Preliminary Overview of Regional Stratigraphy in the Late Paleoproterozoic Athabasca Basin, Saskatchewan and Alberta

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Abstract

Regional stratigraphic investigations continued in the eastern Athabasca Basin, and began in the western Saskatchewan and Alberta parts of the Basin. Detailed investigations continued at McClean Lake and Key Lake, and were undertaken at McArthur River, Cigar Lake, Shea Creek, and Maybelle River. Knowledge of the basin stratigraphy has been improved, but with more detailed subdivision of the formations, terminology is becoming awkward, and a major revision is probably warranted. Within the Athabasca Group, three sequences, bounded by unconformities, are distinguished: the Fair Point sequence, the Manitou Falls–Wolverine Point sequence, and the Locker Lake–Carswell sequence. Second- and third-order sequences are recognized within these. Each first-order sequence records major changes in basin subsidence or marginal uplift, probably related to far-field tectonism. To a large extent, lateral stratigraphic variations within the second sequence correspond to and confirm the development of at least five deposystems in Athabasca Basin. Except for the two uppermost units, the Douglas and Carswell formations, the Athabasca Group is predominantly fluvial.

1. Introduction

The scope and objectives of sub-project 4 (Stratigraphy and Sedimentology) of the EXTECH IV Athabasca uranium project are outlined in detail by Yeo *et al.* (2000). Work in the first year of the project was restricted to the eastern part of the basin (Yeo *et al.*, 2000; Long *et al.*, 2000; Collier and Yeo, this volume), while work in the central part of the basin is planned for the third year. In 2001, stratigraphic studies included regional studies in the western Saskatchewan (Yeo, Collier *et al.*, this volume) and Alberta parts of the basin (Ramaekers, 2001), as well as more detailed work at Shea Creek (Collier *et al.*, this volume), and by Kupsch on the Maybelle River trend in Alberta. Further regional work was continued in the eastern Athabasca Basin (Jefferson *et al.*, this volume), and more detailed studies at McArthur River (Bernier *et al.*, this volume), and Key Lake, Cigar Lake, and McClean Lake (Long, this volume) were undertaken. As part of this subproject, new techniques for semi-quantitative core logging in the field were also developed (Yeo, Jefferson *et al.*, this volume) as was a database to facilitate the manipulation of the generated and compiled data. The main findings of these studies are summarized in this paper, which emphasizes their regional context (Figure 1).

A major objective of our investigations is to test and refine Athabasca Basin stratigraphy. The regional stratigraphy has received little formal attention since the reconnaissance studies of Ramaekers (1975, 1976, 1977, 1978a, 1978b, 1979, 1980, 1981, 1990) and Wilson (1985). As Yeo *et al.* (2000, Table 5) observed in the case of the Manitou Falls Formation, attempts by exploration geologists to subdivide units in more detail, have led to the development of local stratigraphic classifications, based on varying criteria, specific to individual exploration companies, regions, or even individual projects. Hence, an effort to update and unify basin stratigraphy is timely.

2. Stratigraphic Investigations in Athabasca Basin in 2001

As noted above, five stratigraphic investigations were carried out in the Saskatchewan part of the basin, while two were undertaken in the Alberta part. Three of the investigations, including Bernier's study of the McArthur River area, Collier's study of the Shea Creek area, and Kupsch's study of the Maybelle River area, are M.Sc. projects supported through Industry-NSERC-GSC-Province-University partnerships developed under the EXTECH IV project. The senior author was involved in work in both Alberta and Saskatchewan under contract to the Alberta Geological Survey and the Geological Survey of Canada.

a) Eastern Athabasca Basin

Eighteen cores additional to those reported in 2000 (Yeo *et al.*, 2000) were logged in eastern Athabasca Basin on the Hawkrock River, Dawn Lake–La Rocque Lake, Close Lake, and Wheeler River transects (Jefferson *et al.*, this volume). With these new data, a

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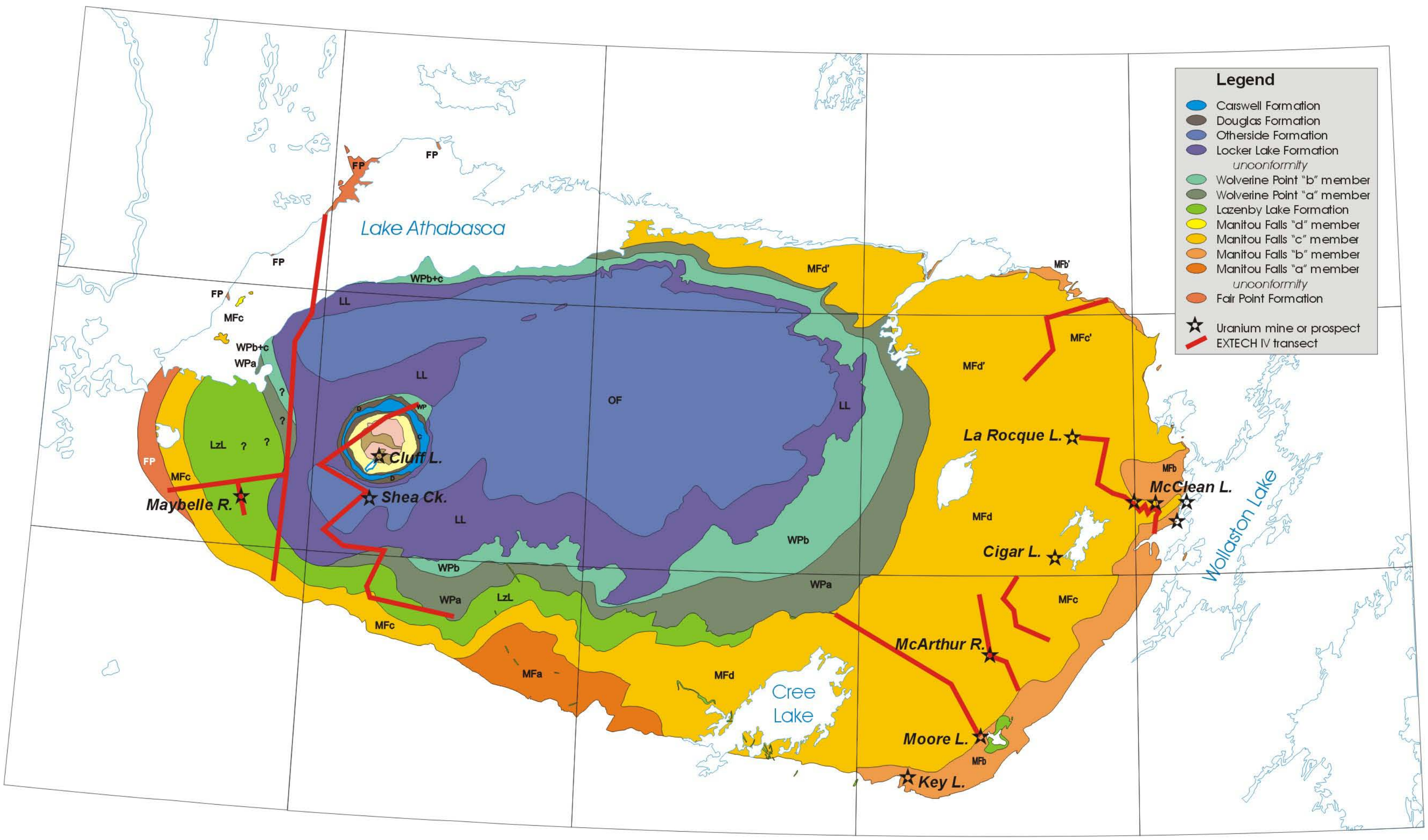

