

# Tectonic accommodation and alluvial sequence stratigraphy of a Paleoproterozoic continental rift, Baker Lake Basin, Canada

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**ABSTRACT:** A model, based upon pre-existing formulations, is presented here for alluvial sequence stratigraphy and applied to the non-marine, Paleoproterozoic Baker Lake Basin. Discharge and sediment supply are considered boundary conditions, subject to feedback effects. Primary control on alluvial facies changes is attributed to the gradient of the alluvial plain. This gradient is determined by the “graded profile”, a topographic profile defined by a graded stream linking a sediment source region to a subaqueous basin. It is argued that coupled source uplift and basin subsidence provide feedback on sediment supply, grade, and flux that reinforce expected facies changes, in part providing justification of initial assumptions. The model provides a rationale for a generally upward-fining alluvial sequence that is coeval with a general upward-fining to –coarsening nearshore sequence, bridging the theoretical gap between subaerial and subaqueous sequences. It also provides an interpretation of basin-scale stratigraphy based on the tectonic evolution of sedimentary basins, in keeping with the models for how they form.

Third-order depositional sequences of tectonic origin from the Baker Lake Basin are subdivided into high accommodation alluvial, low accommodation alluvial, and mixed fluvial-shallow-lacustrine sequences. The succession of 3<sup>rd</sup> order sequences illustrates basin evolution from rift initiation, rift climax accompanied by widespread volcanism, to immediate post-rift that comprises the 2<sup>nd</sup> order Baker Sequence, representing a stage of intracontinental rifting from ca. 1.84–1.79 Ga.

## INTRODUCTION

There has been much debate as to the stratigraphic character and architecture of subaerial depositional sequences and how they relate to subaqueous depositional sequences (Vail et al. 1977; Posamentier and Vail 1988; Miall 1991; Westcott 1993; Wright and Marriott 1993; Shanley and McCabe 1994; Olsen et al. 1995).

Fluvial deposits were initially incorporated into sequence stratigraphic models (Posamentier et al. 1988; Posamentier and Vail 1988) by employing the concept of *stream equilibrium profile*, based on the graded stream concept (Mackin 1948), to link fluvial and marine systems. These models predicted that alluvial accommodation requires seaward migration of the bayline during relative sea level high- or lowstand, implying that alluvial accommodation was inversely related to marine accommodation. This may be accurate with respect to alluvial deposition at nearshore locations, where fluvial deposition would occur during sufficiently low relative sea level in contrast to marine deposition during high relative sea level, but does it apply to fully non-marine successions deposited landward of nearshore environments?

In general, most workers consider a fluvial/alluvial depositional sequence to comprise an upward-fining succession (e.g. Legaretta and Uliana 1991; Westcott 1993; Wright and Marriott 1993; Shanley and McCabe 1994; Olsen et al. 1995; Plint et al. 2001; Atchley et al. 2004), based primarily on the occurrence of paleosols within floodplain deposits at the top (Wright and Marriott 1993; Shanley and McCabe 1994), but including other

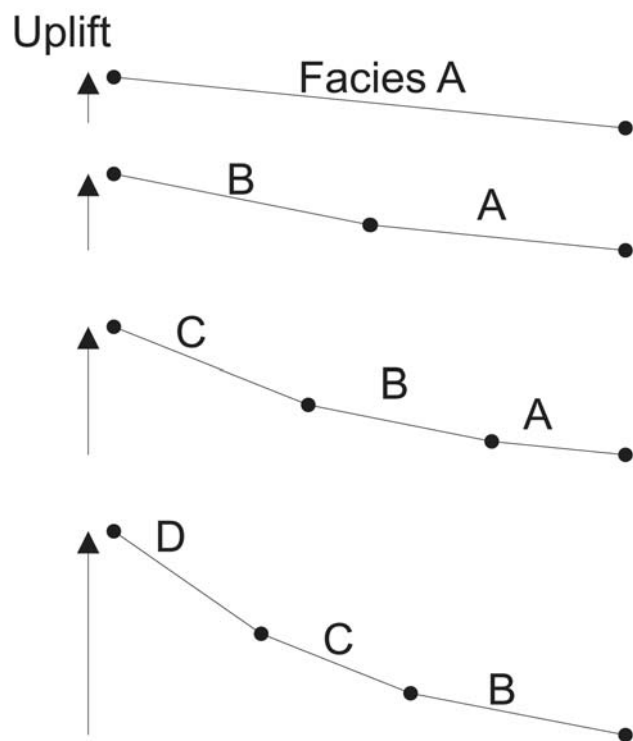
types of sequence boundary criteria (Miall 2001), thought to correlate with unconformities at shelf locations (Vail et al. 1977). This functional definition incorporates low- and high-accommodation systems tracts (Legaretta and Uliana 1991; Shanley and McCabe 1994; Olsen 1995; Plint et al. 2001) reflecting low and high depositional rates that are correlated to established low- (LST/HST) and high- (TST) accommodation, marine systems tracts.

The Baker Lake Basin was a tectonically active, terrestrial, and hydrologically closed basin during deposition of the Baker Lake Group (Donaldson 1967; LeCheminant et al. 1979b, Gall et al. 1992; Rainbird and Hadlari 2000; Rainbird et al. 2003; Hadlari et al. 2006), or equivalent Baker second-order sequence (Rainbird et al. 2003). Thus it provides an opportunity to filter out the effects of sea level in order to examine the relationship between sedimentary dynamics and tectonic parameters. In order to interpret the stratigraphy from a basinal perspective, a model is presented for the sequence stratigraphy of alluvial systems wherein the concepts of alluvial accommodation space and the graded stream are revisited, and which is subsequently applied to the Baker second-order sequence (*sensu* Krapez 1996).

## TERRESTRIAL SEQUENCE STRATIGRAPHY: CONCEPTUAL MODEL

### Factors

A terrestrial sequence stratigraphic model must be based upon the fundamental concepts of established sequence stratigraphy. These include the parameters sediment supply (S), sediment flux (SF), base level, accommodation space (AS), and accom-



TEXT-FIGURE 1  
Subdivision of the graded profile into sedimentary facies, where each facies is defined by a gradient range. Hypothetical facies A, B, C, and D are stable at progressively higher gradient ranges.

modation (A). Sediment supply is the sediment available to the system; it is a function of erosion in the source region or along the course of the river. Non-marine sediment flux is primarily through fluvial pathways. The upper boundary to subaqueous accommodation space is sea or lake level. In the application of sequence stratigraphy to fluvial systems, the definitions of base level and accommodation space require a more complex definition than relative sea or lake level.

As proposed by Posamentier and Vail (1988), a reasonable way to define fluvial accommodation space is to employ the concept of the graded river (Mackin 1948) to define the upper boundary of subaerial accommodation space. Thus subaerial accommodation space can be considered the space between substrate and a graded profile, or potential graded profile, which can be positive, negative, or zero. Accommodation is therefore the change in subaerial accommodation space. Note that Posamentier and Vail (1988) use the term *equilibrium profile* after the state of dynamic equilibrium that the graded stream is thought to exist. Quirk (1996) noted that this term is unnecessary, since the definition is equivalent to (and based on) that proposed by Mackin (1948) for *graded profile*. Also, Posamentier and Vail (1998) posited that the graded profile ends at a bayline whereas Miall (1991) suggested that the shoreline would more properly take into account sediment flux.

Mackin (1948) defined the *graded stream* as, “one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin... readjustment is effected primarily by appropriate modification of slope by up

building or down cutting...” A graded stream is characterized by zero net deposition or erosion along its length. Slope is inversely proportional to discharge and positively proportional to grain size, hence a graded profile decreases in slope downstream.

### Facies

Previous models have focused primarily on sinuosity and channel density (e.g., Schumm 1993; Wright and Marriott 1993), indeed with exceptional datasets these have been found to be valid (e.g., Maynard 2006). In general these characters are difficult to systematically define for most stratigraphic sections, are most applicable to a narrow range of facies (e.g. meandering streams), and so have limited utility. Recent meso-scale experiments have shown that subsidence and facies are intimately linked; Hickson et al. (2005) conclude that “any change in subsidence rate, in our experiment, leads to upstream or downstream facies migration and *this* becomes the dominant control on the two-dimensional architecture.”

So, to apply the graded profile-accommodation space concept to interpretation of stratigraphic successions, facies must be incorporated. Well-established characteristics of streams are:

1. Downstream fining due to grain abrasion and selective deposition of coarse fractions (Paola and Seal 1995);
2. Abrupt transitions in grain size and slope (Sambrook-Smith and Ferguson 1995); for example the transition of gravel to sand accompanied by a decrease in slope, corresponding to a change in transport mode from bedload to mixed load and therefore a different Shields parameter (Dade and Friend 1998);
3. Commonly identified stream types, such as braided and meandering, are discharge- and gradient-dependent (Schumm 1985).

