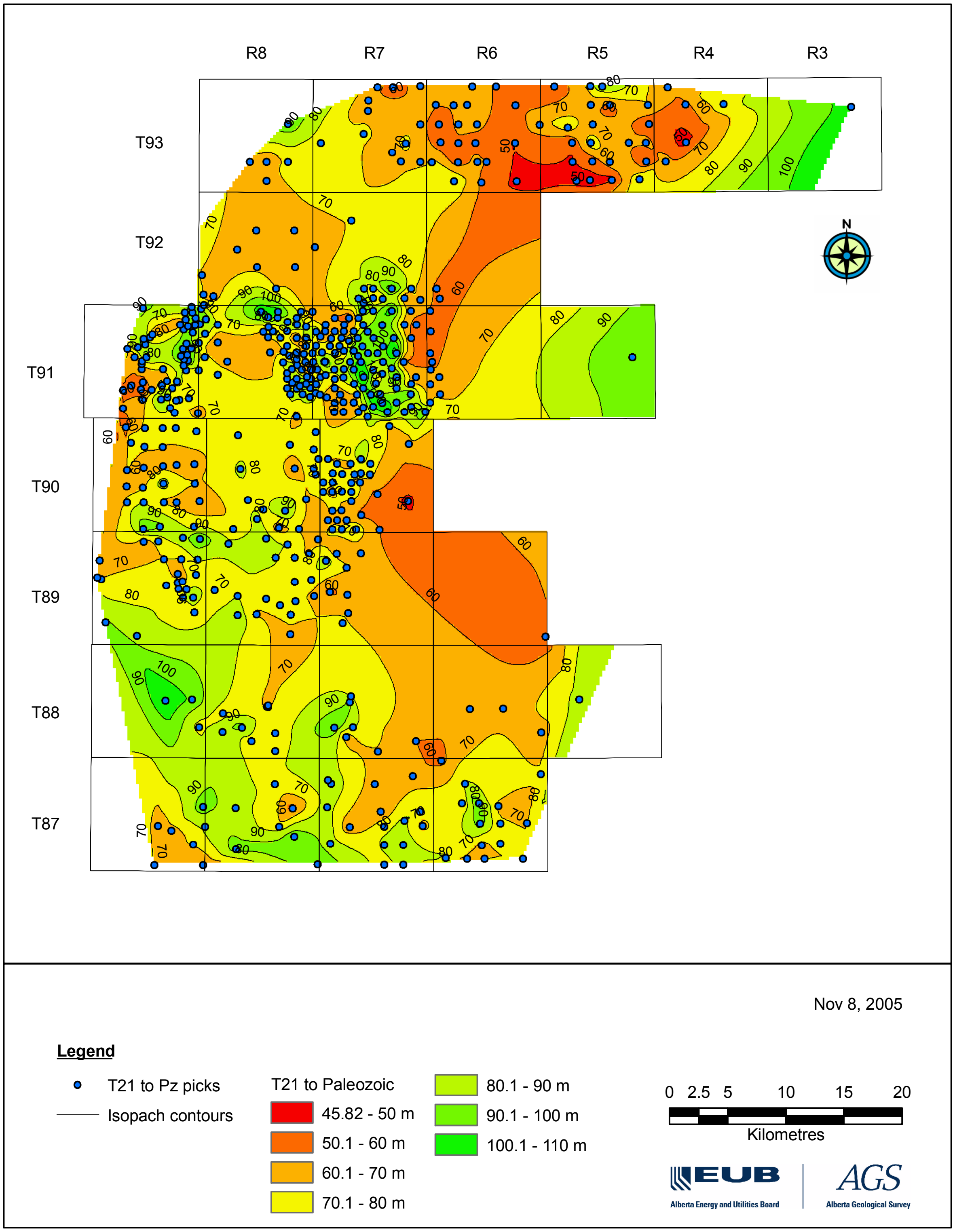


Figure 26. T21 to Paleozoic isopach map (symbols show Pz well penetrations).

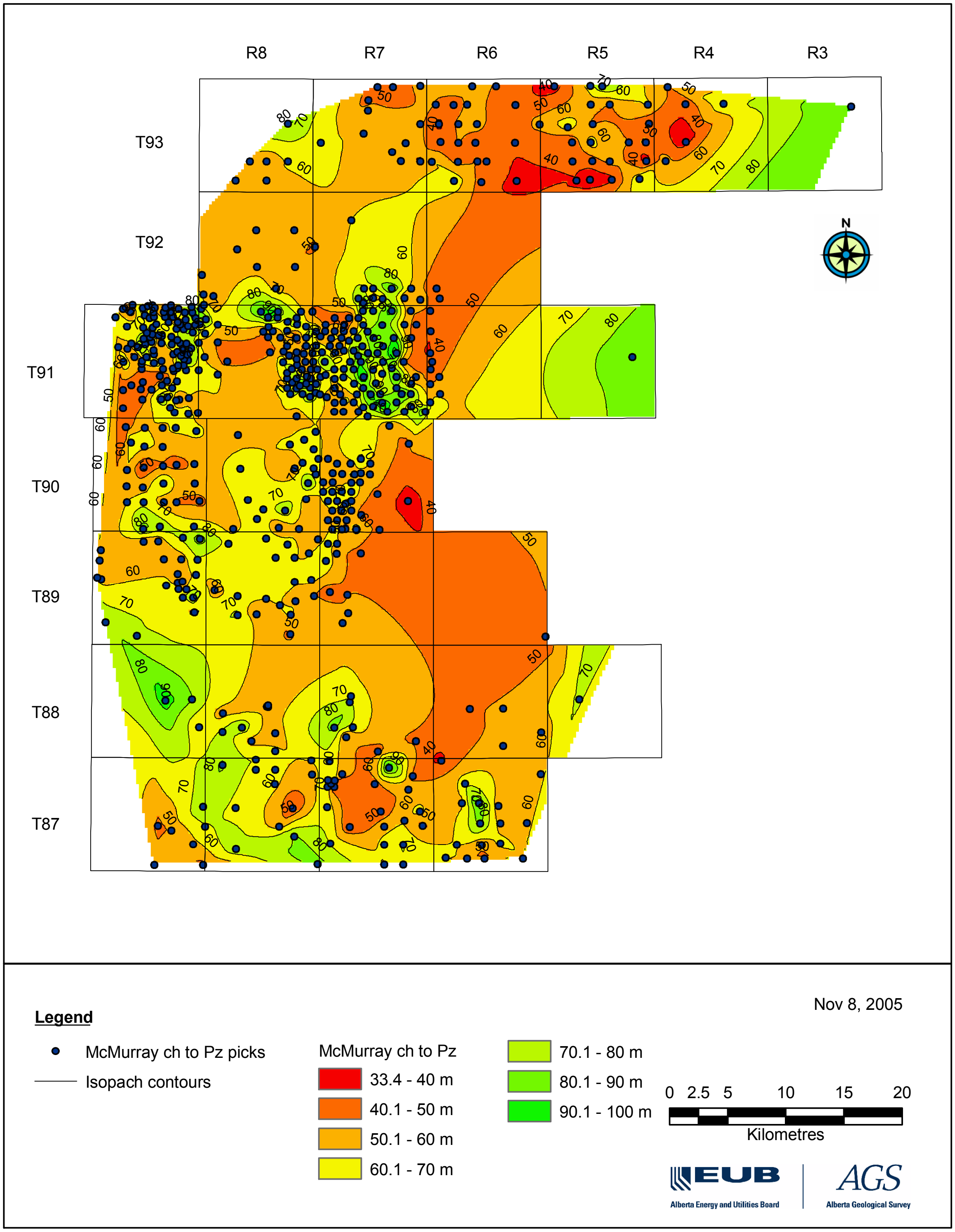


Figure 27. McMurray channel to Paleozoic isopach (symbols show Paleozoic well penetrations).

