Detailed Stratigraphy and Facies Analysis of the Paleoproterozoic Athabasca Group along the Shea Creek–Douglas River Transect, Northern Saskatchewan

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Abstract

Five 3rd-order sequences have been identified in twelve drill cores along the Shea Creek–Douglas River transect south of the Carswell structure in the western Athabasca Basin. In ascending order these are: "Shea Creek", "Lower Manitou Falls", "Upper Manitou Falls", Lazenby Lake–Wolverine Point, and Locker Lake sequences. Sequence boundaries have been chosen on the basis of grain size and sedimentary structures. Sharp unconformable contacts are only observed at the Manitou Falls–Lazenby Lake boundary, where possible biofilm indicators suggest a hiatus in sedimentation. Elsewhere, sequence boundaries appear conformable or are difficult to distinguish from local erosional discontinuities. In these cases, sequences and their respective depositional environments are defined on the basis of sedimentary structures. The lowest sequence in the Athabasca Group, the "Shea Creek sequence", has not previously been distinguished from the overlying Manitou Falls Formation. It is differentiated from the latter on the basis of primary sedimentary structures. Features such as larger scale trough and planar cross-stratified bed forms suggest deposition from perennial braided streams. Low-angle cross- and flat-laminated units suggest flash floods. Inversely graded pinstripe lamination, and possible impact ripples may indicate thin-bedded aeolianites. Their preservation supports a relatively humid setting and a high water table. The better sorting of the "Shea Creek sequence" sandstones resulted in greater permeability than the overlying semi-perennial to ephemeral river deposits. As a result, these sandstones, especially the flat-bedded units, could have acted as preferred conduits for fluid flow along the basal unconformity. Up to 25% flat-laminated and low-angle inclined sandstone beds in the "Lower Manitou Falls" suggest an ephemeral to "flashy" fluvial system. Absence of these types of sandstones near the base of the "Upper Manitou Falls 1" sub-member suggests a semi-perennial or perennial system, but they reappear as low frequency interbeds in the "Upper Manitou Falls 2" sub-member and gradually increase to 10% toward the Lazenby Lake contact, indicating a return to more ephemeral stream conditions. The Lazenby Lake–Locker Lake succession represents a more mud-rich system, with twenty times more fine sediment interbeds than in the Manitou Falls Formation. Up to 20% convoluted/overturned bedding at all levels throughout the Lazenby Lake–Locker Lake succession may be a result of frictional drag in a high-energy flow regime. These strata were deposited in a semi-perennial fluvial system.

Keywords: *Athabasca Group, Proterozoic fluvial systems, terrestrial sequence stratigraphy, Shea Creek sequence.*

1. Introduction

Twelve drill cores have been logged in detail along the north-northwesterly-trending Shea Creek–Douglas River transect south of the Carswell structure in western Athabasca Basin (Figure 1). An additional core was logged 7.5 km west of Shea Creek (DDH ERC-1) to determine variability to the west. Eighteen parameters were recorded at 1 m intervals through approximately 700 m of Athabasca Group sandstone. Five key variables proved to be most useful (e.g., Figure 2): MTG (maximum elongation of grain size); percent of coarse-grained beds (those containing granules and pebbles); percent of muddy beds (mud-bearing sandstone/mudstone); percent of "fines" (massive-appearing, clay-deficient siltstone/very-fine sandstone), and percent of clay intraclasts. The strata at Shea Creek were originally subdivided according to Ramaekers' (1990) stratigraphic framework (Table 1; Collier *et al*., 2001), but the succession is here re-subdivided following sequence stratigraphic principles. MTG is the most useful lithologic parameter. The aim of fieldwork in 2002 was to examine the relationship between grain-size characteristics and sedimentary structures. These data were used to delineate facies associations. All numerical analyses of sedimentary structure data are based on diamond drill hole (DDH) SHE-06, with the exception of the basal sandstones in DDH SHE-22.

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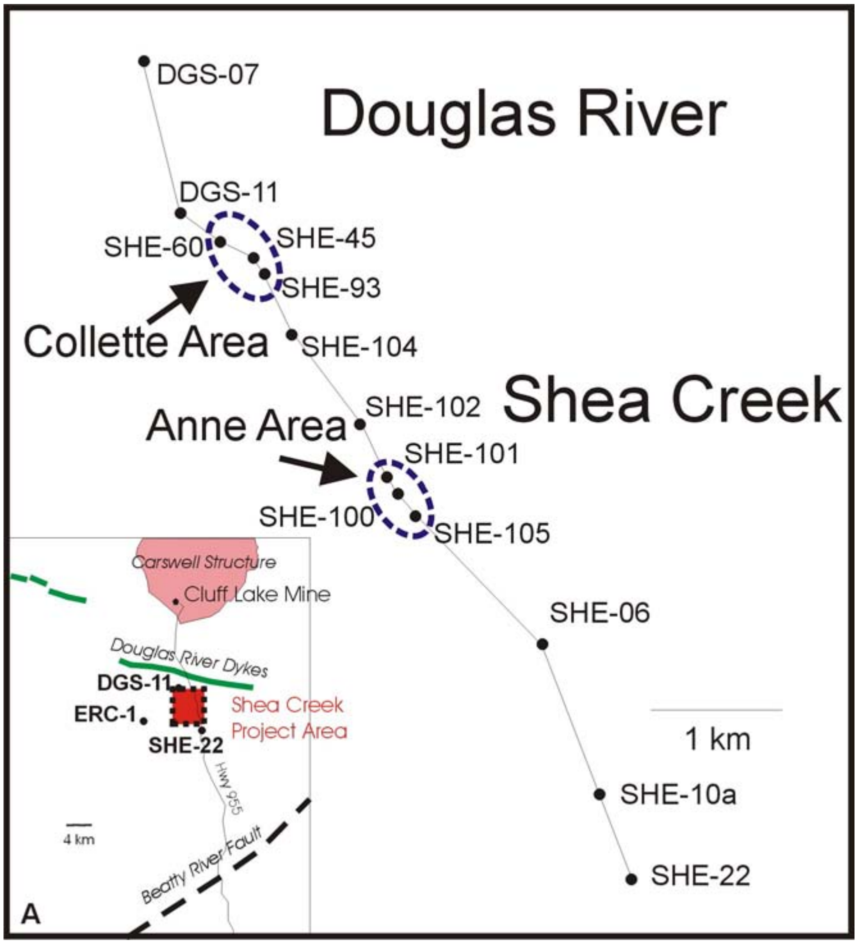

Figure 1 - Location map showing drill holes logged on the Shea Creek–Douglas River transect.

a) Purpose and Objectives

The relative abundance and scale of primary sedimentary structures has been largely ignored in previous studies of core from the Athabasca Basin because the sandstones are typically very uniform over thick intervals, making subtle differences difficult to distinguish. Vertical trends of primary sedimentary structures have not previously been used to differentiate units (e.g., Jefferson *et al*., 2001), as only their occurrence was recorded and not their frequency. Detailed documentation of the types and frequency of sedimentary structures should be useful for identifying changes in sedimentary style, depositional trends, and sequence boundaries. Such data may also be useful for analyzing strata in the eastern basin, and may act as a foundation for basin-wide correlations among fluvial sub-systems.

b) Procedure

DDH SHE-06, located south of the Anne mineralized zone (Figure 1), was selected for detailed analysis (Figure 2) because the low frequency of fractures and hematite staining in this core facilitated recognition of sedimentary structures. Primary features recognized are listed in Table 2. Their abundance was recorded in 1 m intervals. Distinction of flat lamination (Sh) from low-angle cross-beds (Sl) in core was difficult. Only where beds were associated with mud drapes was identification of the former unambiguous. Secondary structures, including convolute and overturned bedding, were also recorded. Each section of core was removed and rotated, to insure that no structures were miss-identified. This helped separate co-sets with similar dip directions that otherwise might have been interpreted as larger bed forms.