The observed trend of downstream fining accompanied by abrupt transitions in grain size and slope should provide lithological sub-divisions of proximal to distal facies.

The empirical relation (Lane 1955) between water discharge,  $Q$ , channel slope,  $S$ , sediment discharge,  $Q_s$ , and median particle size,  $d_{50}$ , can be expressed as:

$$QS \sim Q_s d_{50} \text{ (Lane 1955)}$$

Consider that a stream at grade is characterized by zero net deposition and erosion, therefore downstream sediment flux per unit channel width is constant (Dade and Friend 1998). By this proposition, complications associated with converging channels and increasing total discharge are avoided, and a two-dimensional profile is sufficient to represent the potential graded profile (Dade and Friend 1998). Now, if for a given fluvial system  $SF$  (or  $Q_s$ ) and water flux ( $Q$ ) remain relatively constant, then slope ( $S$ ) is proportional to grain size ( $d_{50}$ ). This is a suitable assumption because recent studies suggest that sediment yield is stable over geologic time scales either due to tectonic control or because the fluvial sediment system is inherently dynamically stable (Phillips 2003). Thus, changes in grain size can be broadly attributed to changes in paleoslope, and combined with downstream fining trends and the gradient dependency of stream types (e.g. braided to meandering), should yield predictable downstream facies transitions. Schumm and Khan (1972) have demonstrated gradient control of facies experimentally, concluding that for a given discharge, as slope is progressively increased a straight river becomes sinuous and then braided.

Based on these principles, a graded profile can be sub-divided into existing proximal to distal facies zones of decreasing grain size and inferred gradient (i.e. gravel-bed to sand-bed braided stream).

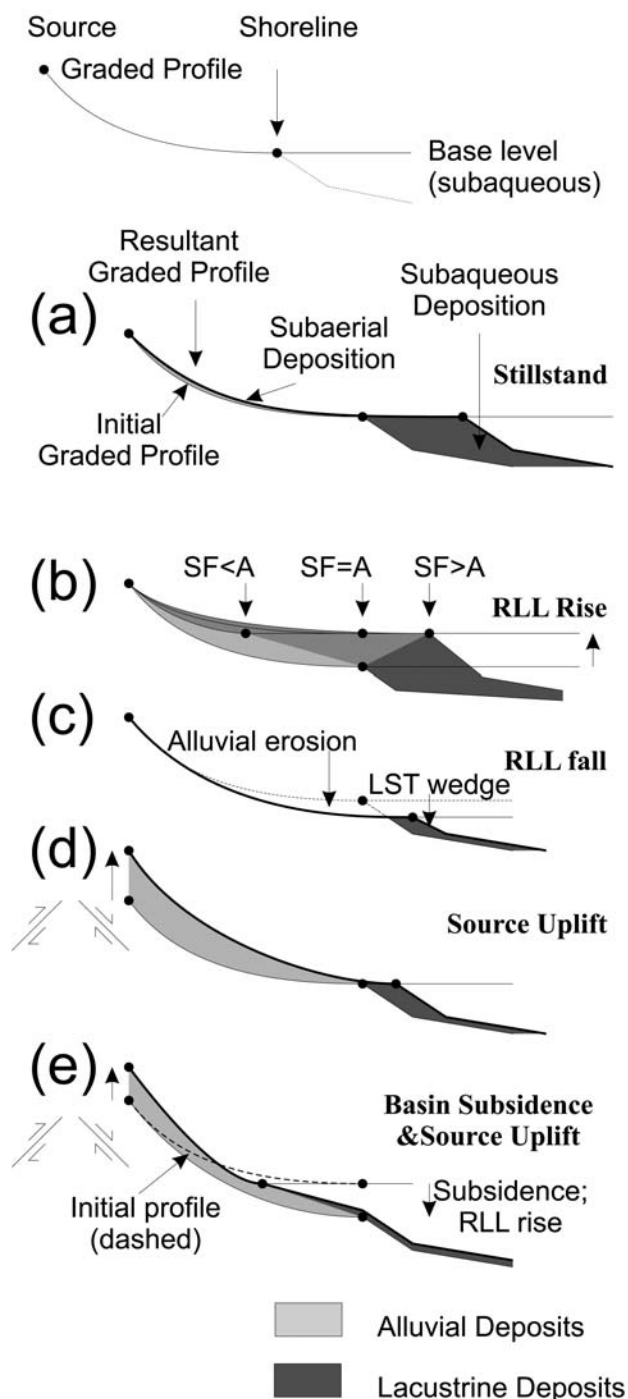
As a hypothetical exercise, assuming that the required grain sizes are available, a graded profile can be constructed with respect to facies for a given discharge regime (text-fig. 1) by considering that hypothetical facies are stable within gradient ranges (e.g. Schumm 1985). If the net gradient between the sediment source point and the shoreline (or end-of-stream) were to fall within the range of the lowest gradient facies A, then the graded state could be defined by that facies (text-fig. 1a). Establishment of grade would involve deposition beginning near the sediment source point, initial selective deposition of coarse grain size fractions, and therefore an upward-fining succession. In a second case, if the net gradient exceeds the range of facies A, then a higher gradient facies B will be established starting at the sediment source point, and comprise the minimum length required as part of the graded profile (text-fig. 1b). With increasing net gradient (or “set up”) this process would continue until a maximum gradient facies is determined by the sediment supply, grain size, or discharge. For example, if cobbles and boulders comprise a small proportion of the sediment available, then only a small component of the graded profile can be alluvial fan facies regardless of the net gradient set up, and the head of the alluvial fan will abut against the presumably uplifted area. Alternatively, since the transition from meandering to braided stream can occur at the same gradient but with increasing water discharge, in high discharge, or ephemeral flash-flood type regimes, braided streams are the predominant stream type even at relatively low gradients.

In accordance with the approach to subaqueous and nearshore deposits, it is not necessary to estimate exact paleoslope (e.g. Paola and Mohrig 1996), but simply to identify relative changes, for a given fluvial system, with respect to basinward or sourceward facies migrations. In this context, over the course of deposition a basinward migration of facies would result in an upward-coarsening progradational succession and a sourceward migration of facies would result in an upward-fining retrogradational succession. Now it is possible to interpret and predict relative facies changes based on graded profile evolution. Quirk (1996) has reviewed and Holbrook et al. (2006) elaborated on how a graded profile would react to various factors including changes in relative sea level (RSL), uplift, and local subsidence; this is expanded upon in text-figure 2. Note that the Baker Lake Basin was a terrestrial system, and so the upper boundary to subaqueous AS is referred to as relative lake level (RLL), but in the general model RLL and RSL are interchangeable.

### Dynamics of the Graded Profile

The graded profile is the upper limit of subaerial accommodation space in much the same way that sea level is the upper limit of accommodation space in marine or lacustrine systems – both represent potential space available, only realized when deposition occurs. Deposits are therefore a function of the relationship between sediment flux and accommodation.