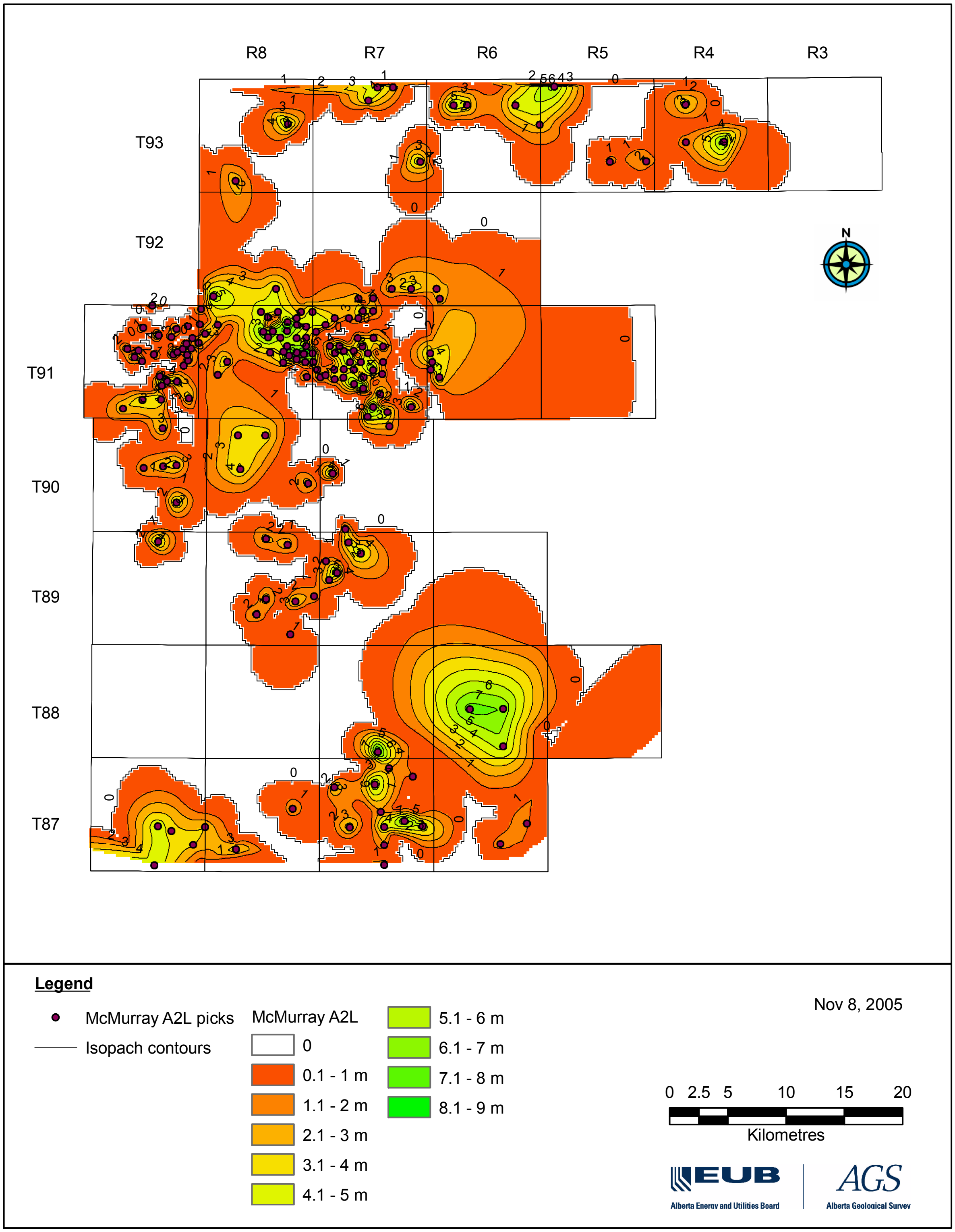


Figure 28. McMurray A2L isopach map (symbols show A2L well penetrations).

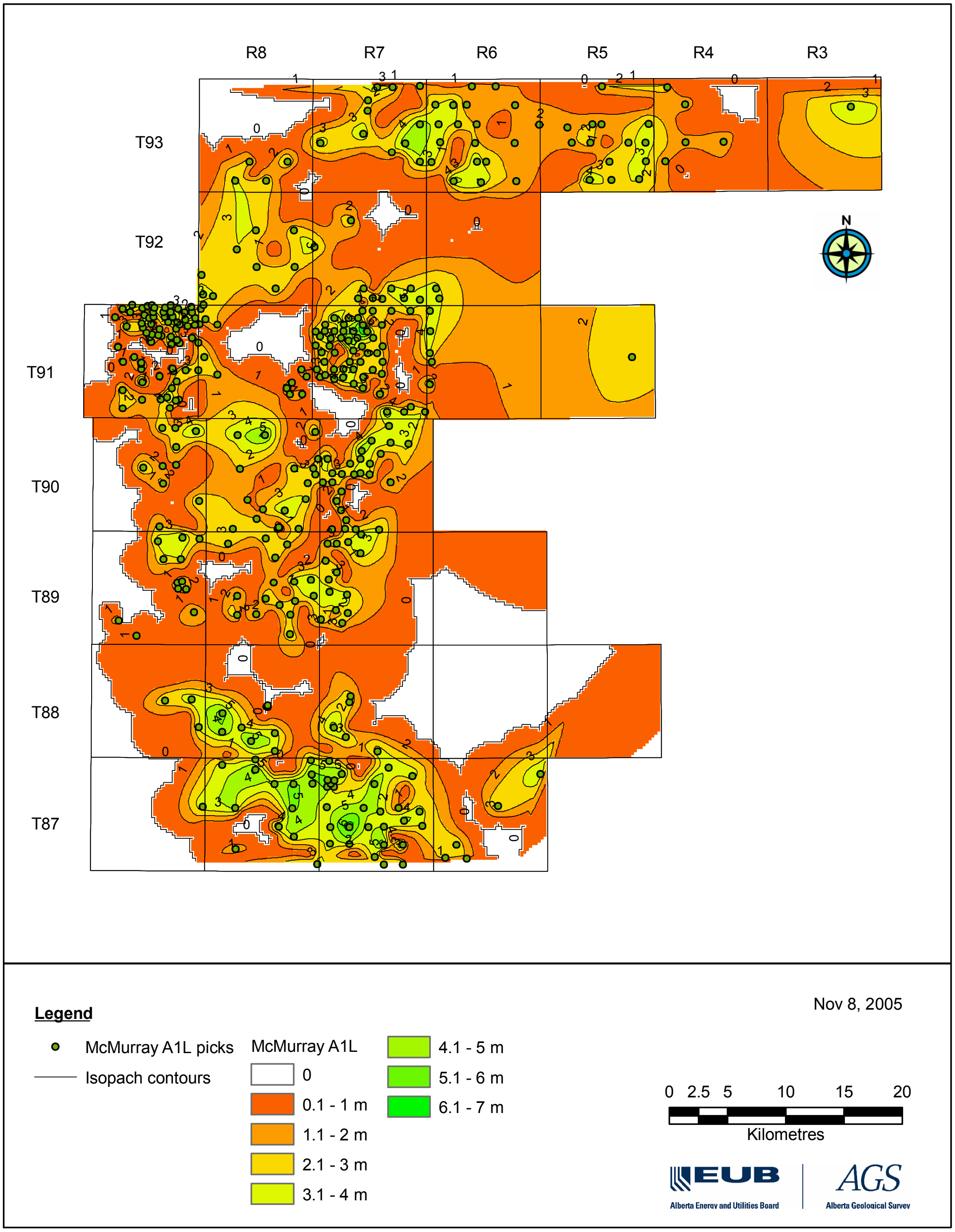


Figure 29. McMurray A1L isopach map (symbols show A1L well penetrations).

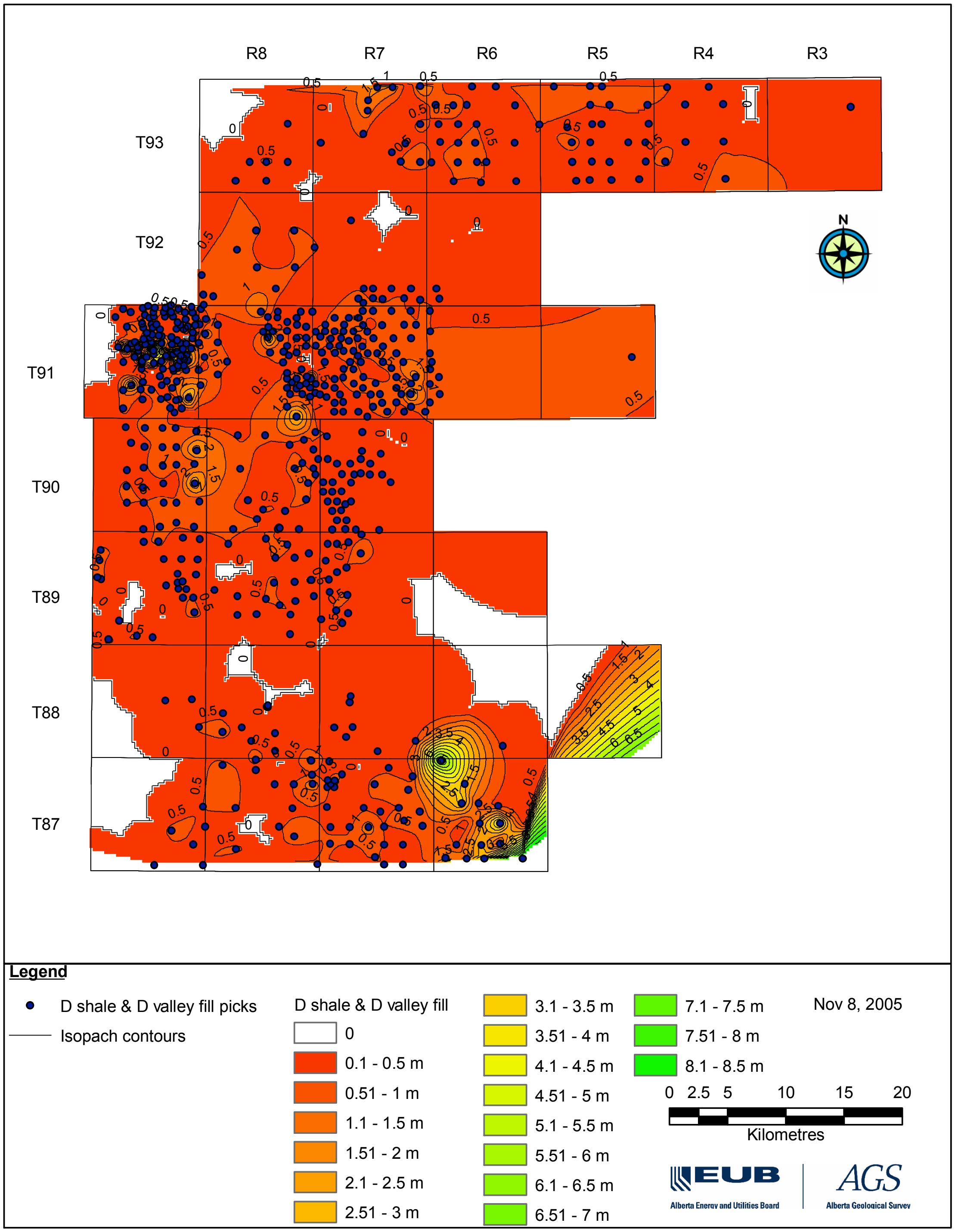


Figure 30. Wabiskaw D valley-fill and Wabiskaw D shale isopach map (symbols show DVF and D shale well penetrations).