The data were manipulated in a spreadsheet and plotted using graphic logging software (LogPlot 2001). The abundances of primary sedimentary structures were normalized over intervals with abundant fracturing, core-loss, or convoluted/overturned bedding. These plots were compared with the other five “key” parameters, which were recorded without rotating the core.

c) Stratigraphic Nomenclature in the Manitou Falls Formation (MF)

The original definition of the members of the Manitou Falls Formation (MF) is biased toward observations in the Ahenakew deposystem of the eastern Athabasca Basin (Ramaekers, 1979, 1990; Ramaekers *et al*., 2001). Although Ramaekers’ (1990) subdivision of the Manitou Falls Formation has been applied in the western Karras-Bourassa depositional system of southwestern Athabasca Basin (Ramaekers, 1990; Mwenifumbo *et al*., 2000; Yeo *et al*., 2001, this volume; Collier *et al*., 2001), which includes the Shea Creek area, there have been difficulties because of differences in stratigraphy across the basin. This paper proposes a significant revision of stratigraphic nomenclature for the Manitou Falls Formation in the Shea Creek area.

The basal 170 m of strata at Shea Creek were originally assigned to the MFc and MFd members (e.g., Mwenifumbo *et al*., 2000). Two stratigraphically distinct units are recognized in this interval, but neither can be correlated with

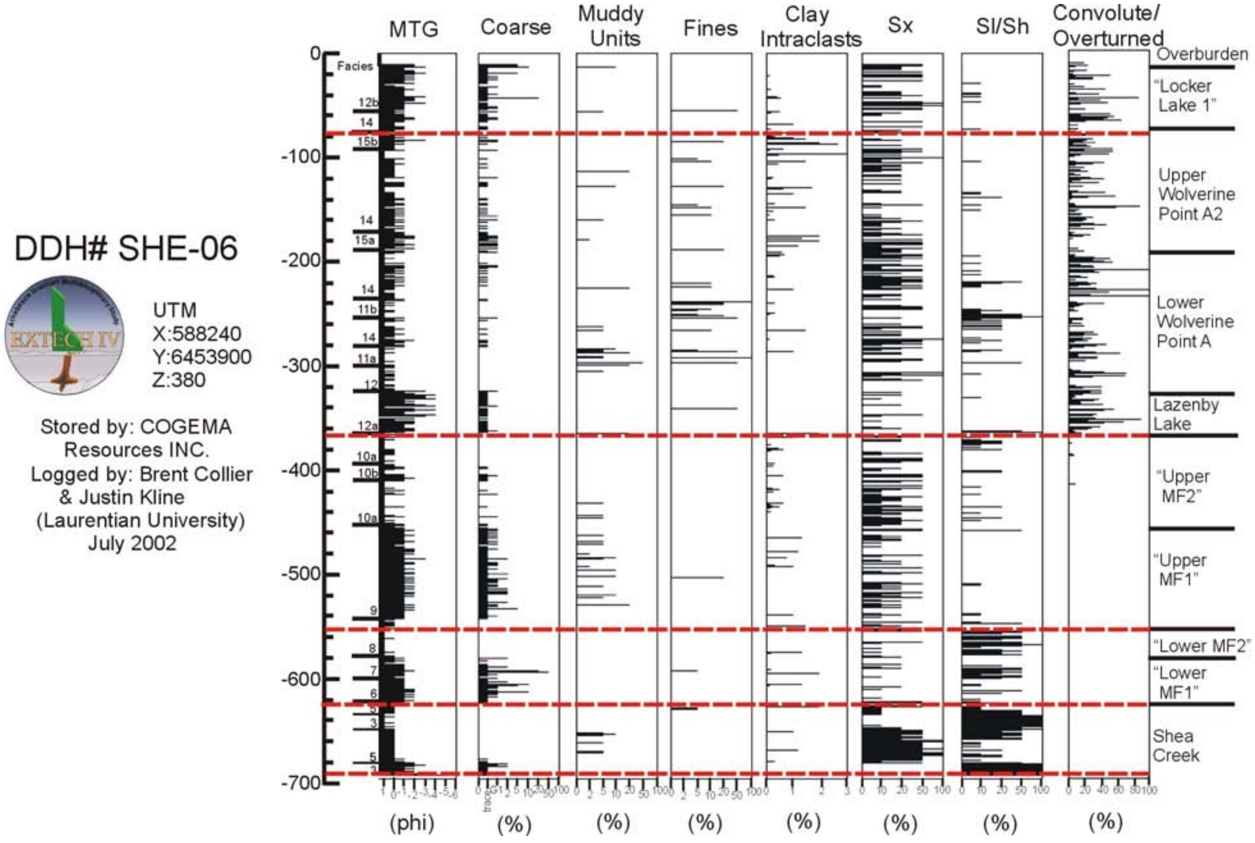

Figure 2 - Multi-parameter graphic log of DDH SHE-06. Third-order sequence boundaries are shown by dashed lines.

those members. The lower 85 m unit is here informally called the "Shea Creek sequence". It is characterized by larger scale planar and trough cross-stratified and ripple-laminated sandstones with less abundant flat-bedded intervals, and is comparable to strata in the Sue C pit at McClean Lake, interpreted to be MFa by Long *et al*. (2000). The "Shea Creek sequence" is widespread south of the Carswell Structure and may be equivalent to the MFa member of Yeo *et al*. (2001, this volume). The overlying 85 m is here informally called the "Lower MF sequence". It is comparable to basal MFa strata at McArthur River (e.g., the SB layers of Bernier *et al*., 2001), in that there are abundant Sh/Sl interbeds. The "Lower MF" is overlain by the "Upper MF sequence". The "Upper MF" was formerly included in the Lazenby Lake Formation (Mwenifumbo *et al*., 2000), but it shares many characteristics with, and is probably correlative with, the MFb-MFd succession in eastern Athabasca Basin. Similarly, although the distinctive pebbly sandstones overlying the "Upper MF" were included in the lower Wolverine Point A member by Mwenifumbo *et al*. (2000), they are here correlated with the Lazenby Lake Formation (Collier *et al*., 2001; Table 1). The Lazenby Lake Formation is overlain by the "Lower Wolverine Point A", "Upper Wolverine Point A", and a remnant of the Locker Lake Formation, here termed "Locker Lake 1".

d) Lithological Units

Stratigraphic boundaries in the western Athabasca Basin were originally defined by changes in maximum grain size (MTG; Ramaekers, 1990; Collier *et al*., 2001). Where frequency of primary sedimentary structures is compared with plots of MTG, changes in assemblages of structures are generally within three metres of the MTG-based boundaries. Sedimentary structures in the units above the Manitou Falls Formation are less useful for sub-division, but can be used in conjunction with the other five "key" variables to delimit higher order sequences. Grain size within the "Shea Creek sequence" (SC), rarely exceeds 2 mm, except in the basal beds. Muddy units, "fines", and clay intraclasts are rare, producing an apparent uniformity, especially toward the top. On the basis of changes in the relative abundance of sedimentary structures, however, the "Shea Creek sequence" is divided into several sub-units, which would otherwise be indistinguishable. The marked difference in sedimentary structures (i.e., abundant Sx and Sh/Sl; see Figure 2) makes SC distinct from MF.