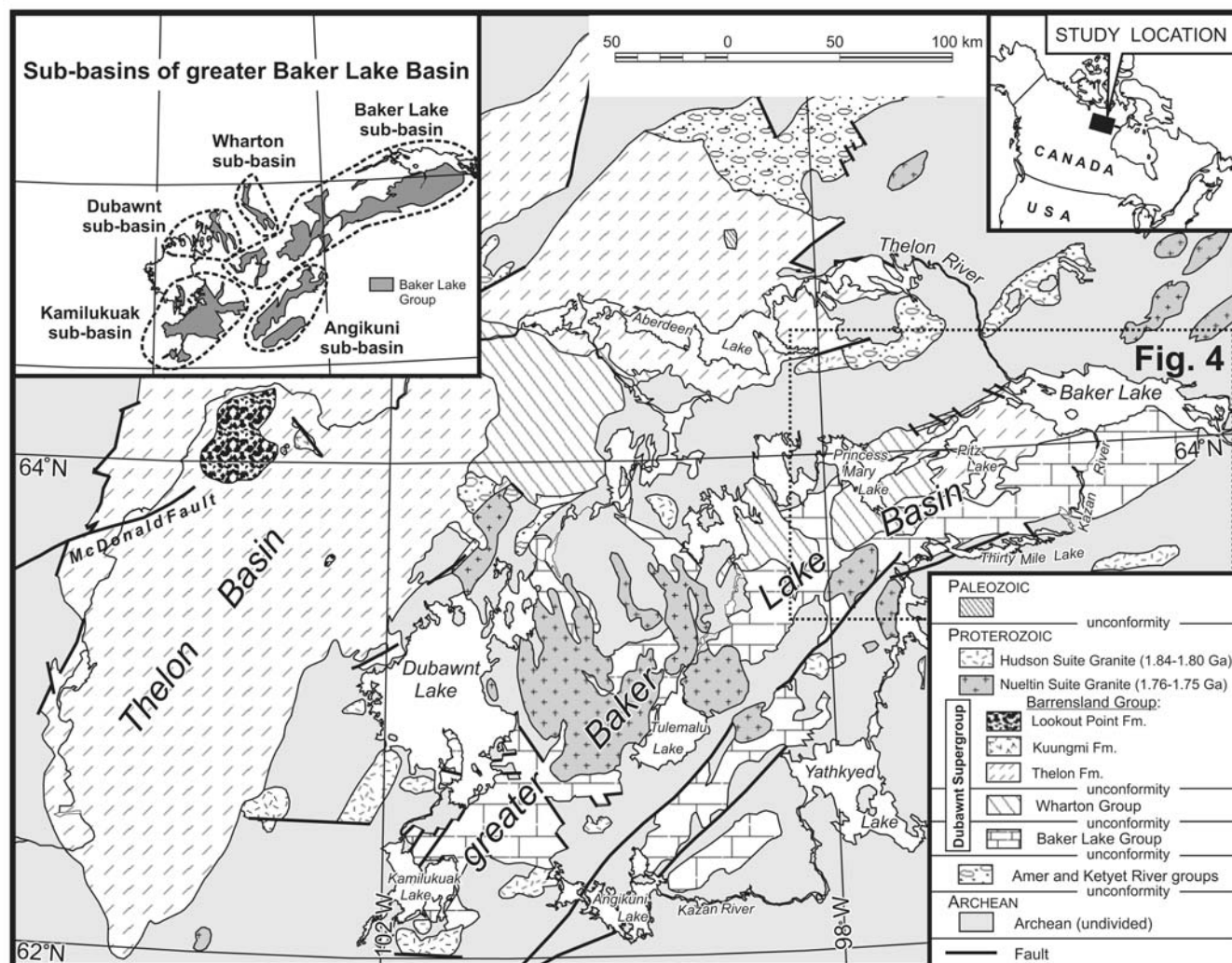
The depositional relationship between graded profile and sediment flux is inherently dynamic because a graded river is defined by zero net deposition; therefore the resulting deposits are a direct result of adjustments made by a river in a non-graded state. Furthermore, even if other factors remain constant, then



TEXT-FIGURE 2

The graded profile. Dynamics of the graded profile with respect to changes in base level, subsidence, and source region uplift or erosion. SF = sediment flux, A = accommodation, RSL = relative sea level (base level), Retro- = retrogradation, and Pro = progradation. Note that certain elements, particularly the subaqueous environments have been exaggerated for clarity.



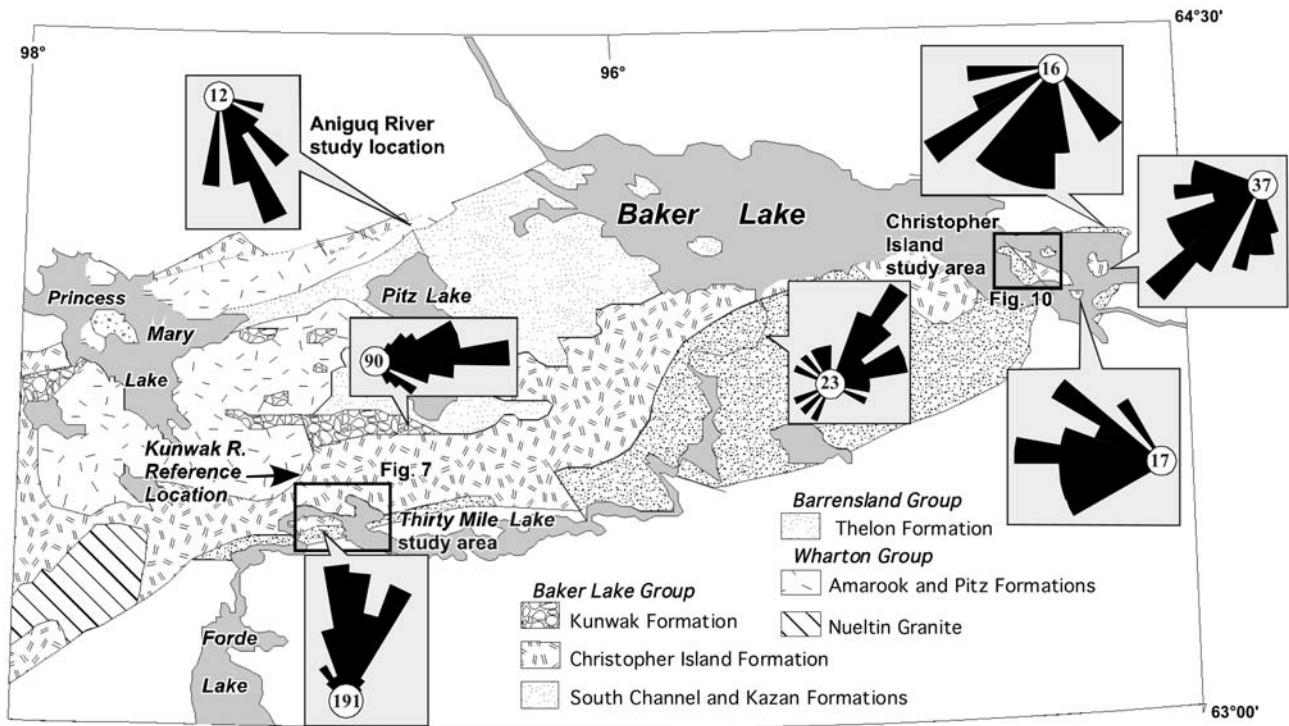


TEXT-FIGURE 3  
Geologic map of the greater Baker Lake Basin highlighting the distribution of sub-basins (after Rainbird et al. 2003).

through positive feedback effects fluvial sediment flux will tend to result in additional subaerial accommodation. This is illustrated in text-figure 2a; the initial state is a graded profile intersecting subaqueous base level at the shoreline. If all relevant factors are positive (SF, discharge, base level), then fluvial sediment flux will result in subaqueous deposition at the shoreline (i.e. delta), and accordingly progradation. Basinward migration of the shoreline will decrease the net gradient of the graded profile and a small amount of fluvial accommodation space will have been created and filled between the initial graded profile and the resultant graded profile. Although not shown on the diagram, erosion of the sediment source region will tend to lower the elevation of the sediment source point, decreasing the gradient further (Nummedal et al. 1993). The decrease in gradient over the course of alluvial deposition will result in a retrogradational succession of fluvial facies concurrent with progradation of nearshore facies. Opposing trends between river-mouth and upper valley locations were envisaged by Nummedal et al. (1993), who suggested that "aggradation characterizes the lower alluvial valley in response to river-mouth progradation, and that the upper valley reaches degrade." This represents the dynamics of the fluvial system during relatively

static boundary conditions, and illustrates the nature of the graded profile concept as a state of dynamic equilibrium.

The response of the graded profile to changes in relative lake level is more complex, and is directly related to the ratio of SF to A, as incorporated into shelf sequence stratigraphic models (Vail et al. 1977). If subaqueous base level rises and accommodation exceeds sediment flux, then the rate of deposition *along* the graded profile *and* at the shoreline is exceeded by base level rise and the shoreline will retreat landward (text-fig. 2b). From text-figure 2b, if other factors remain unchanged, then base level rise will result in a decrease in gradient of the graded profile, hence retrogradation of both fluvial and nearshore subaqueous facies. If  $SF = A$ , then fluvial and nearshore deposition will fill new accommodation space and nearshore facies will aggrade; however, the fluvial gradient will decrease and therefore fluvial facies will retrograde. If  $SF > A$ , then fluvial and nearshore deposition will exceed accommodation and original AS will be filled as nearshore facies prograde; the fluvial gradient will decrease and fluvial facies will retrograde. If, for a given fluvial system sediment flux is approximately constant, then we can restate these SF/A relations as high to low accom-



TEXT-FIGURE 4

Geology of the Baker Lake sub-basin, including paleocurrent data derived from cross-set and primary current lineation measurements. Note that boxes outline Thirty Mile Lake and Christopher Island study areas, whereas Kunwak River and Aniguq River are indicated by arrows.

modation systems representing transgressive and highstand systems tracts. Relative lake level fall will result in alluvial erosion or deposition, depending on the gradient of the newly exposed land surface (Schumm, 1993). Illustrated in text-figure 2c RLL results fall in a basinward migration of the shoreline, and subaerial erosion starting at the old shoreline, and an increase in gradient of the graded profile and thus stream calibre. Basinal facies will prograde in response, and when RLL fall ceases, coarse fluvial deposits will overlie an erosional surface. Note that within the model, lake level rise, exclusively, does not result in an increase in net gradient of the graded profile; in each of the three cases described, alluvial facies are expected to retrograde, a point that would be reinforced if source region denudation were considered.