Figure 1 - Geological sketch map of Athabasca Basin, after Ramaekers (1990) and Wilson (1985). Note that formation boundaries in the western part of the basin are substantially revised. The Tuma Lake Formation is now redundant, as it is part of the Locker Lake Formation. EXTECH IV transects and study areas referred to in the text are indicated.

north-south transect, parallel to the basin margin and perpendicular to the axes of the Moosonees, Ahenakew, and Karras deposystems (Figure 2; Ramaekers, 1976, 1977) in eastern Athabasca Basin, is being constructed. Evidence for progressive growth faulting during deposition of the Manitou Falls Formation was documented in a transect at Wheeler River. Diagenetic zonation from clay mineralogy studies was related to one drill hole in the McArthur River lithostratigraphic cross section (Jefferson *et al.*, this volume).

Investigations begun in the McArthur River area last year were continued with a detailed study of 18 cores along a 40 km transect (Bernier *et al.*, this volume). The four members of the Manitou Falls Formation can be correlated in detail. Cross-beds were measured in available inclined cores (e.g. MAC-123). Results were consistent with those reported in DDH RL-99 (Yeo *et al.*, 2000) and in outcrop by Ramaekers (1981, 1990).

Continuing investigations of basal Athabasca strata in the Sue C Pit at COGEMA Resources' McClean Lake Mine, confirmed two distinct units deposited under different climatic and/or tectonic conditions and separated by a stepped erosion surface (Long, this volume). The basal unit corresponds to the MFa member of the Manitou Falls Formation, and consists predominantly of massive and flat laminated fine to very coarse-grained sandstone with minor discontinuous cobble and boulder conglomerate and rare red mudstone. These strata were probably deposited by sheet-flood and stream-flood processes, perhaps in an arid to hyper-arid climatic setting, with influxes of talus from nearby paleo-scarps. Overlying MFb strata are predominantly coarse to very coarse-grained sandstones with abundant small-scale cross-stratification and minor granule and small pebble conglomerates. These were probably deposited on a braidplain formed by semi-ephemeral to perennial braided rivers under more humid conditions than MFa, or perhaps were just more proximal within the depositional system. Architectural analysis of comparable MFb strata in the upper parts of the Deilmann Pit suggested that larger channels developed, at least locally, in more proximal parts of the basin. Granule and small pebble conglomerate layers in the Deilmann Pit developed both as basal lags and bar-side lags during rising and falling stage erosional events in ephemeral rivers.

b) Western Athabasca Basin

Ten regional cores in the western basin define a broad transect from north of the Carswell Structure to the southern margin of the basin and east as far as Hook Lake (Yeo, Collier *et al.*, this volume). The conglomeratic Fair Point Formation extended to the southern part of the Carswell Structure, but pinches out further south. Manitou Falls A sandstone, overlying either a basal conglomerate, or unconformably overlying Fair Point strata, was traced west of Carswell, while a Manitou Falls B-like pebbly sandstone was recognized locally. Lazenby Lake pebbly sandstones extend at least to the Alberta border. Wolverine Point B mudstones pinch out between Carswell and Shea Creek. As in the eastern Athabasca Basin (Yeo *et al.*, 2000), magnetite-rich heavy mineral