Table 1 - Third-order sequences and facies associations recognized in DDH SHE-06 at Shea Creek. Stratigraphic subdivisions used by Collier et al. *(2001) are indicated. Note that facies associations 11 to 15 are repeated in the Wolverine Point members and are not always in the order shown here (e.g., Figure 5).*

Third-order Sequence	**Unit (this paper)**	**Abbr.**	**Facies Assoc.**	**Lithology**	**Collier *et al.* (2001)**
5	"Locker Lake 1"	LL	12, 13, and 14	See below	LL
4	Upper Wolverine Point A2	Upper WPa	15	Intraclast-rich sandstone with convolute bedding	WPa2
			14	See below	
			11	See below	
			13	See below	
	Lower Wolverine Point A	Lower WPa	14	Fine- to medium-grained sandstone with convolute bedding	WPa1
			11	See below	
			13	Fine- to medium-grained sandstone with common muddy and fine-grained cosets	
	Lazenby Lake	LzL	12	Fine- to medium-grained, pebble-bearing sandstone with convolute bedding	LzL
			11	Fine-grained sandstone with abundant muddy and fine-grained cosets. This association commonly repeats at tops of 4th- and 5th-order sequences in the LzL–LL succession	
3	Upper Manitou Falls	"Upper MF2"	10	Rippled and flat-bedded sandstone with abundant clay intraclasts	MFd
		"Upper MF1"	9	Small-scale rippled, medium- to coarse-grained, granule-rich sandstone	MFc
2	Lower Manitou Falls	"Lower MF2"	8	Clean sandstone with low-angle cross-beds	
		"Lower MF1"	7	Clay-intraclast-rich, granule-bearing sandstone with low-angle interbeds	MFa2
			6	Granule-bearing, rippled, medium-grained sandstone	MFa1
1	Shea Creek	SC	5	Cross-bedded and rippled, heavy mineral-bearing sandstone with muddy units and clay intraclasts	
			4	Cross-bedded, medium-grained sandstone	
			3	Low-angle, cross-bedded or flat-bedded sandstone	
			2	Medium- to coarse-grained, cross-bedded sandstone and basal conglomerate	Basal Cgl.
	Shea Creek or Fair Point	?	1	Cross-bedded, coarse-grained sandstone and pebble conglomerate	

Table 2 - Classification of primary sedimentary structures used in this study (after Miall, 1977).

Facies code	**Facies and sedimentary structures**
Gx	Cross-bedded conglomerate
Gr	Conglomerate with ripple-laminated (<5 cm amplitude) sandstone matrix
G1	One-clast-thick pebble or granule layer
Gm	Massive conglomerate
Sx	Cross-bedded sandstone
Sr	Ripple-laminated (<5 cm amplitude) sandstone
Sl	Sandstone with low angle (<5°) cross-beds
Sh	Sandstone with horizontal lamination
Sm	Massive sandstone

2. Sequences

Sequence stratigraphic methodology, originally developed for marine strata, has been adapted to terrestrial systems by Krapez (1996). The entire Athabasca Group is here interpreted as a 2nd-order sequence, defined as a "set of sequences that define depositional basins and their tectonic stages" (Krapez, 1996). Hence the largest scale internal sequences within the Athabasca Group are 3rd order, "basin filling rhythms defined by sets of parasequences, bedsets and beds" (Krapez, 1996). These in turn comprise 4th and higher order sequences, which are dominantly dependent on climate, or "Milankovitch cycles" as seen in Mesozoic sequences. In pre-Silurian fluvial systems, where rooted vegetation was not available to bind sediment, climate had a much greater effect on sedimentation than in modern systems.

Five 3rd-order sequences are distinguished on the basis of decameter-scale, upward-fining parasequences separated by hiatus deposits and conformable sequence boundaries. In ascending order these are: the "Shea Creek" (SC: 85 m), "Lower Manitou Falls" ("Lower MF": 85 m), "Upper Manitou Falls" ("Upper MF": 185 m), Lazenby Lake–Wolverine Point (LzL–WP: 300 m), and Locker Lake (LL: 35 m) sequences. Of these, the "Lower MF", "Upper MF", and LzL-WP sequences are complete. Internally, 3rd-order sequences contain sandstones that are generally uniform, with more fine-grained facies associations toward their tops. Commonly the only recognizable change in mean grain size is at the lower boundary of these sequences.

The SC sequence is likely to be thicker in deeper parts of the western basin. It is a petrographically distinct package overlying the Fair Point Formation, recognized northwest of the Carswell Structure. As SC facies associations can be traced throughout western Athabasca Basin (e.g., Yeo *et al.*, 2001), this sequence may deserve formation status.

LzL–LL sandstones are more mud prone and are generally finer in grain size than those of underlying formations. Here 4th- and 5th-order sequences can be identified, even though changes in MTG are commonly subtle. Such higher order sequence boundaries are placed at the tops of 1 to 30 m thick accumulations of interbedded, very fine-grained sandstone and siltstone beds (fines) and mud-bearing intervals (muddy units) belonging to Facies Association 11.

Repetition of facies associations is common above MF, whereas with the exception of Facies Association 10, facies associations in the SC-MF succession are analogous with lithologic units. In this respect, sedimentation style is more rhythmic through LzL–LL than within SC and MF (Figure 2).

a) Third-order Sequence Boundaries

Sequence boundaries have only been identified for 3rd-order sequences (Figure 2). They are recognized by: sharp changes in sedimentary style, aggregates of reworked sandstone and clay intraclasts, and distinct changes in MTG and mean grain size. The most convincing boundary lies between MF and LzL (Figure 3).

Figure 3 - Starved sequence below the MF–LzL boundary (middle row) at 365 366 m in DDH SHE-06. Note the rounded mud clasts. Core is 40 cm wide and way up is to the right.

Basement Nonconformity

The basal unconformity may be equivalent to the 1st-order sequence boundary at the base of Sequence A of Young *et al.* (1982). This marks the base of several late Paleoproterozoic-Mesoproterozoic basins in western Canada and the United States, spanning the period 1.7 to 1.2 Ga (Aitken and McMechan, 1991), although this cannot be confirmed without direct dating of diagenetic materials within the Athabasca sequence. According to Krapez (1996), 1st-order sequences commonly span 182 or 364 Ga. The A, B, and C sequences of Young *et al.* (1982) roughly correspond to the longer "megasequence sets" of Krapez (1996). The unconformity incorporates 2nd- and higher order sequence boundaries between the Archean Earl River Complex and the Athabasca Group (ca. 1700 Ma).

The Shea Creek–Lower Manitou Falls (SC–"Lower MF") Boundary

This boundary is marked by a change in primary sedimentary structures. The base of the "Lower MF" unit also shows a large increase in MTG. The abrupt appearance of up to 35% conglomerate (Gr, Gx) over 15 m in DDH ERC-1 west of Shea Creek (see Yeo *et al.*, 2001, Figure 4), suggests that fluvial incision may have occurred.

The Lower Manitou Falls–Upper Manitou Falls ("Lower MF"–"Upper MF") Boundary

An abrupt upward decrease in abundance of Sl/Sh interbeds and a slight increase in Sx sandstones characterizes this boundary. In addition, MTG and mean grain size decrease markedly.

The Manitou Falls–Lazenby Lake (MF–LzL) Boundary

Many attributes change over a couple of metres at the MF–LzL contact (Figure 3). Clay intraclasts, abundant in "Upper MF", become rare. MTG goes from 2 mm in "Upper MF" to medium pebble size in LzL. The frequency of overturned and convolute bedding (Figure 4) changes from negligible in SC–MF to at least 20% in LzL–LL. In half of the cores examined, a succession of interbedded "fines", muddy units, and fine- to medium-grained sandstone approximately 1 m thick marks the MF–LzL contact. Beds in this succession typically have sharp compositional breaks, local scour-and-fill structures, reactivation surfaces, and accumulations of sandstone intraclasts. In addition, rounded clay intraclasts are locally suspended in a fine sandstone matrix, in contrast to other units where intraclasts are concentrated at the base of ripple sets. This interval may represent a starved parasequence (e.g., a condensed Facies Association 11 unit as discussed below).

The Wolverine Point–Locker Lake (WP–LL) Boundary

This contact is marked by an upward increase in grain size, with conglomerate containing ripped-up sandstone intraclasts and rounded clay intraclasts. In DDH SHE-93 (56 m interval), possible microbial binding textures were observed in strata associated with another possible starved parasequence (see Facies Association 11). These were not recognized in other cores, however. The WP–LL contact is difficult to place unequivocally because: 1) starved parasequences are rarely preserved, 2) there are no recognizable changes in abundance or types of sedimentary structure, and 3) the basal LL sequence coarsens upward and may originate in the upper Wolverine Point Formation.