Thus far, changes in relative lake level have been addressed and are consistent with existing literature (Nummedal et al. 1993; Quirk 1996; see review in Blum and Tornqvist 2000). These changes could be the result of lake level fluctuations, and/or basin subsidence/uplift; however, the type of subsidence considered would be quite specific, affecting the source and basin uniformly, a relation that is expected to breakdown toward basin margins due to differential subsidence and source uplift. text-figure 2d and text-figure 2e address tectonic factors. Text-figure 2d considers the effect of source region uplift, which is assumed to be the result of faulting and not a general tilting of the basin margin. The result is an increase in gradient of the graded profile as the alluvial system aggrades to match uplift of the sediment source region. This results in progradation of fluvial facies and deposition between the initial graded profile and the new graded profile. The progradation of facies is highly dependent upon sediment flux and the ability of

the alluvial system to aggrade in response to source uplift. Note that, primarily as a function of the calibre of sediment supplied, the profile would have an upper gradient limit, in which case the depositional part of the stream would abut against the uplifted area. Also, in consideration of the amount of potential alluvial accumulation, nearshore environments may be characterized by low rates of sediment flux. Or, due to selective deposition of coarse fractions upstream near shore environments may be characterized by fine-grained sediment (e.g. Paola and Seal 1995), unless source uplift dramatically increased *S* and *SF* thereby oversupplying the alluvial plain and transporting sediment to nearshore locations.

In the case of differential subsidence increasing toward the basin centre, the effects will be more complex than for lake level rise. The land surface, and hence the graded profile, will become tilted toward the basin. The result is a forced increase in gradient, producing a more competent streamflow, and thus promoting progradation of alluvial facies and increase in grain size. Nearshore locations will experience relative lake level rise, and lacustrine facies will retrograde. It is noted that text-figures 2a-d can be found in various forms throughout the literature (e.g. Quirk 1996; Holbrook et al. 2006).

In tectonically active basins, subsidence and marginal uplift are genetically linked. For example, subsidence in a foreland basin is a response to tectonic loading and crustal thickening in the adjacent orogen (Quinlan and Beaumont 1984). Similarly, normal fault motion in a rift basin provides relative basin subsidence and coeval marginal uplift (e.g. Leeder 1995). The result for a graded profile is concurrent source uplift and basinal subsidence (text-fig. 2e). This will have the simultaneous effects of

Lithostratigraphy				Sequence Stratigraphy		
Dubawnt Supergroup	Group	Formation		Second-order		
					Third-order	
	Barrensland Group	Lookout Point Fm.		Barren Sequence	4	<div>■ 1720 +/- 6 Ma</div>
					3	
		Kuungmi Fm.			2	
					1	
	Wharton Group	Pitz Fm.		Whart Sequence	3	<div>□ 1754 +/- 2 Ma</div>
					2	<div>□ 1758 +/- 3 Ma</div>
Amarook Fm.		1				
Baker Lake Group	Kunwak Fm.	Felsite	Baker Sequence	B-5	<div>● 1785 +/- 3 Ma</div>	
		Minette		B-4		
	Kazan Fm.	Christopher Island Fm.		B-3		
	South Channel Fm.	Felsic Minette		B-2		
				B-1		<div>□ 1833 +/- 3 Ma</div>

■

 Pb-Pb (apatite)

□

 U-Pb (zircon)

●

 Pb-Pb (calcite)

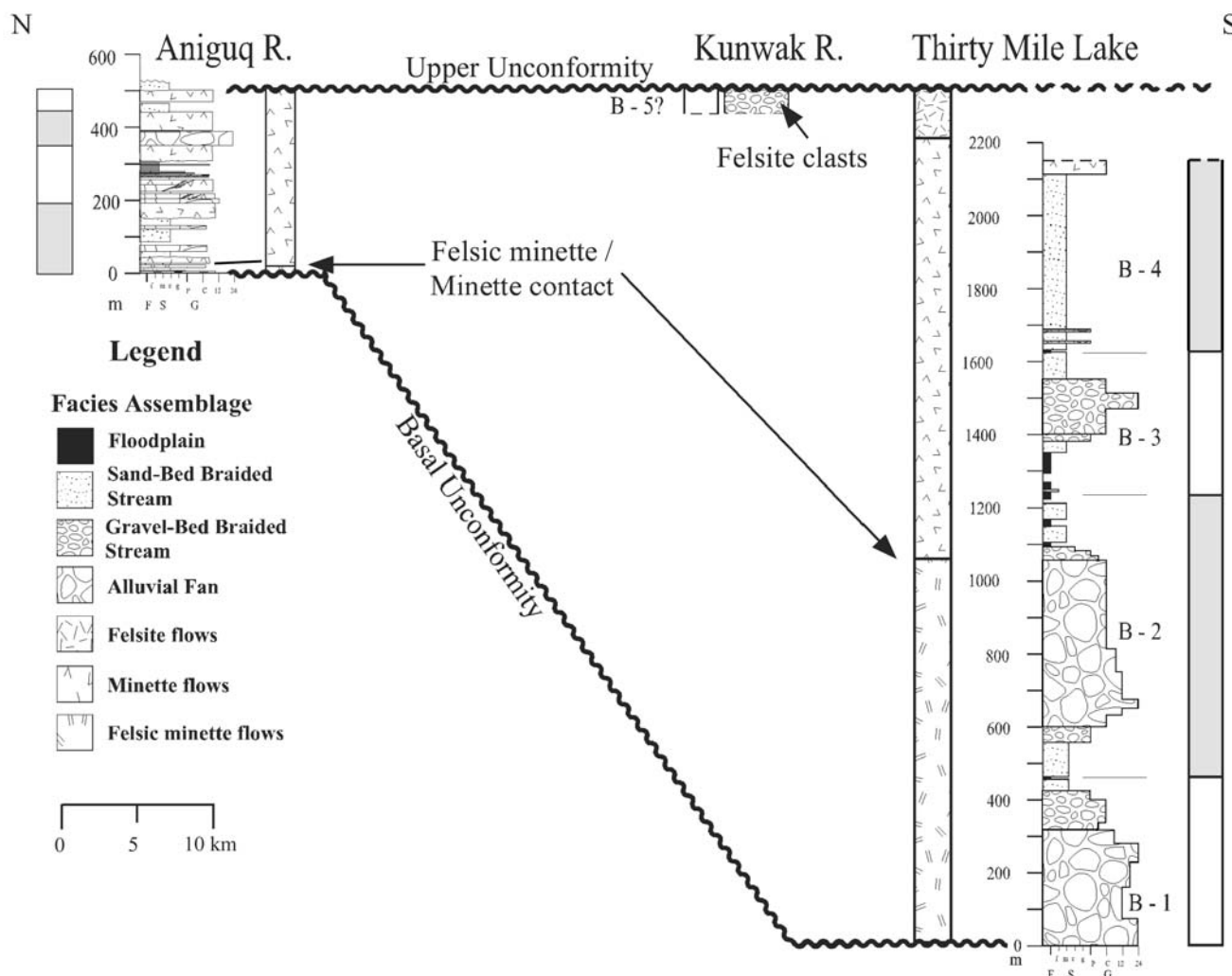
TEXT-FIGURE 5

Litho- and sequence stratigraphy of the Baker Lake Basin. Geochronology sources: Thelon Fm., 1720 +/- 6 Ma (Miller et al. 1989); Pitz Fm., (Rainbird et al. 2001); Baker Lake Grp., 1785 +/- 3 Ma (Rainbird et al. 2002), 1833 +/- 3 Ma (Rainbird et al. 2006).

an increase in gradient of the graded profile and a relative rise in subaqueous base level. The high fluvial accommodation and net increase in gradient will result in progradation of fluvial facies. The high potential for fluvial deposition may result in low nearshore sediment flux, thereby increasing the probability of retrogradation of nearshore facies in response to relative lake level rise. Indeed, there are expected to be feedback effects upon sediment supply and flux which have been omitted for the sake of simplicity. For example, source uplift would be expected to increase the grain size of sediment supply. Within the context of the model this will tend to reinforce the expected progradation of fluvial facies (text-fig. 2d and e). Upon cessation of uplift/subsidence, denudation of the source region would tend to decrease grain size and sediment flux enhancing the expected retrogradation of fluvial facies, in concert with nearshore progradation as in text-fig. 2a.

Since every sedimentary basin is characterized, indeed defined, by some form of tectonic subsidence and that changes in base level will only be recorded in deposits when superimposed on a subsidence curve (e.g. Nummedal et al. 1993), the most relevant models are those that incorporate subsidence (text-fig. 2a, c, d, and e). Successional patterns in proximal alluvial and nearshore subaqueous environments are thus decoupled throughout the accommodation cycle: tectonic subsidence such that  $A > SF$  leads to progradation and retrogradation, respectively (text-fig. 2e); stillstand or  $SF > A$  (tectonic or subaqueous base level) leads to retrogradation and progradation, respectively (text-fig. 2a); and finally base level fall likely leads to erosion in both (text-fig. 2c), transporting coarse detritus to more basinal locations. This model concludes that fluvial accumulation occurs mostly during relative lake or sea level rise and during periods of tectonism and source uplift as suggested by Miall (1991).