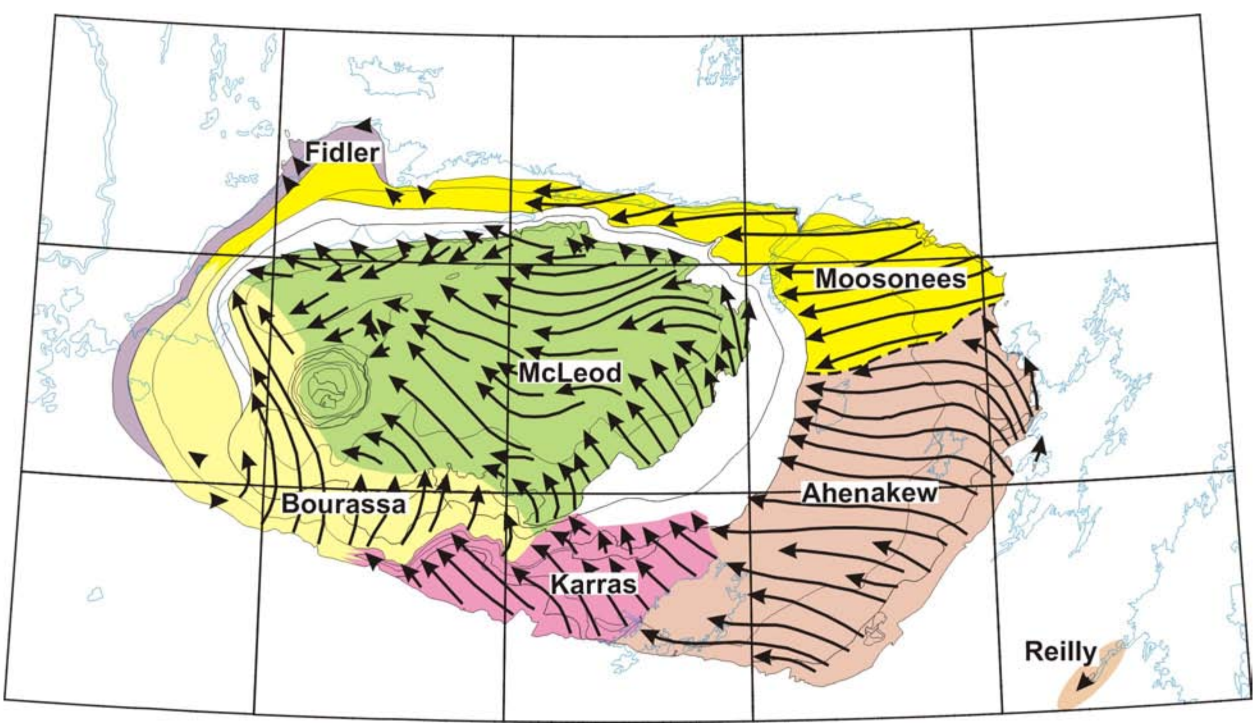

Figure 2 - Deposystems in Athabasca Basin, with generalized paleocurrent patterns.

laminae are common in lower parts of the succession. Probable soil pisolites suggest that some of the thin mudstones interbedded with fluvial sandstones are lateritic paleosols, and hence, that the intervals between floods locally may have been millennia.

A detailed study of 11 cores, mostly along a 7 km transect through the Shea Creek area, south of the Carswell Structure, was undertaken (Collier *et al.*, this volume). Two of the DDHs were previously the subject of the EXTECH IV borehole geophysical project (Mwenifumbo *et al.*, 2000). As at McArthur River and Dawn Lake, this study should provide excellent stratigraphic control for a 1997 high-resolution seismic survey conducted parallel to the Shea Creek trend. Preliminary analysis has shown that there is very strong lateral continuity of units. Lateral and vertical shifts of coarse-grained facies suggest channel migration through time.

Two holes in eastern Alberta, FC-005 and MR-65, were logged in detail as part of a B.Sc. project (Kupsch, 2001). The Fair Point to Locker Lake succession is present, but the absence of the Fair Point in the south suggests greater subsidence to the north early in basin history. The Manitou Falls and Lazenby Lake formations thicken southward, suggesting increased subsidence in the south later. The MFb and MFc members of the Manitou Falls Formation, the Lazenby Lake Formation, and three members of the Wolverine Point Formation (WPa, WPb, and WPc) are now recognized in Alberta. A detailed study of the Maybelle River area is continuing.

3. Regional Stratigraphy

Although there have been minor modifications, the overall stratigraphic framework of the Athabasca Group has stood up well to usage over the past 20 years. Many new members or sub-members, have been distinguished. The preliminary stratigraphic revision outlined here (Table 1) is based on many years of work in the basin by the senior author, as well as recent investigations by Jefferson, Yeo, and co-workers in Saskatchewan and Alberta.

Further refinements await new data from the various EXTECH projects. We realize that the present nomenclature of formation members, especially in the Manitou Falls Formation, has resulted in difficulty distinguishing between lithofacies and the members, which are defined on the basis of the dominant, but never the exclusive presence of a particular lithofacies. Further work on this problem is underway.

a) Fair Point Formation

Pebbly sandstone and conglomerate of the Fair Point Formation (FP) is restricted to the western part of the Athabasca Basin. It rests unconformably on high-grade crystalline basement rocks, greenschist grade metasediments of the Thluicho Lake Group, and unmetamorphosed strata of the Martin Group, and is unconformably overlain by the Manitou Falls Formation.

Four subunits have been distinguished in the few holes logged to date. Whether these are of regional extent remains to be seen. The FPa member is characterized by pebbly sandstones, sandstones, and siltstones, and is variably present. The FPb member is characterized by conglomerate beds, as well as pebbly sandstones and sandstones, which are commonly massive-appearing, and may be, in part, debris flow deposits. The FPb1 sub-member contains interbedded thin and thick conglomerates and sandstones, whereas the FPb2 sub-member contains thin conglomerates and pebbly sandstones. Maximum clast size in the FPa and FPb members is typically greater than 50 mm. The FPc member is similar to the FPb2 sub-member, but maximum clast size is less than 50 mm.