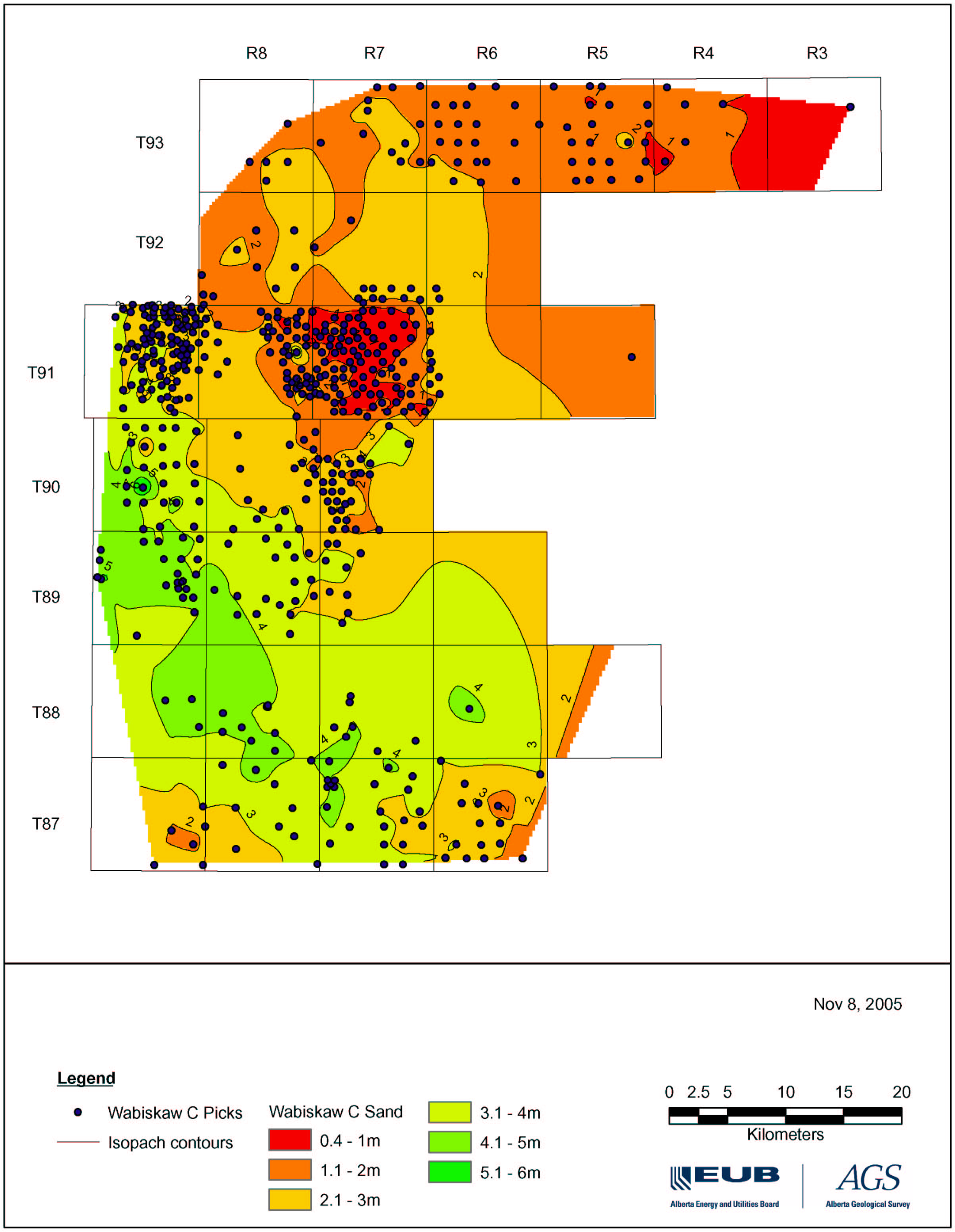


Figure 31. Wabiskaw C isopach map (symbols show Wabiskaw C well penetrations).

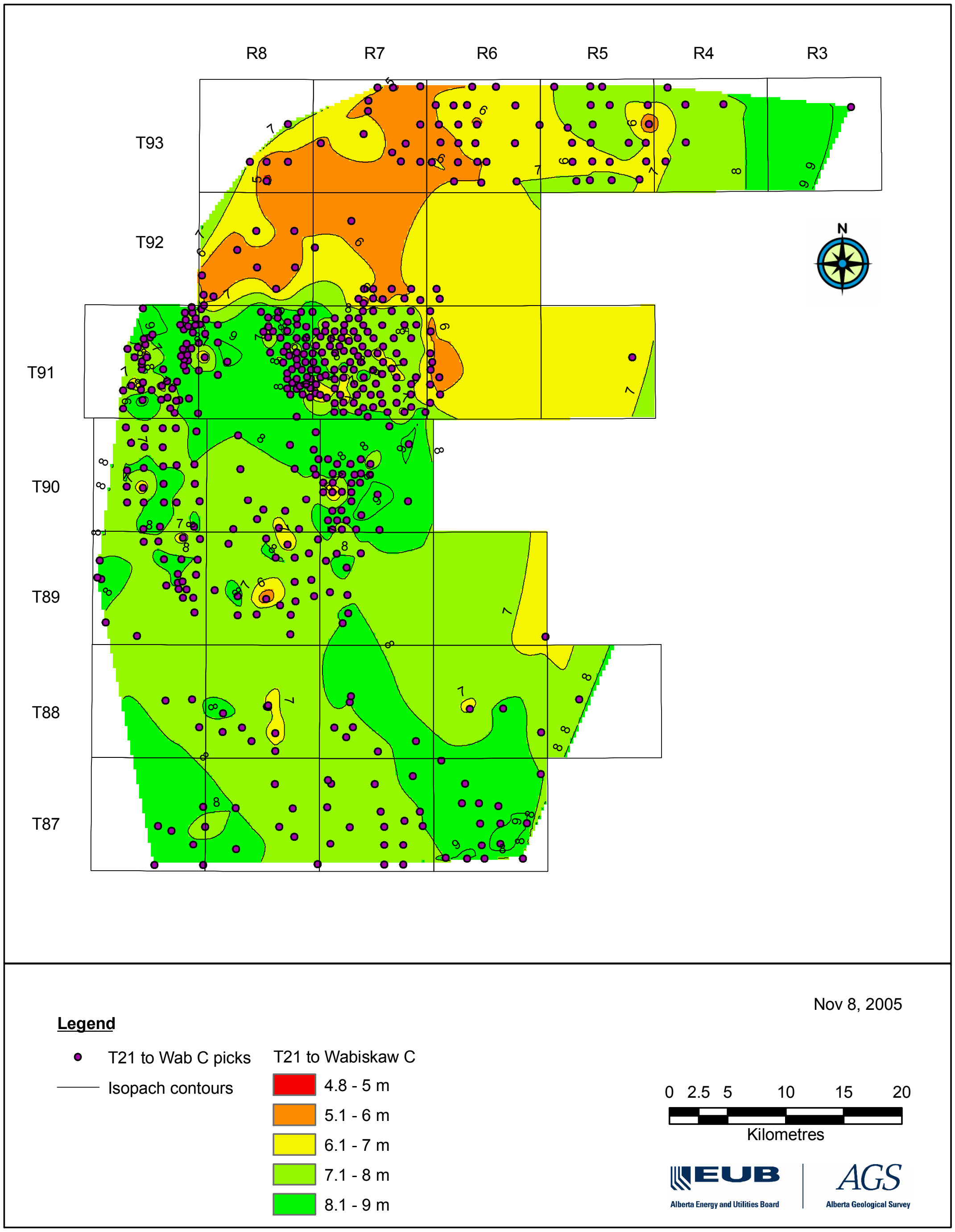


Figure 32. T21 to Wabiskaw C isopach map (symbols show Wabiskaw C well penetrations).