3. Facies Associations

Fifteen facies associations are distinguished at Shea Creek on the basis of primary sedimentary structures and lithology (Figure 5). Some of these can be further subdivided.

a) "Shea Creek Sequence"

The "Shea Creek Sequence" (SC) is a sandstone-dominated succession up to 97 m thick at the base of the Athabasca Group at Shea Creek. The reference section is from 644 to 741 m in DDH SHE-22. It differs significantly from the overlying Manitou Falls Formation (discussed below), and, with the exception of Facies Association 1 (below), differs from the underlying, poorly sorted, sub-arkosic Fair Point Formation. It is difficult to use MTG to subdivide SC sandstones because most lack granules. Within the "Shea Creek sequence", five facies associations can be distinguished mainly on the basis of primary sedimentary structures.

Facies Association 1 (Cross-bedded, Coarse-grained Sandstone and Pebble Conglomerate)

Facies Association 1 (Figure 6) is 9 m thick in DDH SHE-22 and ERC-1, where it directly overlies the unconformity. It consists of 75% cross-bedded gravelly sandstone (Sx) and conglomerate (Gx), in beds commonly greater than 25 cm thick, and up to 5% massive conglomerate beds (Gm). Some cross-beds have steep dips (up to 30°). MTG ranges from granule to cobble grade (maximum 95 mm) and clasts are typically sub-angular and poorly sorted. Clay intraclasts are rare. Mean grain size of the sand fraction is coarse to very coarse, in contrast to the medium-grained sand, which characterizes most of the Shea Creek sequence. The rock is typically beige with patchy dark-red

Figure 4 - Overturned bedding in the Wolverine Point Formation at 147.9 m in DDH DGS-11. Scale card is 8.8 cm long and way up is to the right.

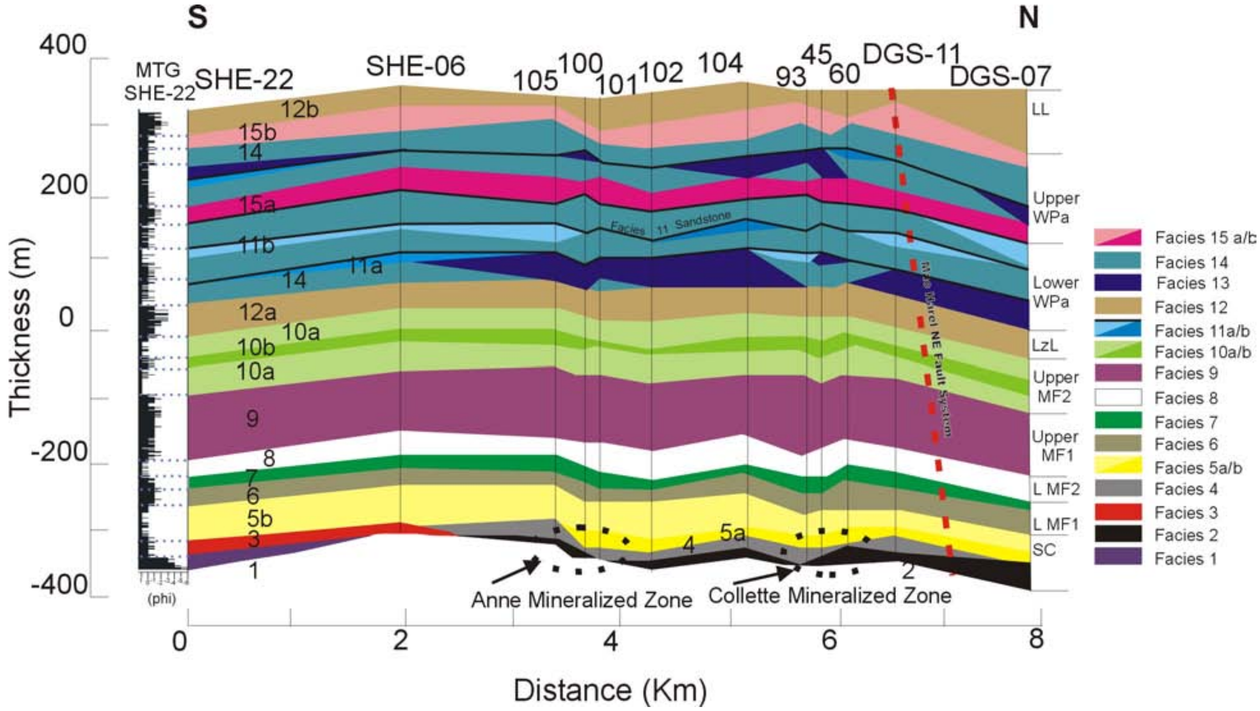

Figure 5 - Distribution of facies associations on the Shea Creek–Douglas River transect. Facies Association 11 intervals are commonly too thin to plot; those found at major sequence boundaries within WP are outlined in black. For reference, the MTG plot for DDH SHE-22 is shown along the left margin; and lithostratigraphic divisions are shown along the right.

hematite staining. Interstitial clay is moderate to abundant throughout. The unit is moderately silicified, with low to moderate porosity.

Facies Association 2 (Cross-bedded, Medium- to Coarse-grained, Pebbly Sandstone and Basal Conglomerate)

Facies Association 2 averages 10 m in thickness in most of the holes at Shea Creek. Where Facies Association 1 is absent, it directly overlies the unconformity, and averages 10 m in thickness. Interbedded sandstone and conglomerate (basal conglomerate) is locally found at the base, but the bulk of Facies Association 2 is pebble-bearing sandstone that generally fines upward. The sandstones are typically medium- to coarse-grained; the conglomerates contain granules and small pebbles. Conglomerate comprises up to 30% of the facies association, and is typically ripple-laminated (Gr) or massive (Gm). Sandstone facies are predominantly moderately to poorly sorted Sx and Sr. Low angle cross-bedded (Sl) and flat-bedded (Sh) sandstones are common. Clay intraclasts and muddy units are rare or absent.

Figure 6 - Cross-bedded sandstone and conglomerate of Facies Association 1 ("Shea Creek" or Fair Point sequence at 737 m in DDH SHE-22. Core is 30 cm wide and way up is the right.

Facies Association 3 (Low-angle Cross-bedded and/or Flat-bedded Sandstone)

Facies Association 3 (Figure 7) is distinguished primarily by its characteristic sedimentary structures. It comprises 90% low-angle cross-bedded (Sl) and/or flat-bedded medium-grained sandstone (Sh), with rare ripple lamination. It was identified only south of the Anne mineralized zone, where it is present either directly above the unconformity or gradationally overlying Facies Association 1 coarse-grained sandstones. Where it directly overlies the unconformity, it is comparable to Facies Association 2, with pebbles up to 32 mm and one-layer-thick granule layers. Higher in the section, it typically has a MTG of 4 mm and contains less than 1% granules. It is moderately to well sorted, with both normal and inversely graded laminae. Although not primary features, its characteristic brick-red colour and high porosity/permeability are distinctive. Matrix clay is moderately abundant. Facies Association 3 is overlain by strata of Facies Association 5 (see below).

Facies Association 4 (Cross-bedded, Medium-grained Sandstone)

Facies Association 4 is present in the Anne-Colette and Douglas River areas, but is absent south of the Anne zone. It consists of approximately 20 m of moderately sorted, cross-bedded and ripple-laminated sandstone (Sx, Sr) lacking clay intraclasts, mudstone, or conglomerate. MTG is typically 1 to 2 mm. One to two metre thick interbeds dominated by Sl are more common toward the base. In most cores, Facies Association 4 is gradationally overlain by Facies Association 5a. In DDH SHE-100 a gravel lag marks the basal contact.