TEXT-FIGURE 6

North-south cross-section of the Baker Lake Basin from Aniguq River to Thirty Mile Lake. The sedimentary and complementary volcanic-dominated sections are lateral equivalents. The Thirty Mile Lake volcanic section is composite. Note that the Kunwak River outcrop contains felsite clasts, equivalent to the youngest volcanic rocks at Thirty Mile Lake. The Aniguq River and Kunwak River sections are from the reference locations shown in text-figure 3.4. Thirty Mile Lake section is section B from text-figure 3.7.

## SEQUENCE STRATIGRAPHY OF BAKER LAKE BASIN

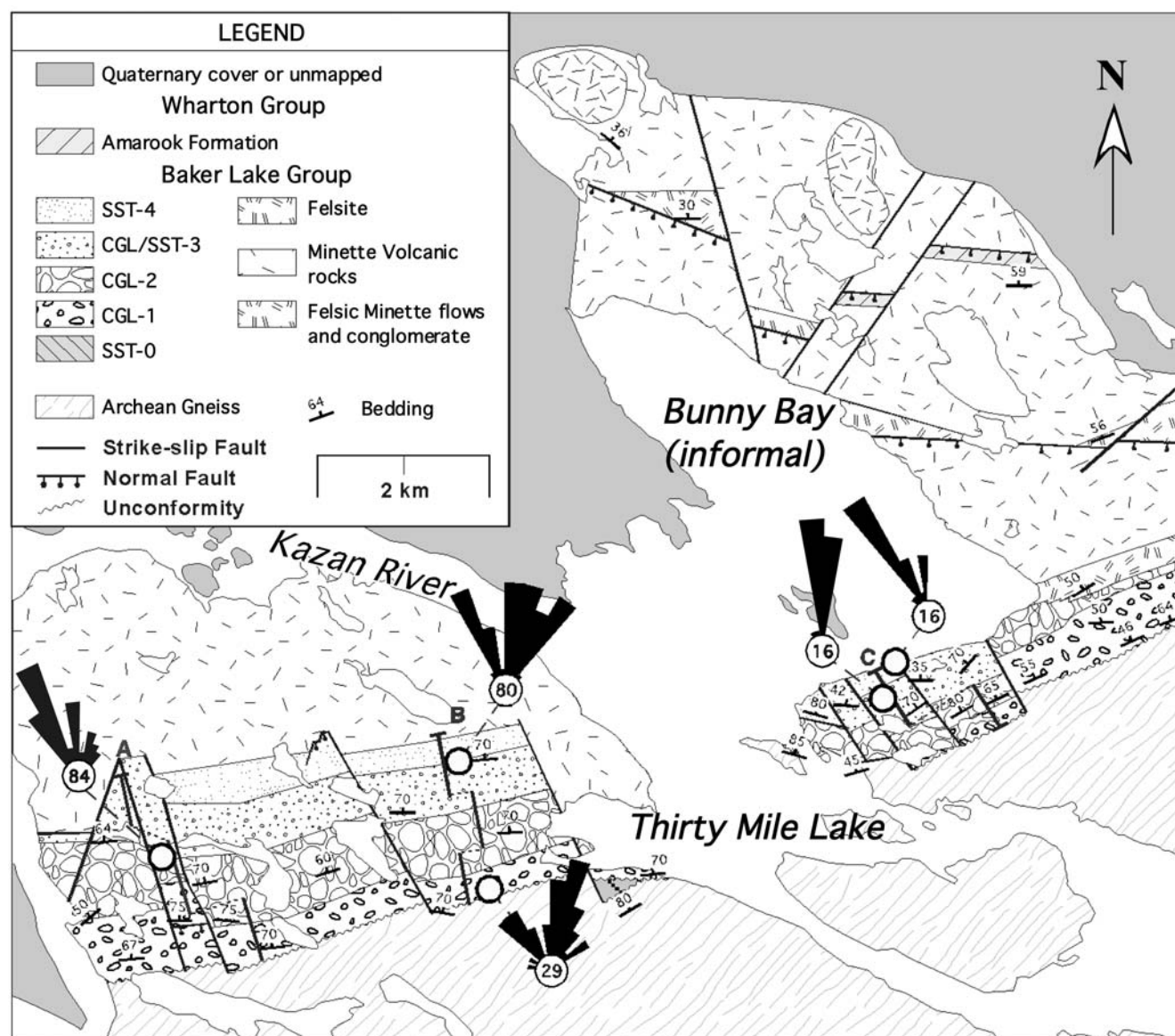
### Regional Geology

Greater Baker Lake Basin extends from Dubawnt Lake northeast to Baker Lake (Nunavut, Canada) and comprises a series of northeast-trending intracontinental basins, including the Baker Lake sub-basin (Rainbird et al. 2003; text-fig. 3; text-fig. 4). Basin fill comprises the faulted but unmetamorphosed, siliciclastic and volcanic rocks of the Dubawnt Supergroup (Wright 1955; Donaldson 1965, 1967; LeCheminant et al. 1979b; Gall et al. 1992; Rainbird and Hadlari 2000; Rainbird et al. 2003; text-fig. 5).

The Dubawnt Supergroup is sub-divided into three unconformity-bounded lithostratigraphic units that correspond to, from oldest to youngest: the Baker Lake, Wharton, and Barrenland groups (Donaldson 1967; Gall et al. 1992; Rainbird and Hadlari 2000); or the Baker, Whart, and Barrens

second-order sequences (text-fig. 5; Rainbird et al. 2003; *sensu* Krapez 1996; 1997). These groups or corresponding second-order sequences have been interpreted to represent the tectonic stages of rift, modified rift, and thermal sag respectively (Rainbird et al. 2003). This paper addresses the third-order sequence stratigraphy of the Baker second-order sequence.

The sedimentology of the Baker Lake Group (Rainbird et al. 2003; Hadlari 2005; Hadlari et al. 2006) indicates a transverse drainage system of alluvial fans to braided streams, with floodplains and eolian dunes adjacent to inactive channels. This transverse system fed an axial drainage system that was directed northeast and less extensively southwest, culminating at a depocentre near Christopher Island (text-fig. 4). At this depocentre, deltas fed into a lake surrounded by floodplains, mudflats, and eolian dunes with prevailing wind from the south-east and northwest. The drainage pattern and distribution of facies are consistent with deposition within a volcanically active



TEXT-FIGURE 7

Geologic map of the Thirty Mile Lake study area. Paleocurrent data were derived from cross-set measurements. CGL = conglomerate and SST = sandstone. Note location of sections A, B, and C of text-figure 8.

half-graben. Formations that compose the Baker Lake Group reflect the lateral distribution of facies (Hadlari et al. 2006): South Channel Formation comprises alluvial fan deposits; Kazan Formation comprises braided stream, eolian, and lacustrine deposits; and Kunwak Formation comprises conglomerate that contains volcanic clasts of the Christopher Island Formation.

The Christopher Island Formation comprises alkaline volcanic rocks inter-bedded with volcanoclastic and siliciclastic sedimentary rocks (Donaldson 1966; LeCheminant et al. 1979a, LeCheminant et al. 1979b; Blake 1980). A generalized volcanic stratigraphy for the greater Baker Lake Basin, from oldest to youngest, consists of: felsic minette flows; minette flows; and felsite flows (Peterson et al. 1989; Hadlari and Rainbird 2001; Rainbird et al. 2003). The felsic minette flows or equivalent volcanoclastic deposits overlie the basal unconformity of the

Baker Lake Group and were erupted less extensively than the younger minette flows. Mantle-derived minette flows record voluminous extrusion throughout the entire basin and represent the largest known ultrapotassic volcanic province (LeCheminant et al. 1987; Peterson et al. 1989; Peterson et al. 1994; Cousens et al. 2001). Felsite flows are the youngest and most areally restricted volcanic rock.

Geochronological information has been primarily derived from volcanic or coeval intrusive rocks and bracket deposition of the Baker Sequence between ~1.84-1.79 Ga (see Rainbird et al. 2006).