FP has not been recognized south or east of the Carswell Structure in Saskatchewan, but is present in the southwestern basin in Alberta. Very limited paleocurrent data (Figure 2; Ramaekers, 1981) indicate sources to the south and east. FP appears to be partly locally derived. Red sandstone pebbles, well rounded quartzite pebbles, and platy limonitic gneiss pebbles (reworked regolith?) are common over much of its range.

b) Manitou Falls Formation

The Manitou Falls Formation (MF) is a broadly upward-fining succession of sandstone, pebbly sandstone, conglomerate, and minor mudstone. It rests unconformably on crystalline basement rocks or on the Fair Point Formation, and is conformably overlain by the Lazenby Lake and Wolverine Point formations. Four informal members (MFa, MFb, MFc, and MFd) are recognized (Ramaekers, 1990). Although they are widespread, not all are present everywhere. Paleocurrent data indicate that Manitou Falls sediments were deposited in at least four deposystems (Moosonees, Ahenakew, Karras, and Bourassa; Figure 2). The informal subdivision into four members (Ramaekers, 1990) was based largely on outcrop studies, and is representative of the most widely exposed Ahenakew Deposystem. The member definitions of some units are ambiguous for much if not all of the Moosonees Deposystem and supplementary definitions are presented here for that area.

The MFa member comprises sandstones, pebbly sandstones, and siltstones. Low angle cross-bedding and large disseminated pebbles are common. The siltstones are largely confined to a variably present basal unit: MFa1. The overlying siltstone-poor unit is referred to as MFa2.

The MFb member is characterized by sandstone with >2% interbedded conglomerate. For purposes of the MFb definition a conglomerate is defined as a bed >2 cm thick consisting of more than 30% clasts greater than 2 mm in diameter.

Table 1 - Stratigraphic summary of the Athabasca Group. Note that this is very much a "work in progress", and some of the sub-members indicated here are restricted in their occurrence; MTG, maximum transported grain.

Subgroup	Formation	"Member"	Lithology	Saskatchewan (Ramaekers, 1990)	Alberta (Wilson, 1985)
Points Lake	Carswell	CF	Dolostones; stromatolites, ooids, and synsedimentary breccia common	CF	Not present
	Douglas	DF	Very fine sandstones, siltstones, black, red, and green mudstones; load casts, mud and syneresis cracks common	DF	Not present
William River	Otherside	OFb	Fine sandstones; MTG <2mm; clay intraclasts	OF, undiff.	OF, undiff.
		OFa	Fine sandstones with granules and pebbles <8 mm; clay intraclasts	OF, undiff.	OF, undiff.
	Locker Lake	LLc	Fine to coarse pebbly sandstones; minor silt and mudstones; MTG 8-16 mm	LL, undiff.	LL, undiff.
		LLb	Fine to coarse pebbly sandstones; minor silt and mudstones; MTG >16 mm; horizontal and low-angle cross-bedding	LL, undiff.	LL, undiff.
		LLa	Fine to coarse pebbly sandstones; minor silt and mudstones; MTG 2-16 mm	LL, undiff.	LL, undiff.
	unconformity				
	Wolverine Point	WPc	Very well-sorted, clay rich, fine to medium sandstone, minor siltstone and mudstone	WPb	WPb
		WPb3	Very fine to medium sandstone, mudstone thicker than 20 cm, tuffaceous relicts; small intraclasts in thin beds	WPb	WPb
		WPb2	Very well-sorted, clay rich, fine to medium sandstone, minor siltstone, and mudstone	WPb	WPb
		WPb1	Very fine to medium sandstone, mudstone thicker than 20 cm, tuffaceous relicts; small intraclasts in thin beds	WPb	WPb
		WPa2	Very fine to coarse sandstones	WPa	WPa
		WPa1	Very fine to coarse sandstone, minor thin siltstone and mudstone	WPa	WPa
	Lazenby Lake	LzL	Basal thin conglomerate, pebbly and coarse to fine sandstones	LzL	Not recognized
	Manitou Falls	MFd MFd'	Fine to medium sandstone; clay intraclasts >2% of rock Fine to coarse sandstone; pebbly sandstone; intraclasts >2% of rock (Moosonees Deposystem)	MFd MFd	MFd MFd
		MFc MFc'	Medium to coarse and pebbly sandstone; intraclasts <2% of rock Medium to coarse and pebbly sandstone; minor silt and mudstone; intraclasts <2% of rock (Moosonees Deposystem)	MFc MFc	MFc MFc
		MFb	Medium to coarse sandstone, pebbly sandstone, conglomerate	MFb	MFb
		MFa2	Pebbly sandstone and conglomerate; horizontal and low-angle cross-bedding common	MFa	Not recognized
		MFa1	Fine to coarse sandstone with disseminated pebbles, mudstones; horizontal and low-angle cross-bedding common	Not recognized	Not recognized
	unconformity				
	Fair Point	FPc	Pebbly sandstone, sandstone; MTG <50 mm; horizontal and low-angle cross-bedding common	FP, undiff.	FP, undiff.
		FPb2	Pebbly sandstone, sandstone, thin conglomerates; MTG >50 mm; horizontal and low-angle cross-bedding common	FP, undiff.	FP, undiff.
		FPb1	Conglomerate and sandstone; horizontal and low-angle cross-bedding common	FP, undiff.	FP, undiff.
		FPa	Conglomerate, pebbly sandstone, sandstone, siltstone; horizontal and low-angle cross-bedding common	FP, undiff.	FP, undiff.
	Basal lag		Disseminated or bedded pebbles to boulders in sandstone		

The MFc member is characterized by sandstone with one-clast-thick pebble beds on bedding planes, scattered pebbles, or clay intraclasts, and less than 2% conglomeratic beds. In the Moosonees Deposystem this member, distinguished as MFc', commonly contains thin and thinly laminated fine to very fine sandstones, siltstones, and mudstones, commonly mapped as 'shales' in drill logs. A very well sorted, almost pebble and intraclast free sandstone unit is present in the Bourassa Deposystem. It is included in the MFc here, but may ultimately prove to be a distinct unit.

The MFd member is characterized in the Ahenakew Deposystem by sandstone with relatively abundant (>1%) clay intraclasts, and a nearly total absence of pebbles. Within the member, the clay pebble-rich beds alternate with beds containing fewer or no intraclasts. Clay pebble content may be greater than 30%. It may be possible to further subdivide the member on the basis of intraclast abundance. In the Moosonees Deposystem, the clay pebble variation of this member, distinguished as MFd', is similar to that of the Ahenakew Deposystem, but the sandstones are coarser, and contain disseminated small to medium pebbles and one-pebble-thick layers throughout.