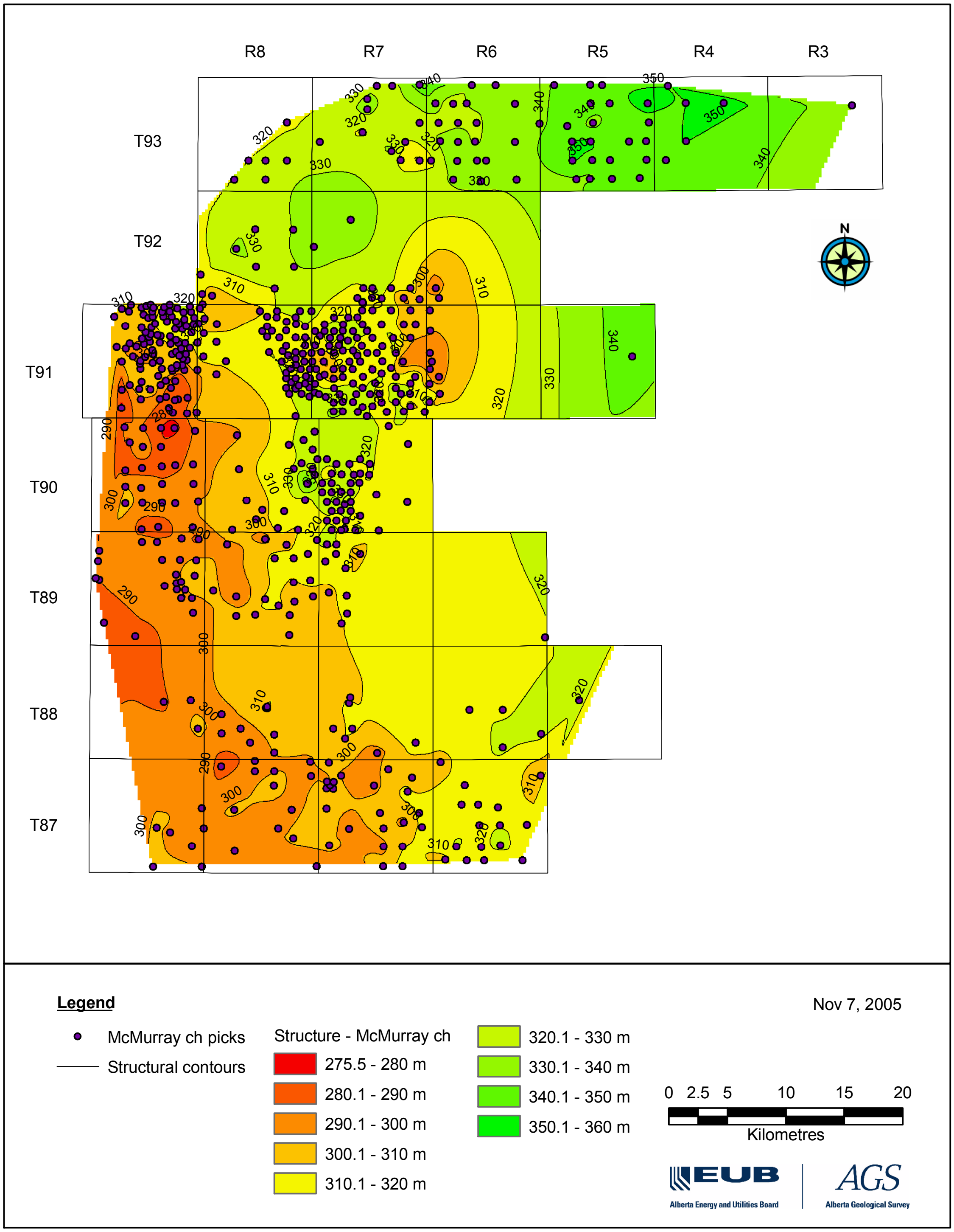


Figure 33. McMurray channel structure map (symbols show McMurray Channel well penetrations).

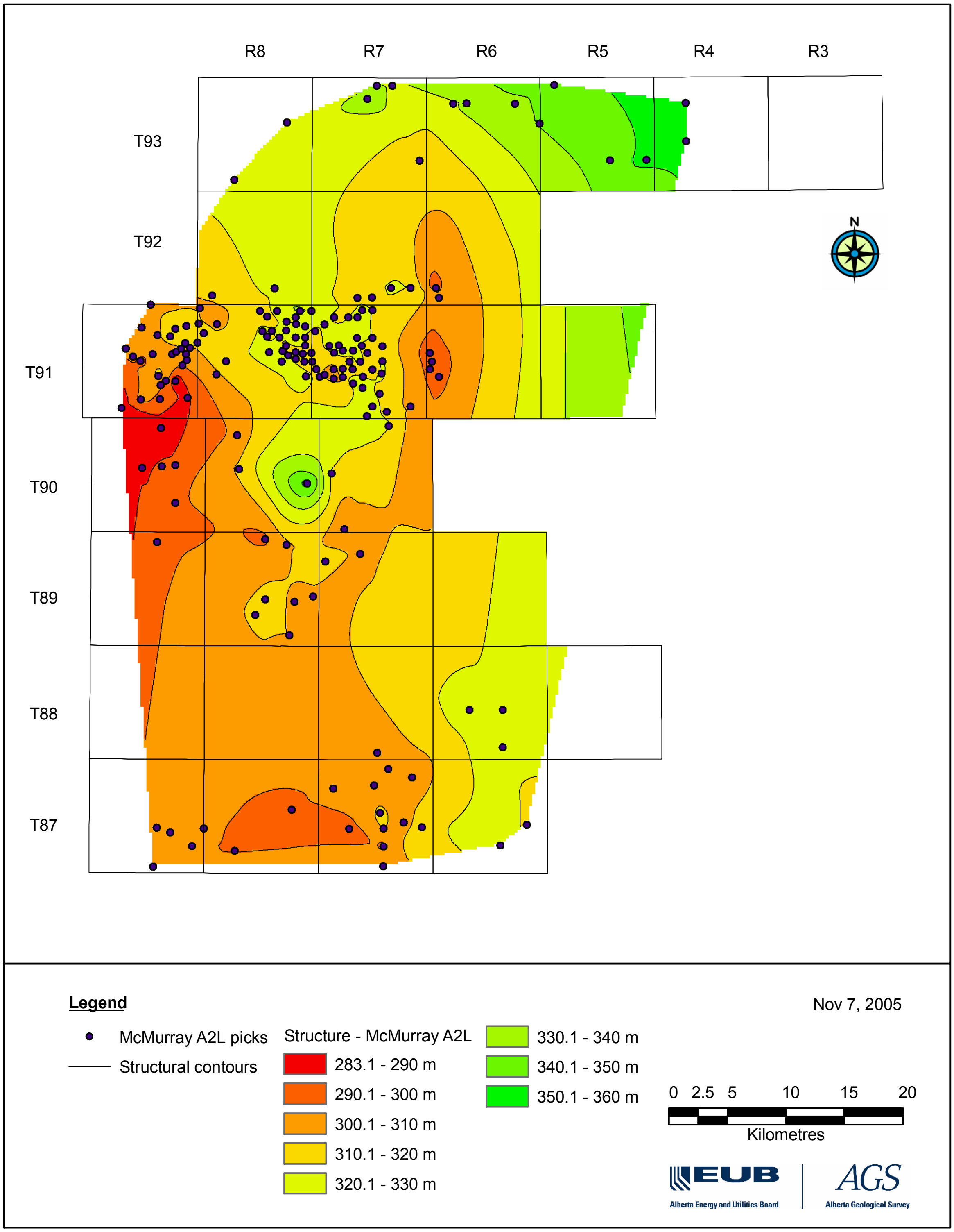


Figure 34. McMurray A2L structure map (symbols show McMurray A2L well penetrations).

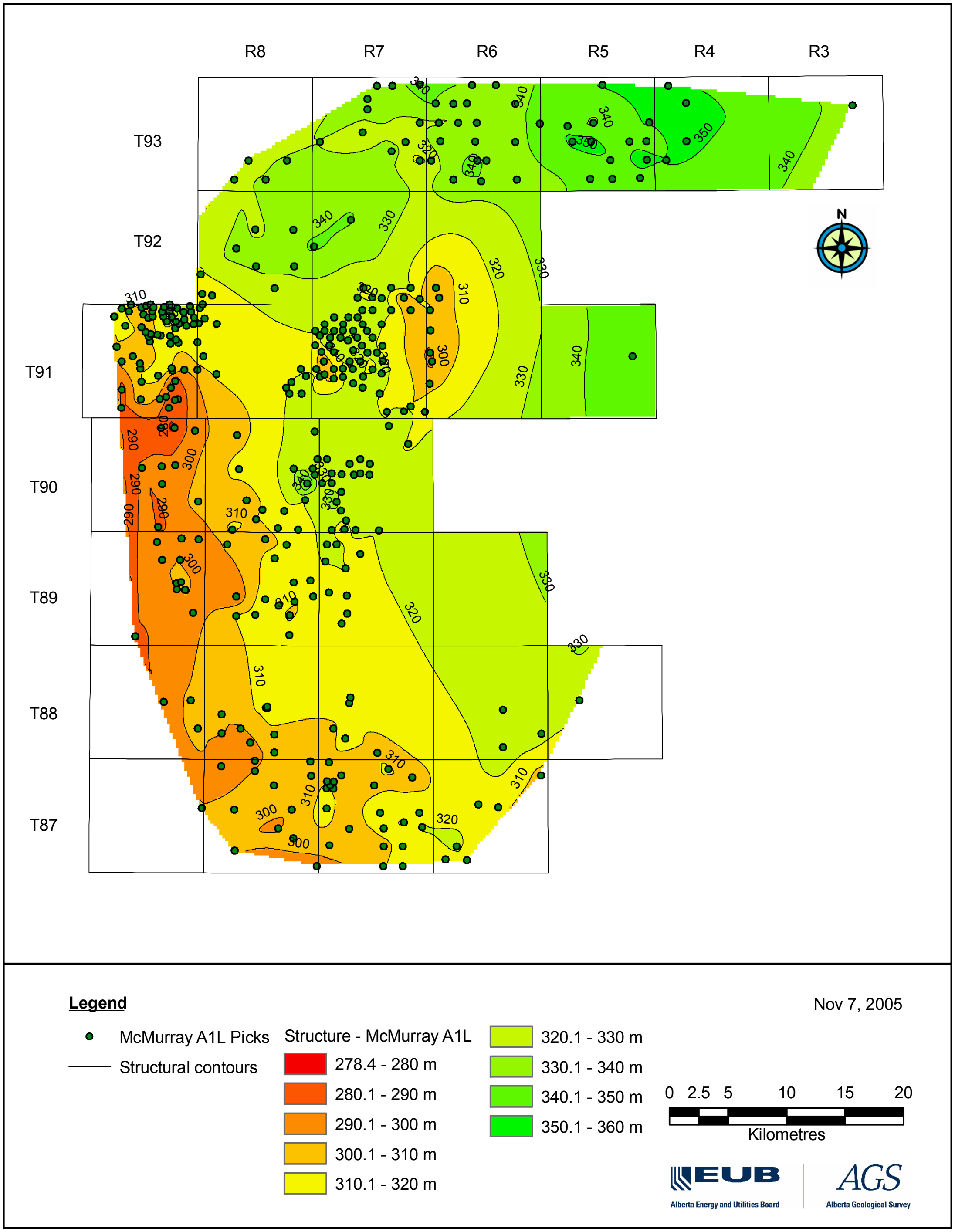


Figure 35. McMurray A1L structure map (symbols show McMurray A1L well penetrations).