#### Methodology

The sequence stratigraphic method utilized herein follows Krapez (1996), after Vail et al. (1977), Van Wagoner et al. (1988), and Posamentier et al. (1993), with respect to the recon-

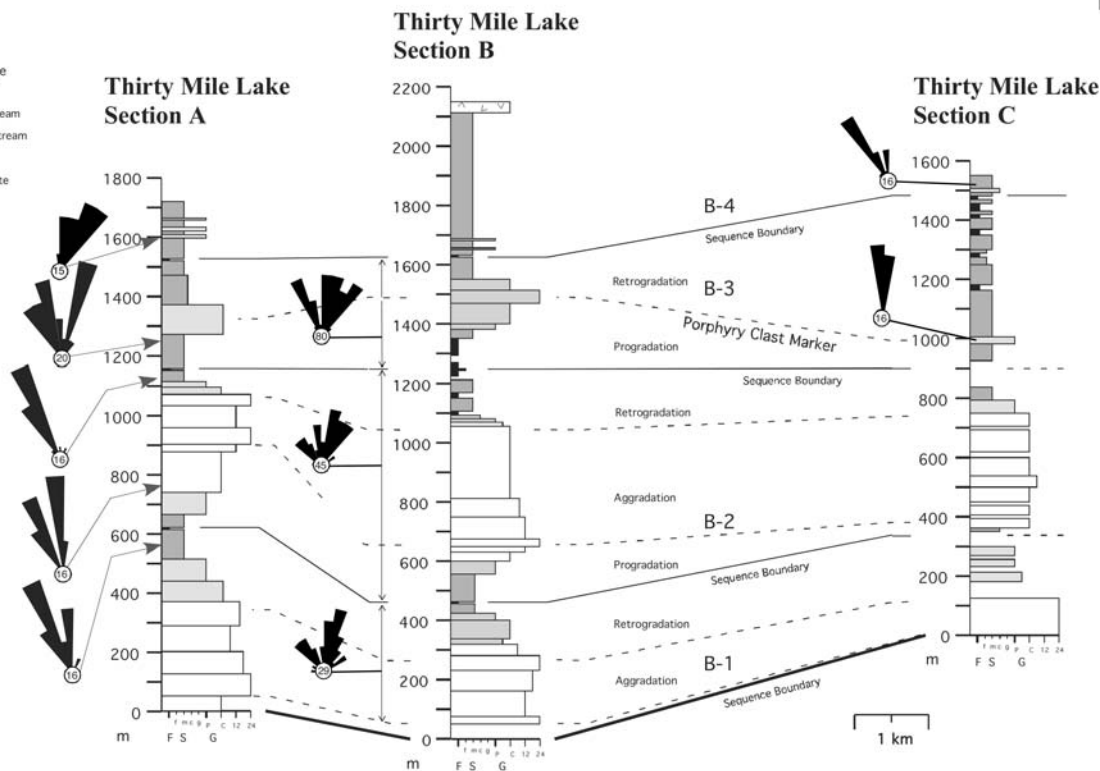


SW

NE

## Legend

- Facies Assemblage
- Floodplain
  - Sand-Bed Braided Stream
  - Gravel-Bed Braided Stream
  - Alluvial Fan
  - Volcanic Conglomerate



TEXT-FIGURE 8

Correlated sections from the Thirty Mile Lake study area displaying 3rd-order sequences, B-1 to B-4, partially comprising the Baker 2nd-order Sequence. F = mudstone, S = Sandstone, and G = conglomerate. Section locations are indicated on text-figure 7.

struction of sedimentary environments and interpretation of successions. Various orders of sequences in the Baker Lake Basin are described from basic metre-scale sedimentary cycles to kilometre-scale tectonic stages. For clarity during description, it is necessary to refer to the stratigraphic order each unit represents; these have been determined according to the framework outlined in Krapez (1996; 1997) after Vail (1977): first-order sequences (~180 m.y.) correspond to the opening or closing of ocean basins - couplets of these correspond to the Wilson Cycle; second-order sequences (~22-45 m.y.) represent tectonic stages of basins (e.g. passive margin, foreland basin, or rift basin); third-order sequences (1-11 m.y.), or basin-filling rhythms, record pulses of accommodation and are a function of basin type (e.g. clastic wedges in foreland basins); and fourth-order sequences correspond to sediment flux patterns or relatively minor base level fluctuations.

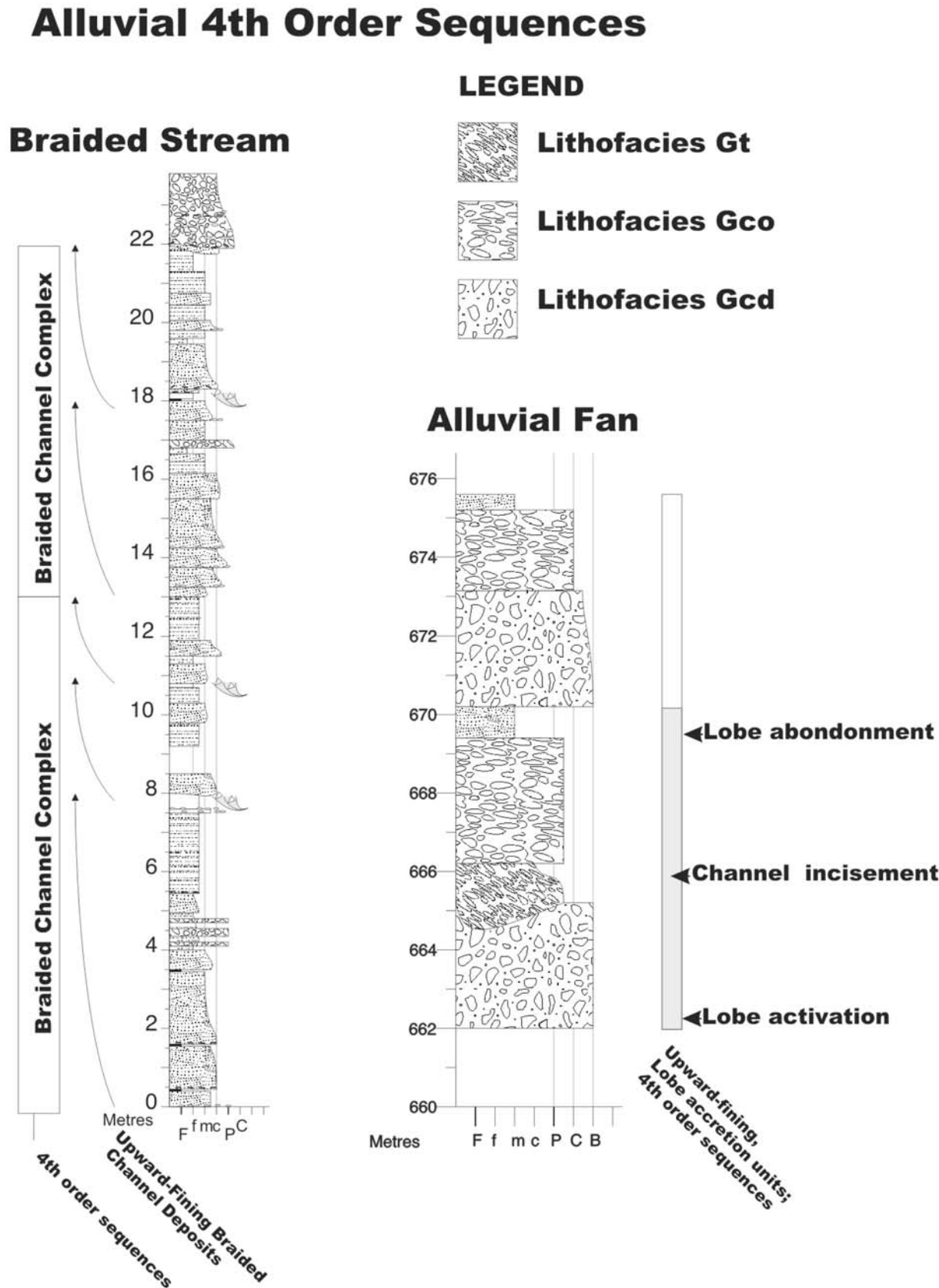
With respect to unconformities, basin paleogeography, volcanic signature, and duration (~40-50 m.y.) the Baker Sequence represents a distinct tectonic stage within the Dubawnt Supergroup, and is therefore considered to be second-order (Rainbird et al. 2003). Within the thickest preserved sections (>2 km thick), alternating coarse alluvial fan and fine braided stream / floodplain deposits hundreds of metres in thickness have been interpreted as third-order sequences, which are composed of lower-order progradational, aggradational, and retrogradational sequence sets (Hadlari and Rainbird 2000; Rainbird et al. 2003). Following the hierarchical sequence concept these lower-order sequences are considered to be fourth order. They are not intended to be equivalent to fourth-order

sequences from basins of different tectonic setting. These interpretations are based on sections from three locations in the Baker Lake sub-basin, Aniguq River, Christopher Island, and Thirty Mile Lake – primarily the latter two (text-fig. 4).