Paleocurrent data (Figure 2; Ramaekers, 1981) indicate that the Manitou Falls Formation was derived from south, east, and northeast of the basin. Previously, only the MFc and MFd members were recognized in the western part of the basin (Ramaekers, 1990), but studies based on drill core show that the MFa and MFb members are also present at the base of the formation in the west-central part of the basin, although they are much thinner and finer grained there than in the eastern part of the basin. The MFd member appears to be absent through much of the Alberta part of the basin

c) Lazenby Lake Formation

The Lazenby Lake Formation (LzL) comprises a local, thin basal conglomerate or pebbly sandstone, overlain by pebbly sandstone, and coarse to fine sandstone with minor mudstone. It is restricted in outcrop to the southern and western parts of the basin. It lies conformably on the MFc and d members of the Manitou Falls Formation, and is conformably overlain by the WPa member of the Wolverine Point Formation. In the southwestern part of the basin, where the Wolverine Point Formation is absent, it is overlain by the Locker Lake Formation. Rare, thin conglomerates are present, but pebbles are mostly disseminated. Low angle cross-bedding is typical. Because its basal beds contrast strongly with the underlying MFc and MFd members, its base is an excellent marker horizon. The upper contact is locally more difficult to place due to lack of contrasting lithofacies and lithologic similarity with the Locker Lake Formation. In the Carswell area, LzL commonly coarsens up and intraclasts appear, with abrupt reduction to fine sand at the base of WPa.

Although not previously recognized in Alberta (Wilson, 1985), the Lazenby Lake Formation can now be traced throughout the western half of the basin. Limited paleocurrent data (Figure 2; Ramaekers, 1978a, 1981), as well as easterly and northerly thinning, indicate a source to the southwest.

d) Wolverine Point Formation

The Wolverine Point Formation (WP) comprises sandstone, siltstone, mudstone, and claystone found throughout the central and western part of the basin. It rests conformably on the Lazenby Lake Formation in the western part of the basin and on the MFd member of the Manitou Falls Formation in the northern and eastern part of the basin, in places with minor unconformity, possibly a ravinement surface.

To date, three informal members have been distinguished in this formation, but recent work suggests that more units may prove to be locally mappable.

The WPa member is characterized by beds of thin (typically 5 to 20 cm) siltstone and mudstone and rare pebbly layers in coarse to very fine sandstones. It comprises two widespread sub-members. The WPa1 sub-member is characterized by sandstone with minor mudstone, whereas the overlying WPa2 sub-member is characterized by sandstone only. In the Carswell area, the upper WPa2 sub-member contains abundant clay intraclasts (WPa3 sub-member of Yeo, Collier *et al.*, this volume). Ongoing work suggests that a number of other units of the WPa may prove to be mappable over parts of the Athabasca Basin.

The WPb member comprises siltstone, mudstone, and claystone beds thicker than 50 cm. Three sub-members are recognized. The WPb1 sub-member is composed of interbedded very fine to medium sandstone and distinctive, very fine sandstone to claystone characterized by rare, small, commonly rounded, hard intraclast layers. In places, both mudstones, intraclasts, and the sandstones are tightly cemented by apatite that has replaced volcanic glass shards. The apatite variously contains intergrown hematite and is variably uraniferous. The WPb2 sub-member is characterized by very well-sorted, clay-rich, fine to medium sandstone and minor siltstone. Because of the washing out of the interstitial clay from the sandstones, the core commonly has a rough appearance, making it appear to consist of coarser sand than is actually present. It is typically mottled with irregular purple bands 5 to 15 cm wide. The WPb3 sub-member is similar to the WPb1 sub-member, but is usually much thicker. It is commonly sideritic. The siderite is typically partly altered to hematite, giving the core a finely mottled pink appearance. The WPc member comprises very well sorted, clay-rich, fine to medium sandstone and minor siltstone, and is lithologically similar to the WPb2 sub-member.

The greatest thicknesses of fines (claystones and siltstones) in the Wolverine Point Formation are along the northern margin of the basin (Ramaekers, 1990, Figure 17). This year's studies in the Cluff Lake area

(Yeo, Collier *et al.*, this volume) show that the fine-grained strata pinch out toward the southwest, suggesting a possible topographic high there during Wolverine Point times and/or before deposition of the Locker Lake Formation.

The clay-rich Wolverine Point Formation is relatively soft, poorly lithified, weathers recessively, and has been preferentially excavated by glaciation wherever it subcrops. As a result it is poorly exposed. It forms an aquitard, with prominent Fe-rich springs where its lower and upper boundaries reach the surface.

Due to its poor exposure, little is known about paleocurrents in the Wolverine Point Formation; hence it is represented as a data gap in the Deposystem map (Figure 2). Data from the few outcrops available suggest that the paleocurrent variance may be higher than in the other sandy units (Ramaekers, 1990).

e) Locker Lake Formation

The Locker Lake Formation (LL) comprises pebbly, clay-poor sandstone with thin conglomerate beds and minor mudstone. It is a relatively resistant unit, and forms prominent escarpments along its northern and eastern contacts (Ramaekers, 1990). It is restricted to the central and western parts of the basin, but approaches the southern basin margin at the Alberta-Saskatchewan border. It rests unconformably on the Wolverine Point or Lazenby Lake formations. An unconformity is suggested by unmetamorphosed sandstone clasts (Ramaekers, 1990), the abrupt appearance of coarse detritus, and the change from the arkosic (prior to diagenesis) to subarkosic sandstones of the Wolverine Point Formation to the quartzitic sandstones of the Locker Lake Formation.