Facies Association 5 (Cross-bedded, Ripple-laminated, Heavy Mineral-bearing Sandstone)

Facies Association 5 (Figure 8) overlies Facies Association 4 across most of the Shea Creek–Douglas River area, but overlies Facies Association 3 south of the Anne zone. Similar, but more coarse-grained sandstones overlie Facies Association 1 in DDH SHE-06. Facies Association 5 includes two sub-assemblages. Facies Association 5a is a 10 to 20 m thick unit stratigraphically below Facies Association 5b, and is restricted to the area between the Anne and Collette zones. It consists of granule-bearing sandstone with MTG less than 12 mm. Pebbles are commonly associated with one-clast-thick layers (G1s). Rare granule conglomerates form beds up to 9 cm thick. Facies Association 5a is overlain by Facies Association 5b, a 30 to 60 m thick unit of clean, medium-grained sandstone with less than 0.5% granules. Facies Association 5 is characterized by 40% Sx in beds 5 to 15 cm thick. Foresets appear to have both angular and tangential lower contacts. Thin, dark green, stylolitized, muddy sandstones (3 to 5 cm) and more thick-bedded “fines” (<40 cm) make up 3% of the unit. Clay intraclasts (<0.35%) are present locally and increase in abundance toward Douglas River. They commonly have a wispy or platy appearance. They lie along the base of cross-bed sets and on foreset laminae. Laminae exhibit both normal and reverse grading and are commonly at oblique angles to adjacent cross-bed sets. Dark-coloured heavy mineral laminae are also common on foresets and increase in abundance toward the bottom of the assemblage. High-angle cross-beds, up to 30°, are found locally. Overturned bedding occurs locally near the contact with Facies Association 4. Sl/Sh interbeds, 2 to 6 m thick, are common throughout Facies Association 5a. Thirty metres of Sl/Sh-dominant strata (Facies Association 3) gradationally overlying cross-bedded sandstone, mark the top of the “Shea Creek sequence” in DDH SHE-06.

Figure 7 - Typical rust-red Sl/Sh strata of Facies Association 3 (“Shea Creek sequence”) at 710 m in DDH SHE-22. Core is 30 cm wide and way up is to the right.

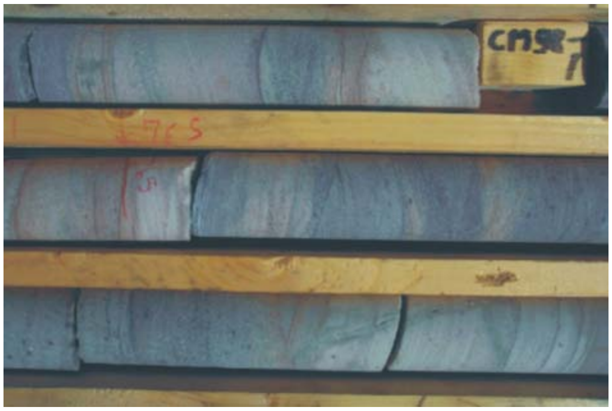

Figure 8 - Typical better-sorted, Sx and Sr sandstones with heavy mineral laminae typical of Facies Association 5 at 765 m in DDH ERC-1. Core is 35 cm wide and way up is to the right.

Much of the Shea Creek sequence is chloritized toward the base. Minor hematitized intervals are locally associated with coarser grain sizes. Frequency of fracturing generally increases toward the bottom, with zones of breccia and clay-rich fault gouge. Matrix clay is moderate to abundant. Parts of the sequence may be moderately to strongly silicified, as drusy quartz seals many faults and fractures. Drusy quartz also locally follows foresets over 1 cm thick intervals. Pyrite, chalcopyrite, and subordinate galena have been identified within the Anne mineralized zone. Facies Association 4 in SHE 105–4 contains 55 cm of massive niccolite associated with a solution breccia.

b) The “Lower Manitou Falls” Sequence

The base of the Manitou Falls Formation is marked by the abrupt upward appearance of granules. The “Lower MF sequence” is dominated by ripple-laminated, medium-grained sandstones (Sr) and is subdivided into three facies associations. All are poor in muddy units and “fines”.

Facies Association 6 (Ripple-laminated, Granule-bearing, Medium-grained Sandstone)

Facies Association 6 forms 20 to 40 m thick units of clay intraclast- and mudstone-poor (<0.1%), granule-bearing, ripple-laminated (Sr), medium-grained sandstone with intervals of one-clast-thick granule layers (G1) and conglomerate (Gm, Gr). Sandstone intraclasts are present locally near the base. The package generally coarsens upward, but metre-scale finer-grained sandstones locally lie at the top. MTG is up to 8 mm. The base is defined by 1 to 2% granules, which form G1 layers toward the top. The package locally coarsens upward into 5 to 18 m of conglomerate-bearing sandstone. Conglomerate constitutes up to15% of the facies association and are dominated by cross-bedded (Gx) and ripple-laminated (Gr) beds up to 15 cm thick. The conglomerate-rich interval locally fines up to about 12 m of granule-bearing sandstone.

Facies Association 7 (Clay Intraclast-rich, Granule-bearing Sandstone with Low-angle Cross-beds)

Facies Association 7 is a ripple-laminated, granule-rich, medium-grained sandstone, with 20% low-angle (Sl) sandstone interbeds up to 45 cm thick. It is characterized by relatively abundant clay intraclasts (>0.5% or 1 to 2 clasts/m), except south of the Anne zone. It is commonly 10 to 25 m thick and contains up to 2% conglomerate. Gravel beds up to 11 cm thick are present locally. MTG is generally finer than in Facies Association 6, at up to 5 mm. Facies Association 7 is commonly bleached or faintly hematitized; dark hematite staining is more abundant south of the Anne zone. Clay intraclasts typically have silicified hematite halos (“lipstick intraclasts”). The upper boundary is transitional to strata of Facies Association 8.

Facies Association 8 (Clean Sandstone with Low-Angle Interbeds)

Facies Association 8 consists of moderately sorted, fine-grained sandstone, dominated by ripple-lamination (Sr), with 25% Sl/Sh interbeds. Granules, clay intraclasts, and mudstones (<0.1%) are rare. It forms a unit 30 to 50 m thick along the Shea Creek transect.

Coarse-grained sandstone in Facies Associations 6 and 7 is typically stained moderate to dark red by multiple generations of hematite. Facies Association 8 is commonly cream in colour with rare hematite staining. Drusy quartz occurs locally at the base of cross-beds.

c) The “Upper Manitou Falls Sequence”

The “Upper Manitou Falls Sequence” contains two members, “Upper MF1” and “Upper MF2”. “Upper MF1” comprises pebble- and granule-rich sandstone, with no apparent trends. In this respect, thinner units cannot be correlated from hole to hole. Sandstones in “Upper MF1” are therefore grouped in a single facies association (9). “Upper MF2” also consists of one facies association (10). A thin granule-bearing unit (Facies Association 10b) in the middle of the Facies Association 10a sandstone is recognizable across Shea Creek. As a result, “Upper MF” can be divided into two higher order, upward-fining sequences.

Facies Association 9 (Small-Scale Rippled, Medium- to Coarse-grained, Granule-rich Sandstone)

“Upper MF1” is 90 to 115 m thick. It comprises 90% small-scale ripple-laminated (<3 cm), medium- to- coarse-grained sandstone (Sr), and up to 10% cross-bedded sandstone (Sx). Cross-bedding generally increases in abundance with increased maximum grain size. MTG is 7 to 12 mm, with large granules dominating and accounting for 1 to 2% of the rock. One-clast-thick granule and pebble layers (G1) are common. Conglomerate units are rare (<0.5%) but are represented locally as 2 to 4 cm thick Gr units. Clay intraclasts are also rare (<0.1%), commonly forming sliver-like clasts associated with granules and stylolitized contacts. Dark green to grey, stylolitized, muddy, medium-grained sandstone in beds 4 to 6 cm thick constitutes 1% of the strata. Rare mudstones form beds 1 to 3 cm thick. Facies Association 9 is the most coarse-grained facies association at Shea Creek, with the exception of basal facies associations 1 and 2. This is reflected by mean grain size and average % Coarse values, but not by MTG.