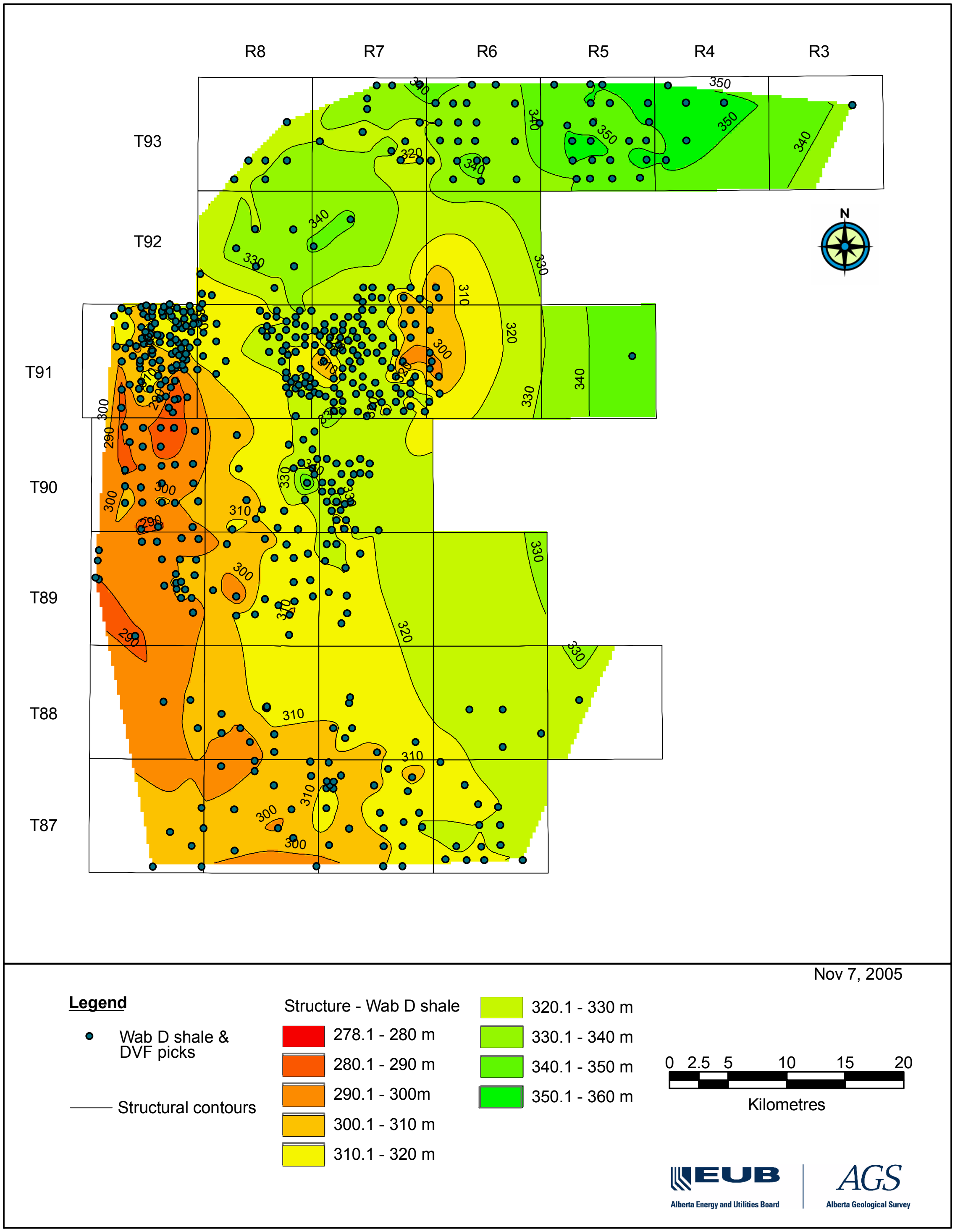


Figure 36. Wabiskaw D valley-fill (DVF) and Wabiskaw D shale structure map (symbols show Wabiskaw DVF and Wabiskaw D shale well pentetrations).

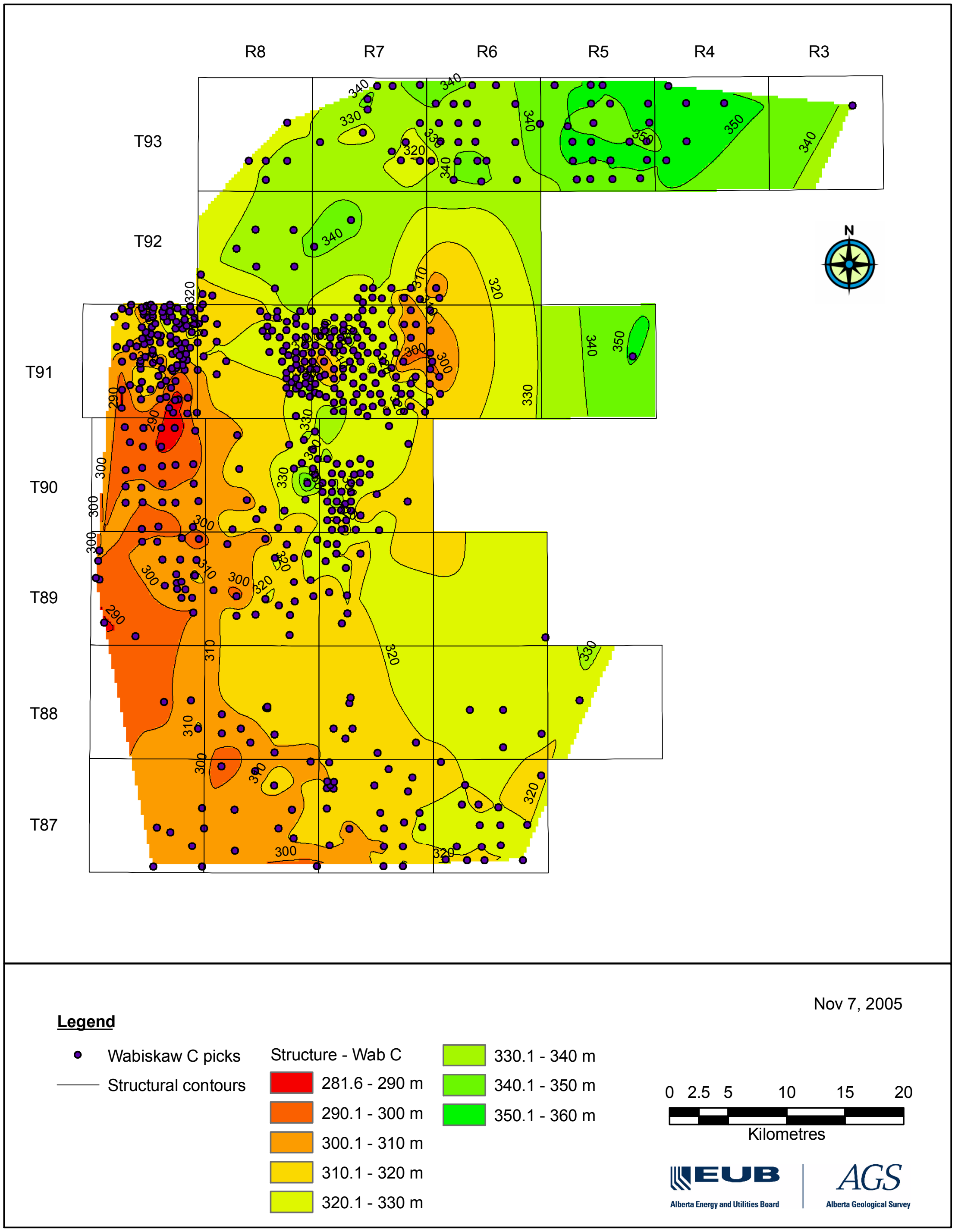


Figure 37. Wabiskaw C structure map (symbols show Wabiskaw C well penetrations).