On the basis of maximum grain size, three members are distinguished. The LLa member is characterized by maximum grain sizes from 2 to 16 mm. The LLb member is distinguished by maximum grain sizes greater than 16 mm. The LLc member is characterized by maximum grain sizes from 8 to 16 mm. Low angle cross-bedding is present in all three members. Slump structures, and overturned cross-beds are also common.

Paleocurrent data (Figure 2; Ramaekers, 1981) indicate derivation from the south and southeast.

f) Otherside Formation

Sandstone and pebbly sandstone of the Otherside Formation (OF) occupy the central area of the basin. It lies conformably on the Locker Lake Formation, but relationships with the overlying Douglas Formation are obscured by faulting.

Two members are distinguished. The OFa member is characterized by sandstone with disseminated granules and pebbles up to 8 mm, whereas the OFb member is characterized by sandstone only.

Paleocurrent measurements (Figure 2; Ramaekers, 1981) indicate derivation from the southeast, east, and northeast, with a higher variance than most of the underlying sandy units (Ramaekers, 1990).

An apparent other pebbly sandstone, the Tuma Lake Formation, was formerly considered to overlie the Otherside Formation (Ramaekers, 1979, 1981, 1990). By integrating the work of Wilson (1985), the Tuma Lake Formation is now shown to be part of the Locker Lake Formation, uplifted in a hook-shaped arch around the western margin of the Carswell Structure and extending northwest along the Grease River Fault Zone (Figure 1).

g) Douglas Formation

Sandstones and green, red, or black mudstones of the Douglas Formation are restricted to the Carswell Structure. The black mudstones are the only ones known in Athabasca Basin. Syneresis and mudcracks are well developed in the mudstones. Faults commonly separate the Douglas Formation from the underlying Otherside Formation, although their stratigraphic relationship is probably conformable.

h) Carswell Formation

Carswell Formation dolostone conformably overlies the Douglas Formation and is also restricted to the Carswell Structure. Features include a variety of stromatolites, ooids, and abundant synsedimentary breccia. Conical stromatolites form a distinctive marker bed in the northern part of the Carswell Structure (Hendry and Wheatley, 1985).

4. Discussion

a) Regional Stratigraphic Relationships

The Athabasca Group was subdivided into two subgroups: the William River Subgroup, comprising the Fair Point, Manitou Falls, Lazenby Lake, Wolverine Point, Locker Lake, and Otherside formations; and the Points Lake Subgroup, comprising the Douglas and Carswell formations (Ramaekers, 1981, 1990). These subgroups separate the lower, predominantly sandy units from the upper, predominantly fine-grained and carbonate units, and serve mainly to distinguish these units within the Carswell Structure where intense disruption makes it very difficult to discriminate formations within the William River Subgroup.

b) Sequence Stratigraphy of the Athabasca Group

The Athabasca Group is now interpreted to include three sequences, bounded by unconformities: the basal Fair Point sequence, the middle Manitou Falls–Wolverine Point sequence, and the upper Locker Lake–Carswell sequence. All formations, except the

Douglas and Carswell, are now considered to be predominantly fluvial.

The Athabasca Group is generally underlain by a major unconformity separating greenschist to granulite grade metamorphosed rock below from strata that were subjected to deep burial diagenesis bordering on the lower end of zeolite grade metamorphism. The Athabasca Group unconformably overlies Martin Group strata that differ very little in metamorphic grade.

The unconformities that separate the three sequences record the passage of enough time to permit a sudden change of sediment type (quartz arenite and lithic quartz arenite overlying arkoses and subarkoses), and the abrupt cessation (e.g. Fair Point to Manitou Falls) or influx (e.g. Wolverine Point to Locker Lake) of coarse detritus. Each sequence represents a large upward fining cycle, most likely reflecting uplift in the source regions and/or climate changes. There is no evidence thus far for dramatic downcutting accompanied by progradation of coarse strata at the base of these cycles, which would be expected if lowered base level due to sea-level fluctuation were a factor. The base of most coarse-grained units appears to be conformable, or even transitional. Indeed, there is no evidence for any marine influence until late in the third major cycle, if there is any at all. Sequence stratigraphic methods have been applied in the Athabasca and other Precambrian Basins (Hiatt, 2000; Krapez, 1996, 1997), although sea-level fluctuation does not appear to have been a control on sedimentation in Athabasca Basin. Sequence analysis in the epicratonic Athabasca Group must be based on fluctuations in sedimentation rate and accommodation space due to a variety of tectonic and climatological developments rather than the passive ocean margin sea-level changes on which traditional sequence stratigraphy is based.

Sandstone pebbles in the Fair Point and, more rarely, Manitou Falls formations might indicate a hiatus long enough to permit lithification, but more likely reflect the influx of detritus from weakly or unmetamorphosed older Proterozoic strata (e.g. Martin, Hurwitz, Dubawnt, or Thluicho Lake groups).

Smaller cycles and lesser discontinuities are evident throughout the Athabasca Group, as is to be expected in a predominantly fluvial depositional succession.

The Fair Point Sequence

The abundance of clay pseudomorphs after detrital feldspar grains within the Fair Point Formation indicates rapid deposition, high rates of erosion, and a proximal source. Restriction of the Fair Point Formation to the western Athabasca Basin, and limited northwesterly directed paleoflow data in the Fidler Deposystem (Figure 2; Ramaekers, 1978b) suggest that these strata were largely derived from the Clearwater/Western Granulite Domain. Overall, the Fair Point Formation fines upward, suggesting its deposition followed a pulse of uplift or subsidence. Low angle cross-beds suggest that sheet floods were common.