Facies Association 9 sandstones are more highly coloured than the rest of the Athabasca Group. Multiple generations of hematite staining are common, but most of the unit is pale pink. Bleaching is apparent along fractures in darker stained intervals. Fracture fillings include: black massive, and nodular pyrite, rhombohedral and prismatic calcite, euhedral quartz, siderite, dravite, and kaolinite. Intervals of light yellow phosphatic staining and light brown hydrocarbon staining are rare. Water soaks into Facies Association 9 core slowly, indicating weak to moderate silicification.

Facies Association 10 (Ripple-laminated and Flat-bedded Sandstone with Abundant Clay Intraclasts)

Facies Association 10 (Figure 9) comprises more than 80% ripple-laminated sandstone (Sr) with approximately 10% cross-bedded (Sx) and 1 to 4% Sh/Sl interbeds. The latter generally increase in abundance toward the top. A 14 m thick zone containing 10% Sl/Sh strata is present near the top of "Upper MF2" in DDH SHE-06. Compositionally, Facies Association 10a is a fine- to medium-grained sandstone containing less than 0.1% granules (or a few over the entire unit), less than 0.5% clay intraclasts, and less than 0.5% muddy units, most of which are composed of stylolitized, dark green to grey, fine- to medium-grained sandstone. Rare mudstones are up to 3 cm thick. Small clay intraclasts are common. They are generally more abundant toward the top of the assemblage and are smaller and more angular than those in units above and below. Overturned bedding is rare. Facies Association 10a is found in units 30 to 45 m thick at the base and top of "Upper MF2". These units are separated by 10 to 20 m of Facies Association 10b sandstone. This contains up to 1% clasts 3 to 7 mm in diameter, commonly in G1 layers. Mean grain size is medium sand, slightly coarser than that of Facies Association 10a.

Facies Association 10 is cream to pale pink with thin intervals showing multiple generations of hematite staining. Fracture linings include massive and nodular pyrite and dravite. Facies Association 10b strata typically have more extensive hematite staining due to coarser grain size.

d) The Lazenby Lake–Locker Lake (LzL–LL) Succession (Facies Associations 11 to 15)

In contrast with most of the Shea Creek–Manitou Falls succession, facies associations in the Lazenby Lake–Locker Lake succession tend to be repeated. This facilitates recognition of rhythmic sedimentation, which here defines higher order sequences. In the Wolverine Point Formation, stratigraphic rhythms are difficult to base solely on MTG because grain size rarely exceeds 2 mm. MTG can be used as an indicator, however, as rhythms commonly fine or coarsen upwards. Only when Facies Association 11 (see below) beds are encountered at the tops of rhythms is there any noticeable difference in mean grain size. Recognition of these units is the best criterion for correlating higher order sequences among cores in the Lazenby Lake–Locker Lake succession.

Facies Association 11 (Fine-grained Sandstone with Abundant Muddy and Fine Cosets)

Facies Association 11 contains two facies sub-assemblages. Facies Association 11a contains abundant muddy units, whereas Facies Association 11b (Figure 10) is characterized by abundant "fines" with rare muddy units. Facies Association 11b locally separates all three major 4th-order sequences in the "Lower WPa", in which individual beds are up to 5 m thick. In general, Facies Association 11 sandstone is found in intervals up to 30 m thick at the top of most 4th-order sequences within WP and in thinner intervals (<5 m) in LzL and LL. It consists predominantly of moderately sorted, fine-grained sandstone with ripple lamination (Sr). It commonly contains more than 50% muddy cosets and "fine" interbeds. Individual beds of "fines" may be over 1 m thick, and are commonly present at the top of small-scale sequences. Muddy units lack any evidence of mud cracks. Contacts between interbedded mudstones and "fines" are commonly marked by erosion or reactivation surfaces. Clay intraclasts are locally abundant (<5%). Condensed Facies Association 11 intervals, commonly 1 m thick, occur locally at 3rd-order sequence boundaries, and are interpreted as starved parasequences.

A 20 m interval containing 12% Sh interbeds is transitional to Facies Association 11b at the top of the second 4th order "Lower WPa" rhythm in DDH SHE-06 (245 to 265 m). With the upward appearance of Facies Association 11b thick-bedded "fines", Sh

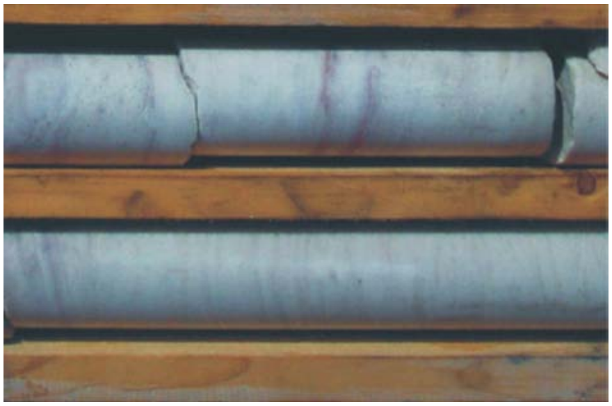

Figure 9 - Typical "Upper Manitou Falls" ripple-laminated sandstone at 395 m in DDH SHE-06. Core width is 30 cm and way up is to the right.

Figure 10 - Highly stained Facies Association 11b sandstones from the "Lower Wolverine Point A" sequence at 260 m in DDH SHE-10a (between SHE-06 and SHE-22). Core is 55 cm wide and way up is to the right.

increases to 20% over 10 m, with up to 60% Sh locally. No Sh interbeds were found within the top 8 m of Facies Association 11b, where siltstones are thickest.

e) Lazenby Lake Formation (LzL)

Facies Association 12 (Fine- to Medium-grained, Pebble-bearing Sandstone with Convolute Bedding)

Facies Association 12a consists of pebble-bearing sandstones that contain two 15 to 30 m thick successions distinguished primarily on the basis of MTG, which can be traced along the Shea Creek transect. The lower succession coarsens upward, while the upper one fines upward. They are commonly separated by Facies Association 11 beds.

Facies Association 12a consists mainly of ripple-laminated, fine- to medium-grained sandstone (Sr) with up to10% cross-beds (Sx). Pebbles and granules make up 1 to 2% of the strata, with MTG of 10 to 28 mm (average 3 to 4 mm). Pebbles are commonly oblate. G1 layers are commonly associated with larger pebble sizes and are best developed at the base of internal upward-fining successions that cannot be correlated among cores. Ripple-laminated conglomerate layers (Gr) up to 8 cm thick occur locally. Facies Association 12a contains at least 30% convolute and overturned bedding. Similar rocks are found at the base of the Locker Lake Formation and are assigned to Facies Association 12b.

Facies Association 12a is typically pale yellow, with low permeability, and moderate to extensive silicification. Fracture fillings include massive and prismatic calcite, massive and nodular pyrite, and euhedral quartz. Multiple generations of hematite staining are commonly associated with coarser grain sizes, and Facies Association 11 intervals. Yellow-green phosphatic staining is local.

Facies Association 12b (LL)

Facies Association 12b is more conglomeratic than the Facies Association 12a sandstones in the Lazenby Lake Formation. It contains two 20 to 35 m thick, upward-coarsening (MTG) successions; the lower of which is the only one preserved in the Anne-Collette area. Facies Association 12b is dominated by medium-grained, ripple-laminated sandstone (Sr) with 15% cross-beds (Sx). Clay intraclasts, muddy units, and "fines" are rare, except in Facies Association 11 intervals between sequences. MTG rarely exceeds 10 mm in Facies Association 12b. It contains 1 to 2% conglomerate in beds up to 20 cm thick, which, along with frequency of G1 layers and MTG, increases toward the top of the sequences. Sandstone intraclasts are common near the bottom of the LL. At least 15% of the sandstones are overturned or convoluted. At the top of DDH ERC-1 west of Shea Creek a second unit of Facies Association 12b, 60 m thick, is found.

f) Wolverine Point Formation (WP)

Two main lithostratigraphic divisions of the Wolverine Point Formation (WP) are recognized along the Shea Creek trend, WPa1 and WPa2 (Table 1; Collier *et al*., 2001). To avoid confusion with pre-existing lithostratigraphy, their respective sequences are here referred to as the "Lower WPa" and "Upper WPa". Each of these 4th-order sequences can be further subdivided into three 5th-order sequences whose boundaries are placed at the tops of Facies Association 11 intervals.