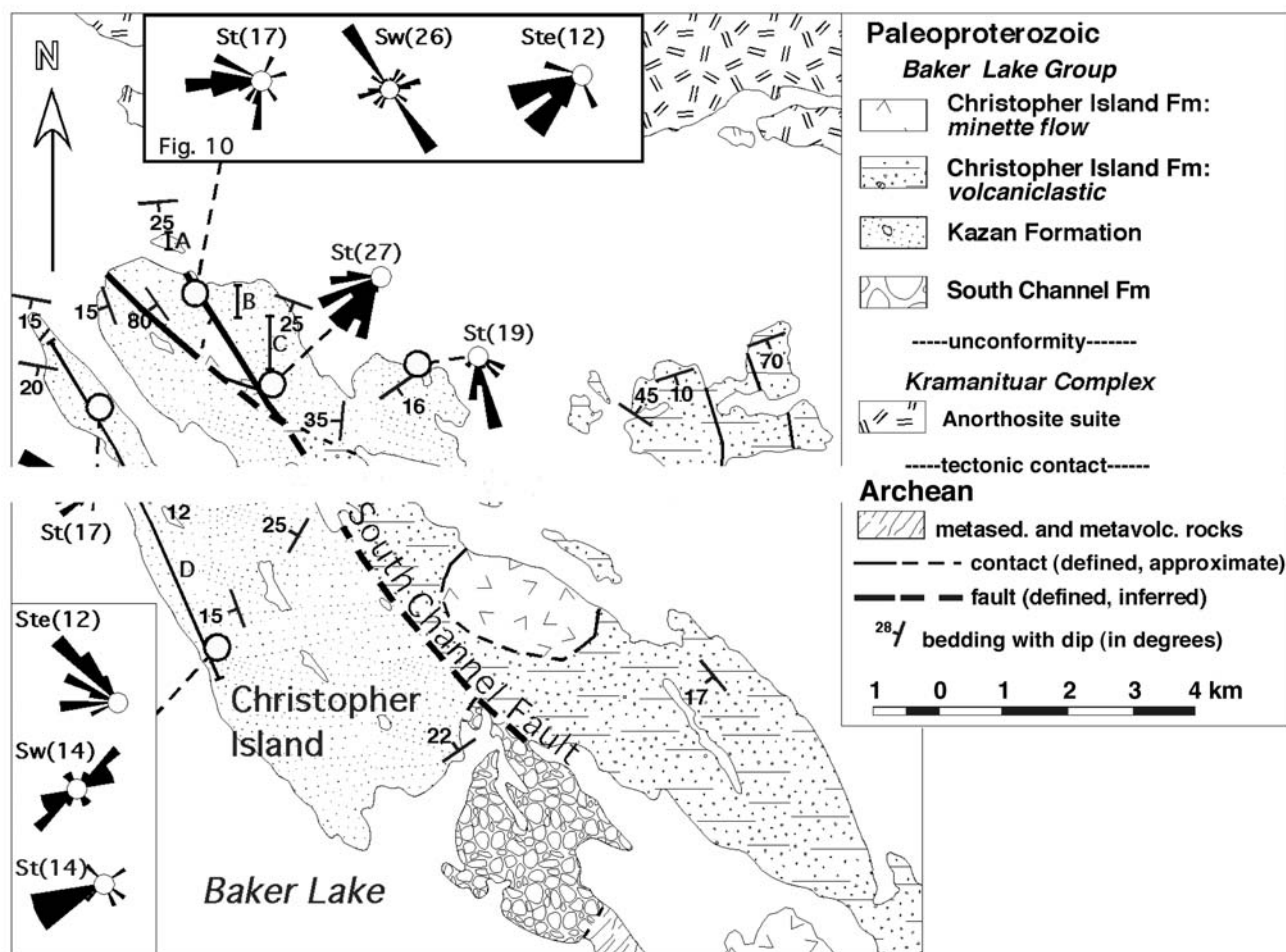
### Thirty Mile Lake

Baker sequence rocks near Thirty Mile Lake generally dip more than 45°, allowing sections measured to be from this area that are relatively thick. The stratigraphic thickness is much greater on the south side (Thirty Mile Lake) than on the north side of the basin (Aniguq River), reflecting proximity to the inferred main bounding fault of the half-graben (text-fig. 6). A volcanic section is correlated to the predominantly sedimentary section based on lateral facies transitions and conglomerate clast lithologies (text-fig. 6). Alluvial fan, braided stream, floodplain, eolian, and volcanic facies comprise three sections from the western end of Thirty Mile Lake (text-fig. 7). Although stratigraphic analysis here focuses on the sedimentary sections, basal correlations largely depend on the volcanic sections.

Stratigraphic sections from Thirty Mile Lake are composed of alluvial fan, braided stream, and floodplain deposits, sub-divided into four distinct intervals hundreds of metres thick that can be correlated within the western Thirty Mile Lake area (text-fig. 8). These represent the next hierarchical subdivision down from the Baker second-order sequence, interpreted as third-order sequences termed B-1, B-2, B-3, B-4, and considering the felsite bearing conglomerate at Kunwak River, B-5. B-1 is stratigraphically equivalent to felsic minette flows. B-3 is dominated by felsic minette clasts, but also contains minette



TEXT-FIGURE 9  
Fourth-order sequences of the alluvial fan, braided stream, and floodplain facies assemblages. Alluvial fan and braided stream sections are from Thirty Mile Lake sections B and C respectively, text-figure 7.



TEXT-FIGURE 10

Geology map of the Christopher Island study area including paleocurrent data (St = fluvial; Sw = wave ripple crests; Ste = eolian cross-sets). Note locations of sections A, B, C, and D displayed in text-figures 11 and 12.

clasts, indicating that minette volcanism had initiated during or immediately after sequence B-2. Sequence B-5 contains minette and felsite clasts, indicating that it is younger or equivalent to the felsite volcanic sub-division.

The 3<sup>rd</sup>-order sequences are composed of distinct upward-fining intervals approximately 5-15m thick, interpreted as 4<sup>th</sup>-order sequences (text-fig. 9) which are composed of sedimentary elements. Fourth-order sequences from the alluvial fan facies association consist of multiple conglomerate sheets that generally fine-upward, are alternately incised by channel-filling conglomerate, and capped by sandstone or laminated mudstone (text-fig. 9). These are considered to be units of lobe accretion, and the punctuated succession to be a product of alluvial fan lobe activation and abandonment (Hadlari et al. 2006). Fourth-order sequences from the braided stream facies association are also upward-fining, and interpreted as 5-15m thick channel complexes (Hadlari et al. 2006).

Fourth-order sequences from the floodplain facies association also fine-upward, with intercalated sandstone- and mudstone-dominated intervals representing small crevasse-type channels within an overbank setting. Floodplain deposits from Thirty Mile Lake display wet-condition features such as an abundance

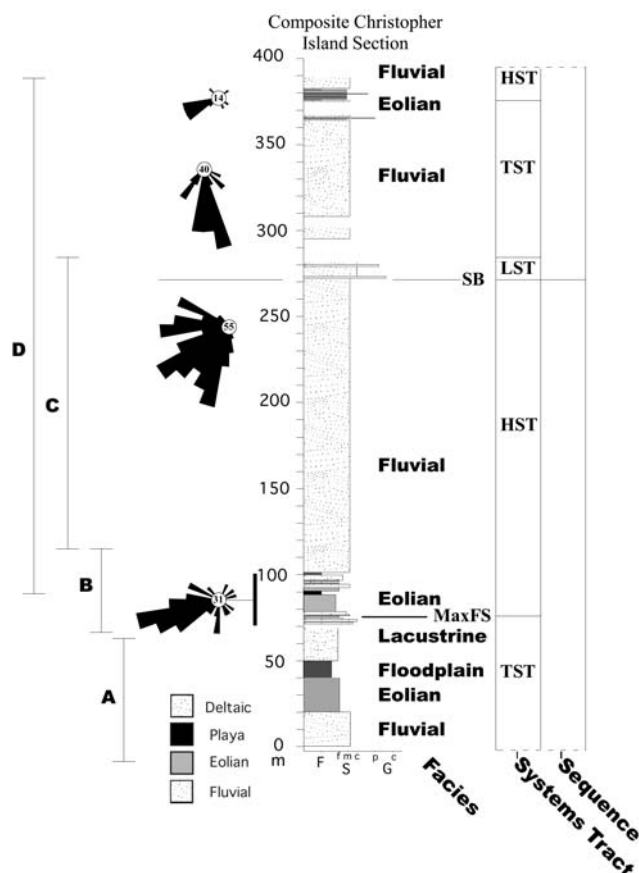
of wave ripples, indicating a near surface water table. Similarly, the eolian deposits from Christopher Island tend to contain wet-condition interdune intervals; their preservation appears to be linked to water table fluctuations (Hadlari et al. 2006).