The Manitou Falls–Wolverine Point Sequence

The second sequence records clastic input from several directions into distinctive depositional systems, referred to as the Bourassa (southwest), Karras (southeast), Ahenakew (southeast and east), and Moosonees (northeast) deposystems (Figure 2; Ramaekers, 1976, 1977, 1978a, 1978b). Two large, upward-fining cycles are distinguished in all but the Moosonees Deposystem: the Manitou Falls cycle and the Lazenby Lake–Wolverine Point cycle (variations in stratigraphy and paleocurrent directions within the Manitou Falls cycle suggest that the Moosonees and perhaps the Bourassa deposystems originated at different times from the others, and, and perhaps should be distinguished as separate stratigraphic units). At least locally within the Manitou Falls Formation, three lower order upward-fining cycles are apparent: the basal conglomerate – MFa cycle, the MFb – lower MFc cycle, and the upper MFc-MFd cycle.

The second sequence of the Athabasca Group seems to have developed asymmetrically. In the Bourassa, Karras, and Ahenakew deposystems the coarse units show more northerly to northeasterly directed paleocurrents than the generally westerly directed paleocurrents seen in the finer grained units. The Wolverine Point Formation shows an increase in the finer grained clastics towards the northern side of the basin. This suggests that at times of high rates of sediment input the usual axial east-west flow within the basin was overwhelmed by input from the southern margin. It may also indicate greater subsidence along the northern margin, at least during Wolverine Point times.

Glassy volcanic material and tuff fragments in the Manitou Falls and Wolverine Point formations and their absence (to date) in the overlying units suggest that the middle sequence may have been deposited at the time of the Pitz volcanics (1753.7 ±1.6 to 1757.6 ±3.3 Ma, U-Pb zircon, Rainbird and Hadlari, 2001) and Nueltin intrusions (1751 +5/-3 to 1756 ±11 Ma, U-Pb zircon, Peterson and Van Breeman, 1999) in the Baker Lake and Thelon basins. Note that the Moosonees Deposystem source area lies to the northeast, within 200 km of some of the Nueltin intrusions.

The Locker Lake–Carswell Sequence

The third sequence records input from the south, southeast, and northeast into the McLeod Deposystem (Figure 2; Ramaekers, 1978b). The lower, Locker Lake–Otherside–Douglas succession is comparable to the Lazenby Lake–Wolverine Point pebbly sandstone–sandstone–mudstone succession, but is capped by carbonates of the Carswell Formation. In contrast to the underlying cycles, which appear to be predominantly fluvial, the Carswell and much of the

Douglas Formation are shallow, quiet water, possibly saline deposits. To what extent they are lacustrine or marine remains uncertain.

The asymmetric development of the basin that controlled deposition of the preceding sequence continued, with generally westerly paleocurrents in the finer grained Otherside Formation units. The coarser Locker Lake units show northerly and northwesterly directed paleocurrents right across the basin to their northern limits.

The increasing amounts of claystones and the abundant presence of syneresis cracks in the upper units of the Douglas Formation may indicate a transition to a brackish water depositional environment. The overlying stromatolitic, oolitic dolostones of the Carswell Formation suggest that a fully marine, or saline lacustrine environment developed at the conclusion of Athabasca Group deposition.

c) Stratigraphic Terminology

With the introduction of numerous sub-members, the stratigraphic terminology of the Athabasca Group has become increasingly awkward, and consideration should be given to a major revision: raising the members to formation status (i.e. defining type sections for all of them), making or re-combining the established formations into groups, and naming the entire succession the Athabasca Supergroup.

There is a need to get away from a lithofacies-based stratigraphic *nomenclature*, especially for members, whether formal or informal. The present system makes discussion of the stratigraphy cumbersome and confusing, because it invites use of member *names* to identify lithofacies. This is particularly the case with the Fair Point, Manitou Falls, Wolverine Point, and Locker Lake formations. The result is that the presence of a subordinate lithofacies within a member tends to be ignored or mapped with a member designation rather than a proper lithofacies designation. Examples of such misuse may be found in the paper first defining the current stratigraphic scheme (Ramaekers, 1990).

Related to this is the need to describe the differing stratigraphies within the various deposystems. For example, the Manitou Falls subdivisions, as presently used, were largely based on work in the Ahenakew Deposystem, and they cannot be convincingly applied to the strata of the Moosonees Deposystem. Type descriptions for the different deposystems and proximal-distal and transverse cross sections for each would help delineate these differences. The EXTECH stratigraphy sub-project has made progress toward this for the Ahenakew (Bernier *et al.*, this volume; Jefferson *et al.*, this volume), and Bourassa (Yeo, Collier *et al.*, this volume) deposystems.

There is a need to establish a better and more complete set of lithofacies definitions and descriptions. This is another item on which the EXTECH project has made significant progress.

A related need is better description and mapping of the major unconformities, their varied expressions in drill holes, and their significance. As in all unfossiliferous orthoquartzite-dominated successions, unconformities are commonly difficult to recognize within the Athabasca Group. In Phanerozoic sequences such features are usually identified using paleontologic dating, trace fossils, and root zones, rather than the purely sedimentologic methods available for work in Precambrian strata. Major unrecognized unconformities may be present between Manitou Falls strata of the Ahenakew and Moosonees deposystems, the Bourassa and Karras deposystems, and between the MFa member and overlying units.

We must be careful to distinguish between the lithostratigraphic description and nomenclature such as that used at present, and the chronostratigraphic description of the Athabasca Group. Most lithostratigraphic units of the Athabasca Group are likely to be diachronous. The detailed, metre-by-metre descriptions generated by the EXTECH IV teams, as well as many company geologists, may make this possible in the future, if not before the end of the EXTECH project.

d) Tectonic Implications

With the exception of the Wolverine Point B member, and the Douglas and Carswell formations, relatively coarse-grained strata predominate in Athabasca Basin. This infers that sediment accumulation or relative basin subsidence, was not gradual, but relatively rapid. Cyclic sedimentation suggests that such subsidence was episodic. Uplift in the source regions outside the basin or along fault zones within the basin, in response to tectonism or climate change, possibly induced by tectonism, is more likely than slow intracratonic thermal subsidence. Fluctuations in the rate of sediment supply due to climate change may also have been a factor. The continuing contraction of the crust between the Slave and Superior plates may have been one source for the tectonism.