Facies Association 13 (Fine- to Medium-grained Sandstone with Abundant "Muddy Units" and "Fines")

Facies Association 13a, developed near the base of the "Lower WPa", is locally up to 30 m thick. It contains fine- to medium-grained, ripple-laminated sandstone (Sr) with rare granules (<0.2%), and up to10% cross-bedded sandstone (Sx). Clay intraclasts are relatively common (0.1 to 0.5%). Muddy units and "fines" comprise 2 to 5% each. Flat-bedded sandstones (Sh) are common (2 to 3%), and increase in abundance up-section. Facies Association 13 strata generally fine upward and are overlain by Facies Association 11 intervals. Overturned and convolute bedding comprises at least 15% of the assemblage. Facies Association 13 sandstones are less common in the "Upper WPa" and are restricted to the base. Similar sandstones overlie Facies Association 12b (LL) in DDH ERC-1 west of Shea Creek.

Facies Association 14 (Fine- to Medium-grained Sandstone with Convolute Bedding)

Facies Association 14 includes all the sandstones than do not fit in facies associations 11, 12, 13, or 15. Found throughout the Wolverine Point Formation in units 10 to 50 m thick, it is dominated by ripple-laminated, fine- to medium-grained sandstone (Sr) with 10 to 20% cross-beds (Sx). Cross-bed frequency is up to10%. Flat- bedded sandstones (Sh) are rare in the "Upper WPa" but common towards the tops of 5th-order sequences in the "Lower

WPa". Granules are rare in the "Lower WPa" but locally common in the "Upper WPa". Muddy units, "fines", and clay intraclasts are uncommon (collectively 0 to 4%) and are generally confined to Facies Association 11 intervals. At least 20% of Facies Association 14 is overturned or convolute bedded.

Facies Association 15 (Intraclast-rich Sandstone with Convolute Bedding)

Two distinct Facies Association 15 intervals are respectively found at the upper and lower boundaries of the "Upper WPa" sequence. Both are associated with coarser MTG. Facies Association 15a refers to the lower interval, whereas Facies Association 15b refers to the upper interval.

Facies Association 15a is 20 to 30 m thick. It is characterized by 1% granule-bearing, ripple-laminated (Sr), fine- to medium-grained sandstone, with abundant clay intraclasts (0.5%) and G1 layers. MTG for the unit is 5 to 10 mm. Conglomerate, in beds up to 3 cm thick (Gr), is rare (<0.5%). Muddy units and "fines" collectively constitute 1 to 5% of the unit. Two 10 to 20 m thick successions can be recognized within Facies Association 15a. The lower one coarsens upward, whereas the upper fines upward.

Facies Association 15b is 20 to 30 m thick. It is similar to Facies Association 15a, but contains more than 1% clay intraclasts, increasing to 3% near the top of the interval. Unlike Facies Association 15a, it lacks conglomerate and has less than 0.5% granules, with MTG of 4 mm. It contains 2% muddy units and "fines". Facies Association 15b may be overlain by up to 15 m of intraclast-poor clean sandstone (Facies Association 14).

The Wolverine Point Formation is typically pale pink to brown in colour. It contains minor to moderate matrix clay. Dark hematite staining is associated with Facies Association 11 intervals and "coarser" sandstones. Yellow-green phosphatic staining is diagnostic, and generally decreases up from the Lazenby Lake Formation. Limonite staining is common towards the Locker Lake Formation. Fracture linings include: green and black massive pyrite, calcite, siderite, and drusy quartz. Bleaching is common along fractures, where multiple generation hematite staining is prominent.

g) Locker Lake Formation (LL)

Less than 35 m of the Locker Lake Formation is preserved in the Shea Creek area. In contrast, approximately 100 m is preserved a few kilometers north (Douglas River), and there is 180 m of LL west of Shea Creek in DDH ERC-1. The lower 70 m consists of pebble-bearing Facies Association 12b sandstone. A clay intraclast-poor interval of Facies Association 14 sandstone locally underlies this. Thirty metres of cleaner Facies Association 13 and 14 sandstone overlies the lower Facies Association 12b sandstone in DDH ERC-1, and is overlain in turn by another 60 m of Facies Association 12b sandstone.

LL is distinguished by its fleshy pink-brown colour. It is commonly extensively fractured. Fracture fillings include limonite and subordinate pyrite. It is moderately silicified, with zones of extensive silicification near the LL-WP contact.

4. Interpretation and Discussion

a) Sequence Stratigraphy

Lithofacies analysis may be the best approach to defining parasequence boundaries in the Athabasca Basin (e.g., Figure 2) because unconformities and erosional discontinuities commonly appear conformable in drill core. The uniformity of the Athabasca Group makes recognition of differences in sedimentation style difficult; in most cases changes are too subtle to pick in core. This is typical of pre-Silurian systems (Rainbird, 1992; McCormick and Grotzinger, 1993; Martins-Neto, 1994). Only after comparing numerous graphic logs do breaks become evident.

b) Facies Interpretations

"Shea Creek Sequence" (Facies Associations 2 to 5)

Facies Association 1 sandstones and conglomerates may be correlative with the Fair Point Formation, not previously identified south of the Carswell Structure (Yeo *et al*., 2001). The overlying SC strata differ from the Fair Point in its type area (Ramaekers, 1990) in containing less lithic and feldspathic material, and little conglomerate, besides basal lags. These have relatively high matrix clay, however, which suggests a source similar to that of the sub-arkosic Fair Point Formation. The discontinuous nature of the Facies Association 1 conglomerates suggests that they may be alluvial fan deposits emanating from local topographic highs. Alternatively, as they appear to occupy a paleo-topographically low position in the restored profile, they may represent deposits of shallow, sandy to gravelly braided streams. The latter interpretation is supported by well-developed cross-stratification in the sandstone and conglomerate, and the absence of massive, matrix-supported beds typical of debris flows.

Strata of Facies Association 2 were deposited in shallow ephemeral stream systems, as many of the conglomerates are ripple cross-laminated, like the bar tops in the Platte River (e.g., Miall, 1977, 1996). Massive, clast-supported conglomerates suggest deposition under lower flow-regime conditions. Pebbly beds in Facies Association 2 are interpreted as residual lags associated with high-energy flood events.

Strata of Facies Association 3 are dominated by flat-laminated and low-angle cross-stratified sandstones. This suggests deposition by upper flow-regime sheet-floods, as suggested for parts of the Manitou Falls A member in the Sue C Pit by Long *et al*. (2000). Inversely graded laminae may represent aeolian "pin-stripe lamination", produced by adhesion of wind-blown sand grains to a damp surface (Simpson and Eriksson, 1993; Tirsgaard and Øxnevad, 1998).

Facies Associations 4 and 5 are the deposits of shallow, low-gradient, sandy braided rivers. The main difference between the two facies associations is the presence of muddy units and clay intraclasts in Facies Association 5. These may reflect changing climate. The muddy material accumulated in pools within small channels or on the floodplain during falling water stages of floods, and was reworked by later flood events. Although much of the fine material may have been removed by aeolian winnowing (Long, 1978; Fuller 1985), increased humidity may have raised the groundwater table sufficiently to allow fixation of the muds by adhesion or microbial binding.