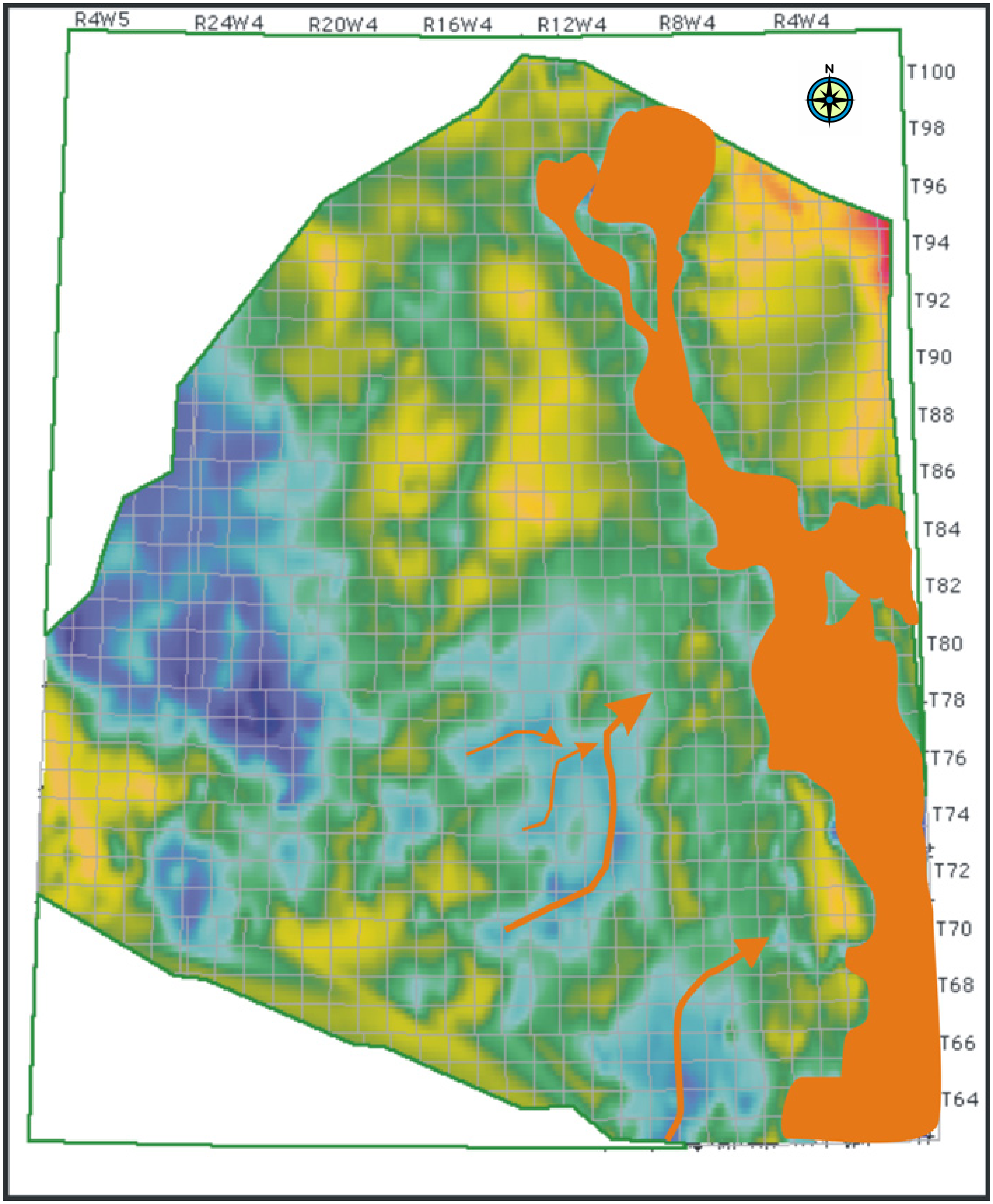


Figure 38. Lowstand Time 1: distribution fluvial facies association (orange highlights) draped over topography of the sub-Cretaceous unconformity, over the area from T64-100, R1W4 to 4W5.

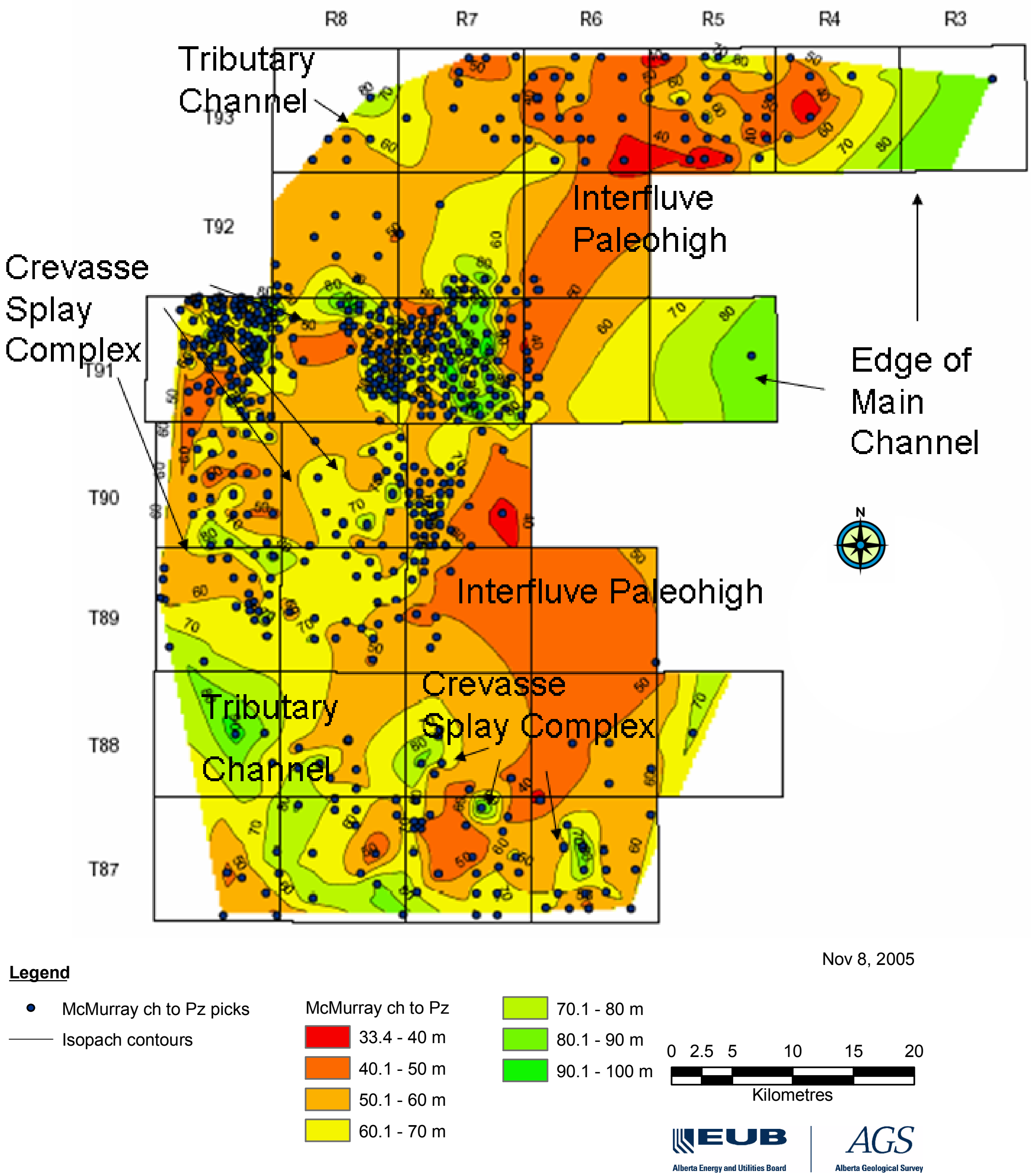


Figure 39a. Paleogeographic evolution of the Wabiskaw-McMurray, McMurray channel deposits, in the Lewis-Fort McMurray area.