Overall upward fining in each of the three sequences suggests a progressive increase in distance from source. This might reflect the eastward retreat of the areas of uplift and tectonic activity over time. Sedimentation in the Athabasca Basin reflects a continued eastward shift in the locus of successive late Paleoproterozoic sedimentary basins, including the pre-Athabasca Nonacho/Thluicho Lake and Martin basins.

The proximal character of the Fair Point Sequence suggests derivation from the Clearwater Domain area and indicates that this was still a topographically positive feature in Fair Point time.

Paleocurrent directions indicate a number of source areas for the second sequence of the Athabasca Group. The Moosonees Deposystem paleocurrents and the volcanic relics seen in the Wolverine Point Formation, suggest derivation of much of the second sequence detritus from the northeast, where there may have been uplifts associated with the Nueltin intrusions and their extrusive equivalents, of which the Pitz Formation is prominent in the Baker Lake and Thelon Basin area. If this is the case, then the second sequence of the Athabasca Group has an age of about 1760 to 1750 Ma. The recurring evidence of southern source areas suggest uplift to the south, perhaps related to the 1.78 to 1.69 Ga Central Plains Orogeny (Sims and Peterman, 1986; Klasner and King, 1990). A series of folds to the southeast of the Athabasca Basin and deep, low-angle reverse faults on the LITHOPROBE seismic sections have been interpreted (e.g. Hajnal *et al.*, 1996) as due to post-collisional contraction of the Trans-Hudson Orogen, Hearne, and Rae provinces over an extended interval (1800 to 1700 Ma). The uplifts associated with these were the probable source areas for much of the detritus of the Ahenakew, Karras, and Bourassa deposystems.

The third and latest sequence suggests initial derivation from the south during a period of rapid erosion, possibly also related to the Central Plains Orogeny. This was followed by easterly transport of sediment during a period with less relief. The youngest dated uplifts (about 1720 Ma) to the east of the Athabasca Basin are associated with Phase 2 of the Reindeer-Superior collision (Machado, 1990), and these may be responsible in part for the third depositional sequence of the Athabasca Group.

The uplifted exposures of Locker Lake Formation to the south of the Grease River Fault indicate that there was minor post-depositional movement along the Grease River Fault where it underlies the Athabasca Group.

Preservation of the Douglas and Carswell formations in the rim of the Carswell Structure is due to subsidence in compensation for the rapid uplift of crystalline basement in the core of the structure, during its formation in the early Paleozoic.

e) Implications for Exploration

All of the major uranium deposits found to date in the Athabasca Basin occur at the base of the Manitou Falls Formation, although the Maybelle River prospect is located at the base of the Fair Point Formation. Recognition that the Fair Point Formation extends southeast, beneath the Carswell Structure and the Cluff Lake deposits, confirms that it is the generation of a hydrothermal system associated with a redox trap, and not the specific overlying strata, that is the critical stratigraphic control on uranium mineralization.

EM surveys are commonly carried out in Athabasca Basin to identify basement conductors caused by graphitic pelite and/or fault zones which are, in turn, potential controls on uranium mineralization. The presence of thick pelites, including black shales, in the WPb member inhibits the effectiveness of EM surveys north and east of the Carswell Structure. The erosion or nondeposition of the WPb unit south of the Carswell Structure thus facilitated geophysical exploration and the discovery of the Shea Creek zone.

The Wolverine Point Formation is an aquitard and deflects rising deep formation water to its lower subcrop margins. Thus, geochemical anomalies from waters that may have sampled unconformity mineralization may have been displaced from their source below the WP Formation to the margins of the WP subcrop belt.

5. Conclusions

A team of university, geological survey, and industry geologists is continuing both regional, deposystem-scale, and local, detailed studies of stratigraphy in the eastern and western Athabasca Basin. Results of this work are described in detail in other papers in this volume. The map "border fault" in western Athabasca Basin is now resolved.

Three, upward fining, unconformity-bounded sequences are distinguished in the Athabasca Group: the Fair Point, Manitou Falls–Wolverine Point, and Locker Lake–Carswell sequences. They reflect episodic uplifts to the north, east, and south, probably in response to distal tectonic events. Six distinctive deposystems are recognized in the basin. The Fidler and McLeod deposystems are respectively associated with the Fair Point and Locker Lake–Carswell sequences. The Moosonees, Ahenakew, Karras, and Bourassa deposystems are all associated with the Manitou Falls–Wolverine Point sequence.

Exploration in the Athabasca Basin over the last 15 years has highlighted several problems with the current description of the Athabasca Group stratigraphy. An ultimate goal of the EXTECH IV stratigraphy sub-project should be to revise the stratigraphy in light of our increased knowledge of the basin. We need to develop distinct stratigraphic nomenclature, lithofacies descriptions, and chronostratigraphic subdivisions for the Athabasca Group. We also need to continue to document the characteristics of each deposystem, and the relationships among them, and look for evidence for cryptic unconformities.

There is a need for a 3D diagenetic description of the basin, one of the most useful regional level exploration tools (e.g. Jefferson *et al.*, this volume). Such a set of maps and sections should discriminate between diagenetic and lithostratigraphic facies. Primary, depositional mineral assemblages (locally preserved in areas of early complete cementation or lack of permeability), early diagenetic mineral assemblages, deep burial or "hydrothermal" diagenetic mineral assemblages, and late diagenetic assemblages related to unroofing of the basin should be distinguished. Better understanding of the regional aspects of "hydrothermal" alteration is needed (e.g. the temperature differences within a single hydrothermal cell at a given time). Hand-specimen criteria to distinguish some of these diagenetic facies would be useful. It may also be important to determine to what extent the diagenetic facies are affected in their expression by early differences in the permeability of the sediment.

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