Overall, the "Shea Creek sequence" suggests low-gradient, perennial, sandy braided stream deposits with episodic flash floods. Inversely graded laminae, including possible pinstripe laminae (Simpson and Eriksson, 1993), suggests interbedded aeolianites.

"Lower Manitou Falls Sequence" ("Lower MF": Facies Association 6 to 8)

The Manitou Falls Formation and all overlying sandstones are dominated by ripple lamination. Hence the sandy braided streams in which they formed were very shallow, with high width-to-depth ratios. These sandstones may represent ephemeral or semi-perennial systems. The progressive upward increase of Sh/Sl, from 15% near the base to 25% near the top of the "Lower MF" sequence, suggests increased aridity with time.

The "Lower MF1" (Facies Associations 6 and 7) is slightly granular, with minor conglomerate. Facies Association 6 generally contains few clay intraclasts, whereas they are common in Facies Association 7. This may be a result of increased flashy discharge, or a reduction in stream gradient, which allowed a higher permanent water table. "Lower MF" contains no evidence for muddy units. This is typical of many pre-Silurian ephemeral river systems, in which such sediment would have been removed by aeolian activity between floods (Long, 1978; Fuller, 1985).

The scarcity of clay intraclasts in Facies Association 8 suggests a lower energy, distal, flashy, stream system. This is supported by the marked decrease in mean grain size and the increase in abundance of interbedded Sl/Sh sandstone. Time intervals between flows were likely longer than in Facies Associations 6 and 7, allowing winds more chance to remove mud.

"Upper Manitou Falls Sequence" ("Upper MF": Facies Associations 9 and 10)

The onset of the "Upper MF1" is marked by the upward loss of Sh/Sl interbeds. This suggests transition to a sandy braided system with little flashy discharge. The dominance of ripples suggests relatively shallow streams, which lacked the large-scale composite bar forms evident in Platte- and Brahmaputra-type river deposits (c.f. Miall, 1977, 1996). Sh/Sl interbeds, though scarce, increase in abundance in the "Upper MF2" (Facies Association 10). The abundance of muddy units is slightly higher in Facies Association 9 than any underlying one. These decrease in abundance in Facies Association 10, however.

The rivers that deposited Facies Association 9 may have been perennial or semi-perennial, with consequently improved preservation of muddy units and reduced production of clay intraclasts compared to the overlying Facies Association 10 system. The marked decrease in muddy units in Facies Association 10, combined with an increase in clay intraclasts and Sl/Sh interbeds, is reminiscent of the vertical changes in the "Lower MF1" sandstone. The distinctive small size of the clay intraclasts may be a function of stream power. Abundant Sh/Sl interbeds below the upper sequence boundary suggest a return to flashy discharge at the top of the sequence.

Lazenby Lake-Locker Lake Succession (Facies Associations 11 to 15)

The MF–LzL contact is marked by a major change in fluvial style, which persists to the top of the LL. Ripple-laminated sandstone continues to predominate, but there are considerable intervals with more than 20% overturned or convolute bedding. The succession contains approximately 20 times more "fines" and muddy units than MF. Soft-sediment deformation occurs throughout the package. Its non-episodic distribution suggests that a seismic origin is unlikely. Convolute stratification in these beds may have been produced by frictional drag over water-saturated sediments during high-energy flows (Owen, 1995).

Facies Association 11 sandstones were likely deposited in a lower gradient (distal) fluvial system marked by broad shallow flows with only limited ability to move sands. This facilitated preservation of muddy units and "fines" at the tops of sequences. Sh (as opposed to Sh/Sl) is fairly abundant within and just below Facies Association 11 sandstones and probably reflects deposition from suspended sediment laden flows or under upper flow regime. Muds may have accumulated during falling flood stage in scour pools within channels or on bar tops.

Quartz pebbles in Facies Association 12A (LzL) may indicate uplift of the basin margins during the hiatus between deposition of MF and LzL. These clasts were deposited as "armoured" channel lags. The abrupt upward disappearance of pebbles suggests that the uplift was short lived.

Facies Associations 13 and 14 are similar except that Facies Association 13 is more mud rich, with approximately 5% muddy units and "fines". Greater preservation of muddy units probably occurred during periods of lower discharge, as in Facies Association 11. Larger, angular clay intraclasts in the Wolverine Point Formation, as opposed to the sliver-like clay intraclasts found in underlying units, indicates that muddy units did not flake. This feature, and the absence of mud cracks in muddy units, indicates a high water table, which also facilitated preservation of muddy units.

Clay intraclast-rich strata of Facies Association 15 occur both at the "Lower WPa"–"Upper WPa" contact (Facies Association 15a) and at the "Upper WPa"–LL contact (Figure 5). The abundance of clay intraclasts in Facies Association 15a may be related to erosion of Facies Association 11 mudstone after a brief hiatus in sedimentation, or a change in stream power. In some cores, Facies Association 15b lies at the top of a fining-upward succession in lithostratigraphic WP; in others, it lies at the base of a coarsening-upward cycle in LL. Increased quantities of clay intraclasts toward the top of sequences may be related to more "flashy" discharge toward the ends of cycles, or may reflect changing preservation potential of muddy units due to changes in level of the water table between floods.

The sedimentary style of LL appears similar to that of WP. Muddy units, "fines", and clay intraclasts are lacking near the base, where sediment supply was likely high. The occurrence of pebbly material may be a result of uplift of the basin margins. Above the pebbly sandstones is a more mud-rich assemblage similar to the Facies Association 13 and 14 sandstones of WP. A second unit of Facies Association 12b sandstone overlies these, perhaps indicating another 3rd-order sequence boundary, possibly a result of basin margin uplift.

5. Conclusions

1) Changes in primary sedimentary structures, though commonly subtle, generally correlate with stratigraphic boundaries defined from other criteria such as grain size. Changes in relative abundance of sedimentary structures allow a more refined subdivision of the Athabasca succession at Shea Creek than those based on lithological parameters alone (e.g., Collier *et al.*, 2001).
2) Five 3rd-order sequences are distinguished: the "Shea Creek", "Lower Manitou Falls", "Upper Manitou Falls", Lazenby Lake–Wolverine Point, and Locker Lake. Three of these are complete. Major sequence boundaries (unconformities) are indicated by changes in maximum grain size (MTG) and primary sedimentary structures.
3) The only unequivocal unconformity in core is the contact between the Manitou Falls and Lazenby Lake formations. In 50% of the cores, an interval of interbedded muddy units, "fines", and fine-grained sandstone with scoured contacts and reactivation surfaces, characterizes that boundary. The preservation potential of possible algal-bound mud clasts may be greatest above sequence boundaries, where soil forming processes had time to develop.
4) The lower 80 to 100 m of sandstone at Shea Creek can be clearly distinguished from the Manitou Falls on the basis of primary sedimentary structures, such as low-angle cross- and flat-lamination (Sh/Sl), and is referred to here as the "Shea Creek sequence". It includes several indicators of humid fluvial conditions, including large-scale sheetflood, and larger-scale bed-form-dominated, perennial, braided river deposits, which contrast with the overlying ripple-laminated, semi-perennial to ephemeral stream deposits. Thick, high-permeability, sheet-flood sandstones might have acted as a conduit for fluid flow along the basement unconformity.

5) Sh/Sl and rippled sandstones of the "Lower Manitou Falls sequence" were probably deposited in ephemeral braided streams with marked "flashy" discharge toward the top of the section.

6) The "Upper Manitou Falls sequence" suggests a semi-perennial river system, although increased Sh/Sl interbeds in "Upper MF2" suggest increased flashy discharge toward the Lazenby Lake Formation contact.

7) The Lazenby Lake–Locker Lake succession appears to have been deposited in a more mud-rich, semi-perennial to ephemeral, fluvial system. Evidence for a higher water table suggests more humid conditions. The abundance of overturned and convolute bedding probably resulted from frictional drag from high-energy stream flows over water-saturated sediments.

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