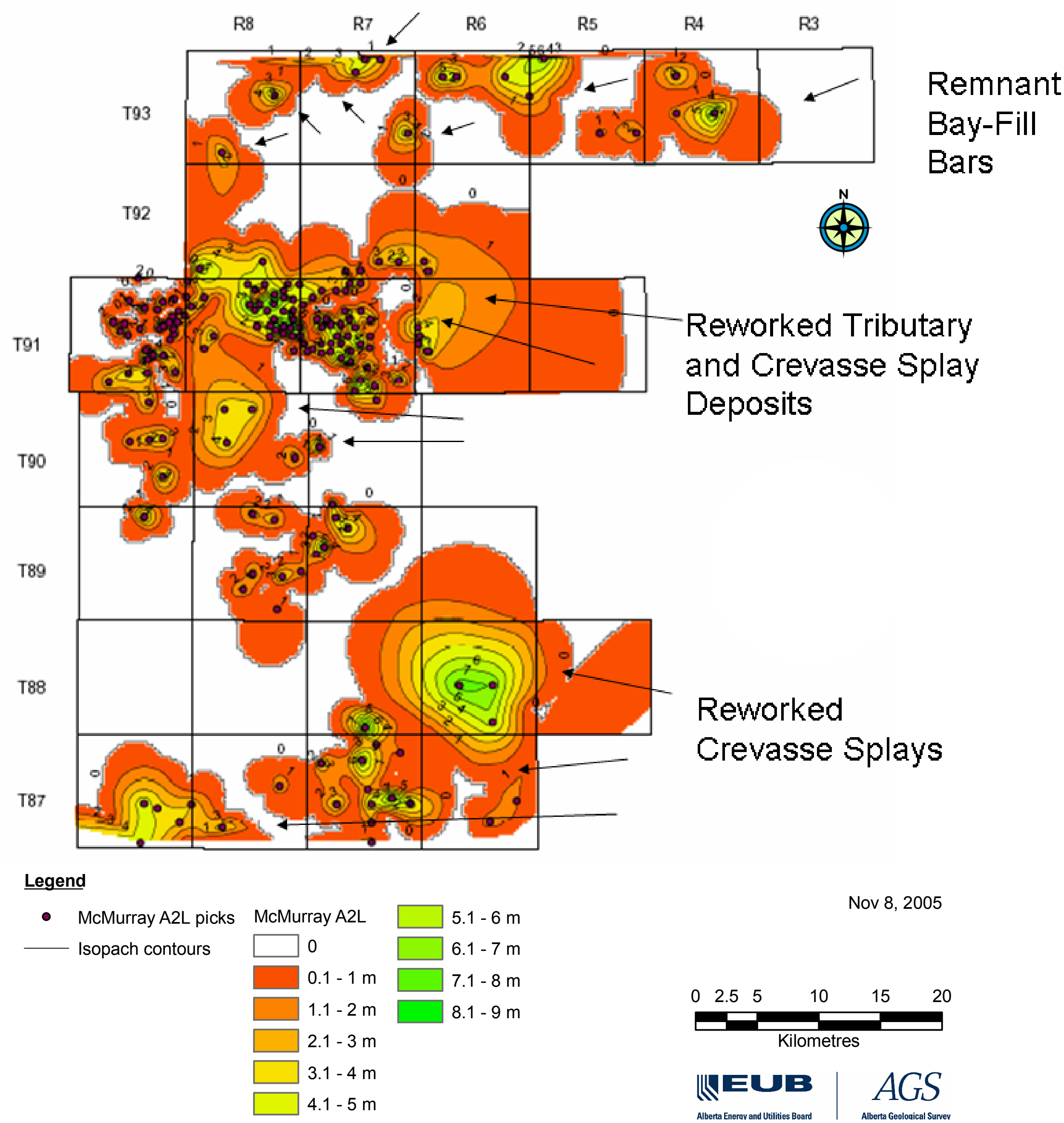


Figure 39b. Paleogeographic evolution of the Wabiskaw-McMurray, McMurray A2L deposits, in the Lewis-Fort McMurray area.

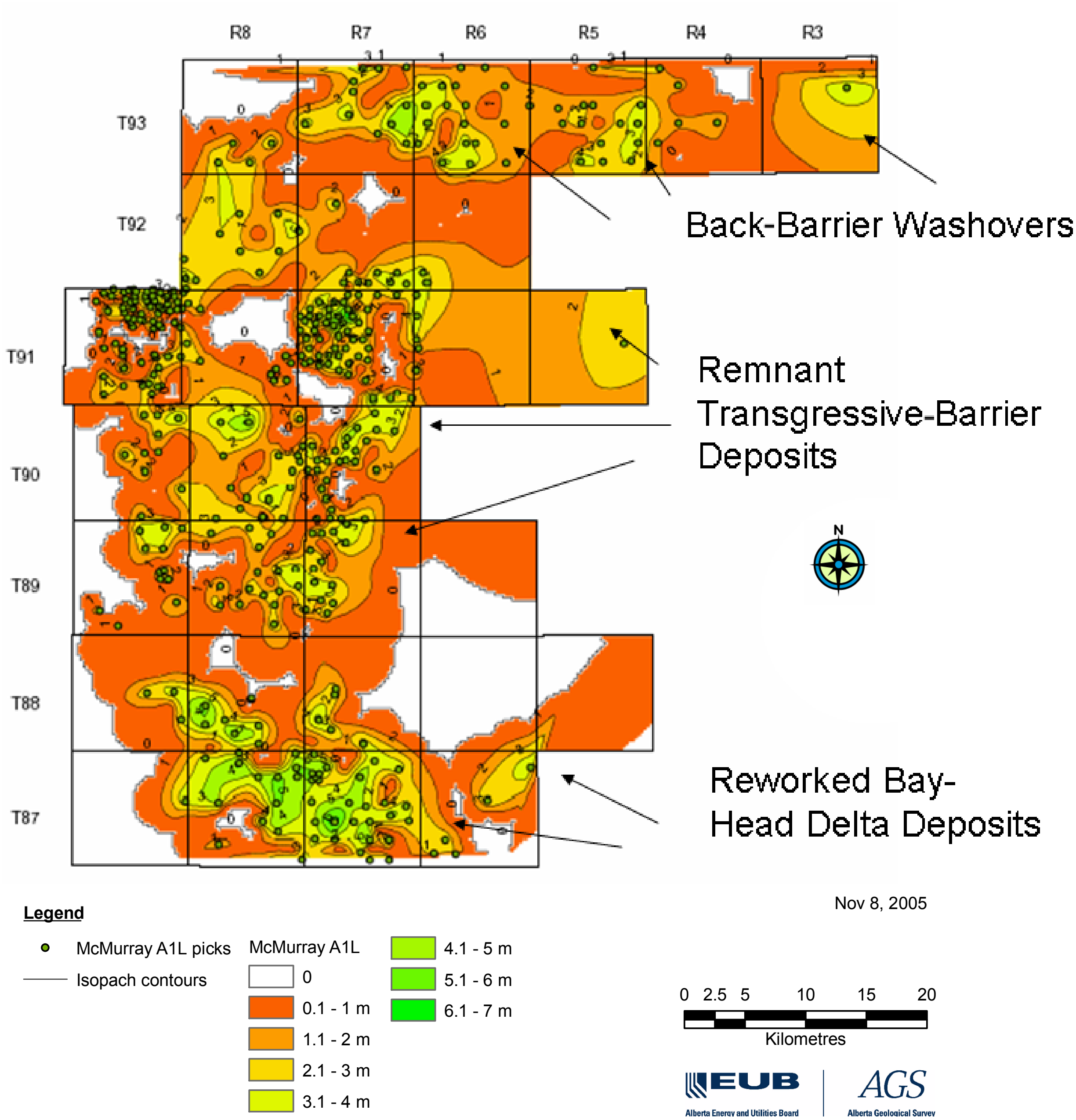


Figure 39c. Paleogeographic evolution of the Wabiskaw-McMurray, McMurray A1L deposits, in the Lewis-Fort McMurray area.

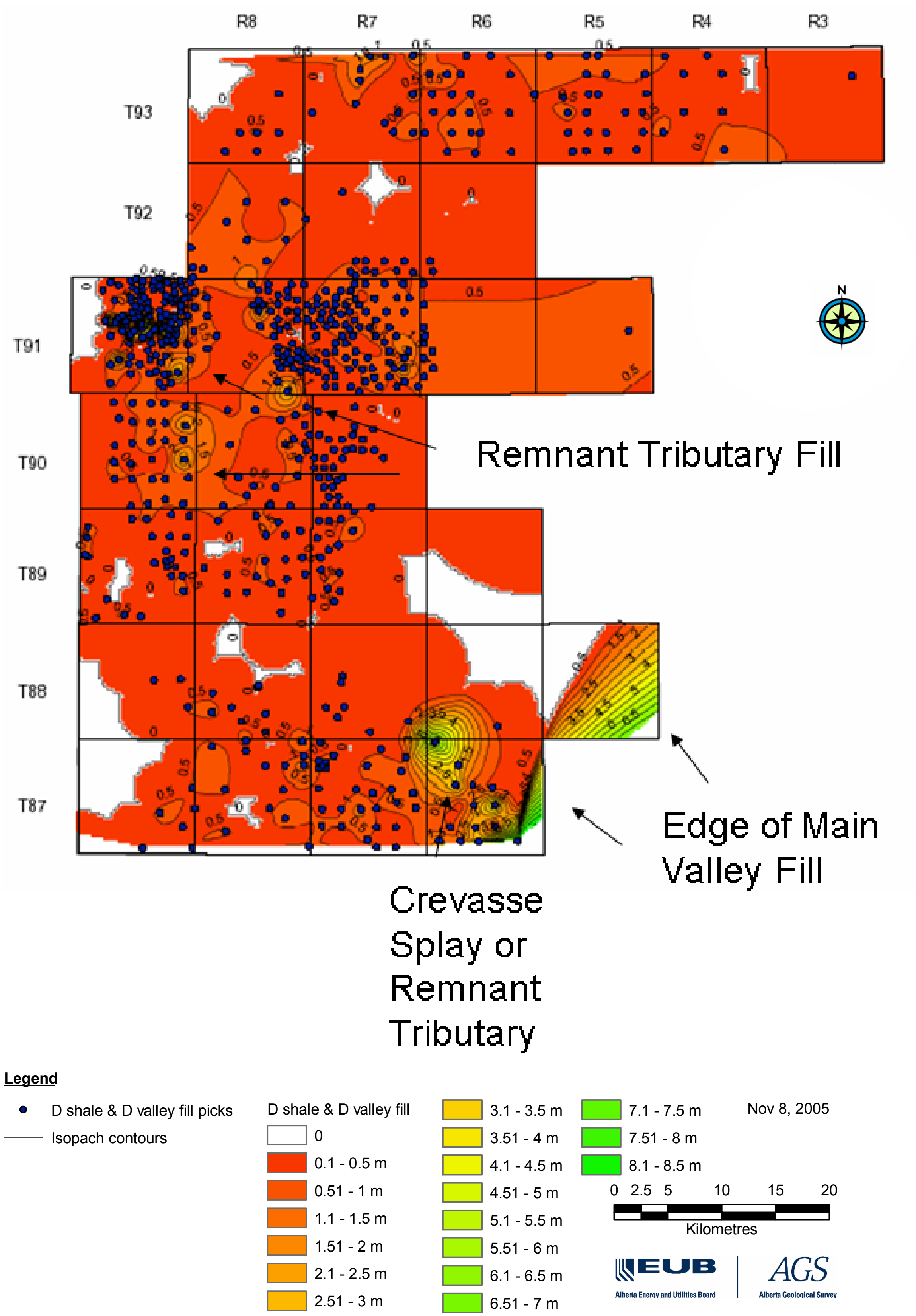


Figure 39d. Paleogeographic evolution of the Wabiskaw-McMurray, Wabiskaw D valley-fill and D Shale deposits, in the Lewis-Fort McMurray area.

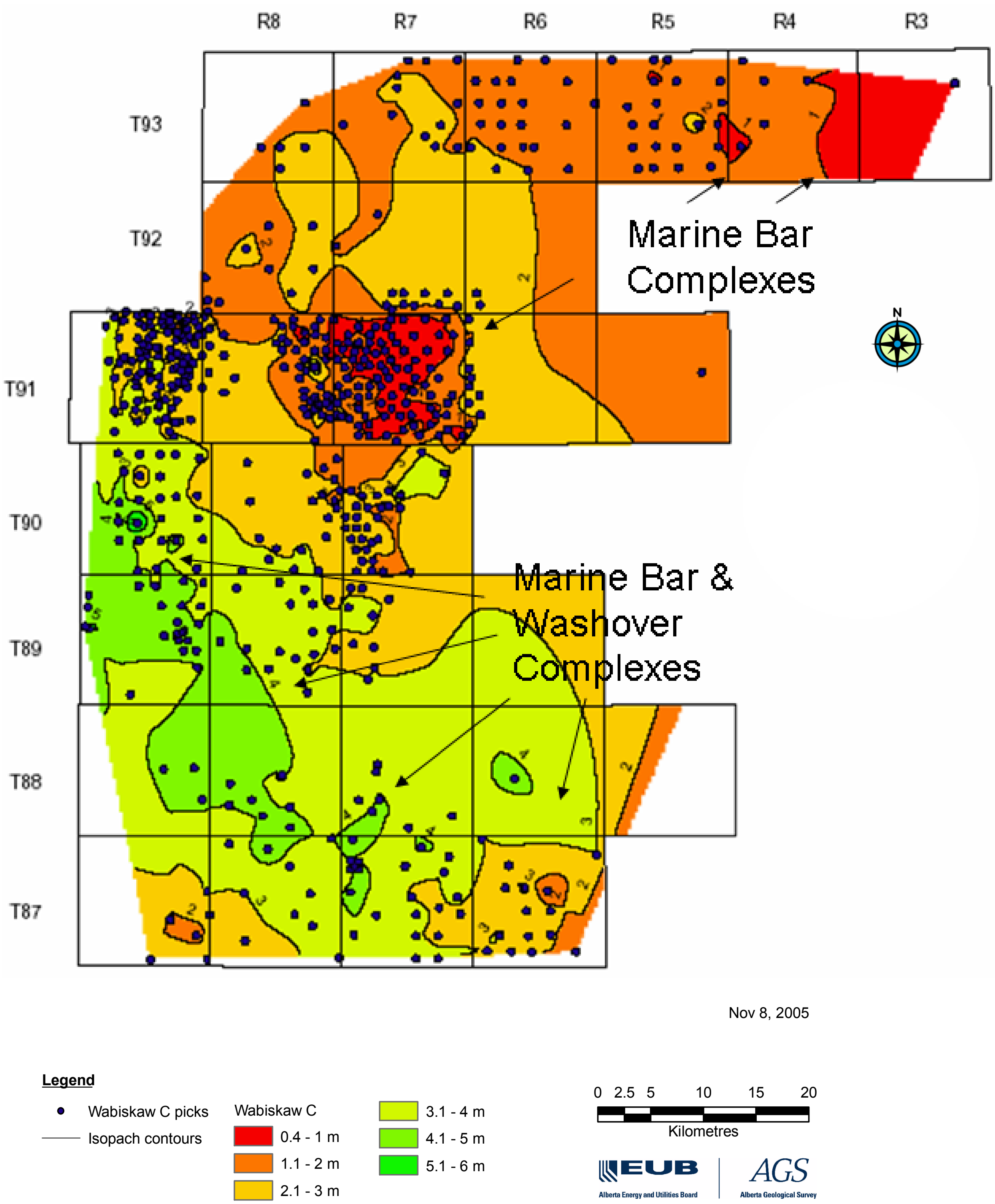


Figure 39e. Paleogeographic evolution of the Wabiskaw-McMurray, Wabiskaw C deposits, in the Lewis-Fort McMurray area.

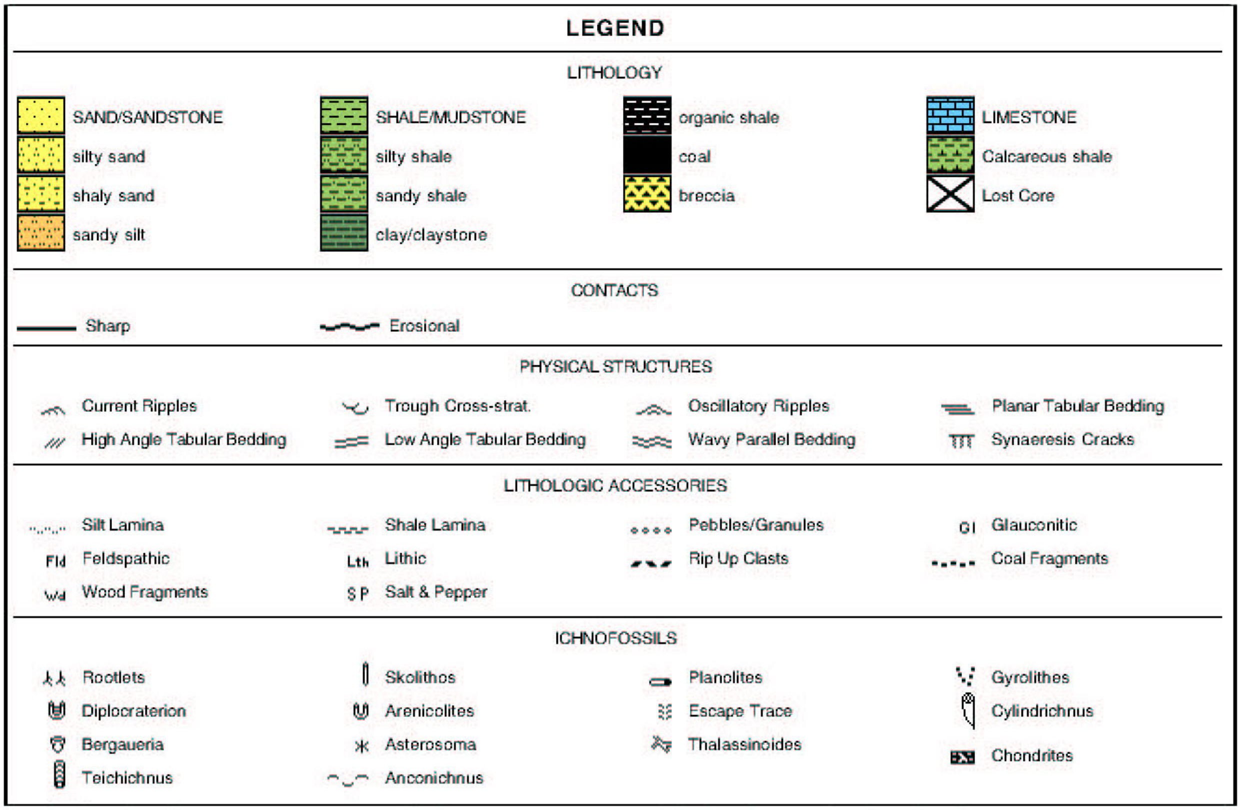
Appendix 1 - Definition of Stratigraphic Markers ('picks') with Quality Codes (modified from Wynne et al., 1994 and Hein et al., 2000)*

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 Major Erosion Surface	Excellent – Very Good
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 wire-line logs and seismic; Poor to Very Poor, need to be confirmed by outcrops or core, difficult to pick on wire-line logs, somewhat easier to pick on seismic.

Appendix 2 - Applecore™ Legend for Representative McMurray Cores.



Appendix 3 - Colour Legend for the Interpreted Facies Associations on the Wire-Line Logs

Appendix 4 - Detailed Listing of Attachments on CD

Title	Description
AGS_ESR Table 1 02_14.xls	Digital version of Table 1 in the text.
Type log.jpg	Schematic type core log for the study area
Lewis core map plotter sizepdf.pdf	Core examined and cross-sections, Lewis area
AGS_ESR Edited Photos List.doc	Well list for cores with digital photos
Edited photos Folder	Includes all annotated digital core photos
AGS_ESR Edited Core Logs List.doc	Well list for interpreted coloured raster logs
Edited Colour Logs Folder	Includes all interpreted raster log images
ColorCoreLegend.jpg	Core Logging Legend for raster log images
Lewis Folder	
all_picks.xls	Picks table for producing maps; used for large isopach and structure maps
all_picks zero edges -999.xls	Picks table with true zeros versus‘not picked’ entries (-999); used for producing zero-edge maps
open the folder for listing	All files for producing ArcGIS maps