### Third-Order Sequences

Third-order sequence B-1 unconformably overlies crystalline basement rocks (text-fig. 7). It comprises a thin (< 50m) to absent progradational set of 4<sup>th</sup>-order alluvial fan sequences at its base. These pass upward into an approximately 300m thick aggradational set of 4<sup>th</sup>-order alluvial fan sequences including boulder-grade conglomerate, overlain by a 100-200m thick retrogradational set of 4<sup>th</sup>-order sequences from alluvial fan through gravel-bed to sand-bed braided stream deposits. The top of sequence B-1 is placed at the point of maximum retrogradation, marking the point of lowest depositional gradient.

At the base of sequence B-2, a progradational set of 4<sup>th</sup>-order sequences grade from sand-bed braided stream through gravel-bed braided stream to alluvial fan deposits that demarcate a significant upward increase in depositional gradient. An aggradational set 300-400m thick records the maximum gradient. This is succeeded by a set that retrogrades from alluvial fan to gravel-bed, to sand-bed braided stream, and finally to





TEXT-FIGURE 11

Third-order sequences from the depocentre of the Baker paleobasin, at Christopher Island, that are composed of fourth-order sequence sets. Composite section composed of sections A, B, C, and D from text-figure 10. Note that section B is illustrated in text-figure 12. LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract, and SB = sequence boundary.

floodplain deposits from 10 to 100m thick. The top of sequence B-2 is determined by maximum retrogradation. This is represented by eolian deposits within the floodplain facies. Above the eolian deposits, fluvial sandstone progressively dominates the floodplain facies, which then grades upward into sand-bed braided stream facies.

The base of B-3 is a progradational set of 4<sup>th</sup> order sequences, from floodplain through sand-bed to gravel-bed braided stream facies. At outcrop scale and between sections, thickness of the conglomerate and its stratigraphic level relative to the underlying floodplain mudstone are laterally variable over hundreds of metres, consistent with channelized flow as opposed to the steep unconfined flow of alluvial fans. Aggradation of coarse conglomerate is not as pronounced as it is in sequences B-1 and B-2; a retrogradational set of 4<sup>th</sup> order sequences defines the upper part of B-3. The facies that define the retrogradation differ slightly between sections. In section C (text-fig. 8), gravel-bed braided stream facies grade upward into sand-bed braided stream, and then into approximately 100m of floodplain-rich facies. At the top, floodplain fines are sharply overlain by sandstone and pebbly sandstone. In sections A and

B, floodplain fines are less abundant, and laterally equivalent deposits comprise coarser, more proximal facies, consistent with thicker and coarser progradation-maximum deposits of sequence B-3 in sections A and B, and therefore a mark long term, more channel- proximal location.

Sequence B-4 has a very thin progradational component, from floodplain to thin gravel-bed braided stream deposits. This passes upward into > 200m of sand-bed braided stream deposits. This sequence is interrupted at the top by minette flows (text-fig. 8, section B).

At the west end of Thirty Mile Lake (text-fig. 8), minette flows are overlain by felsite flows. On the Kunwak River, approximately 15km north-northeast of section A, Baker Sequence conglomerate that contains both minette and felsite clasts is unconformably overlain by the Whart Sequence, and therefore is considered to be the youngest Baker Sequence siliciclastic deposit in the area. This conglomerate is considered to overlie the sandstone of B-4, and is therefore assigned to sequence B-5.

#### Application of the Terrestrial Sequence Stratigraphic Model

The first step in applying the terrestrial sequence stratigraphic model to the Baker Sequence is to define the sedimentary facies tracts. Based on gradational facies boundaries within the sections at Thirty Mile Lake, linked facies of decreasing depositional gradient from proximal to distal are: alluvial fan, gravel-bed braided stream, to sand-bed braided stream and floodplain facies associations (Hadlari et al. 2006). Since this is an alluvial system and the location is inferred to have been adjacent to the basin margin, with respect to text-figure 2 these sections, illustrated in text-figure 8, are considered to lie in the proximal alluvial zone.

Fourth-order sequences represent accumulation-abandonment episodes of alluvial fan lobes, braided channel complexes, and floodplain channels. Thus, within the alluvial deposits, 4<sup>th</sup> order sequences represent lateral shifting of sediment flux pathways, and the upward-fining character does not necessarily indicate large-scale sediment flux/accommodation (SF/A) relations, and therefore basin scale correlation is inappropriate (Krapez 1996). However the vertical succession of these 4<sup>th</sup> order sequences does reflect changes that can be interpreted with respect to basin-scale sediment flux and accommodation.

Third-order sequences B-1 and B-2 are composed of similar facies and 4<sup>th</sup> order sequence sets. The progradational component of B-1 consists of upward-coarsening alluvial fan deposits that are thin and discontinuous, reflecting infill of paleotopography on the basal unconformity. The progradational 4<sup>th</sup> order sequence set of B-2 grades from sand-bed braided stream, through gravel-bed braided stream, to alluvial fan deposits. This represents increasing depositional gradient during alluvial accumulation as shown in text-figure 2e, in response to basin subsidence and coeval marginal uplift. At Thirty Mile Lake near the inferred master fault of the half-graben, this increase in gradient resulted in the formation of alluvial fans. The aggradational 4<sup>th</sup> order sequence set represents the maximum gradient determined by the maximum grain size of sediment supply. Note that the central "aggradational" component of each sequence actually fines-upward or coarsens-upward and that this is complementary between sections of the same sequence (e.g. B-2 coarsens-upward in section A and fines-upward in section B, Fig. 8). Since the coarsest grain size of each sequence, or the progradation-maximum, occurs at different points within the

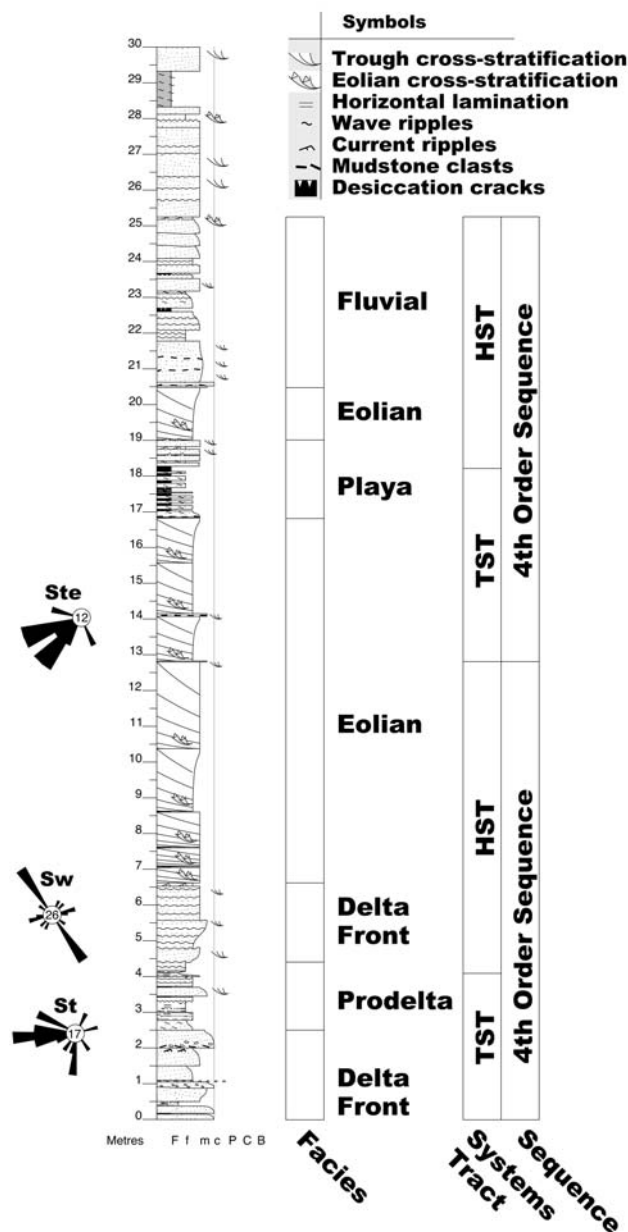
vertical succession between sections, kilometre-scale lateral sediment flux patterns have a significant effect upon the succession, and therefore the exact point of maximum grain size is non-unique, in contrast to a maximum flooding surface.

The upper component of sequences B-1 and B-2 consists of retrogradational 4<sup>th</sup>-order sequence sets, from alluvial fan to sand-bed braided stream, or floodplain facies respectively. This represents a decrease in depositional gradient over the course of alluvial accumulation, and signifies a decrease in accommodation such that sediment accumulation in the basin was able to infill new and old accommodation space, thus decreasing the net gradient through vertical end-of-slope aggradation and lateral, basinward migration of the shoreline as in text-figure 2a. The retrogradational 4<sup>th</sup>-order sequence set of sequence B-2 culminates in floodplain facies that represent the lowest depositional gradient, and a phase of a high proportion of sediment throughput. When relating fluvial deposits to a graded profile and inferred paleoslope, it is important to note that floodplain fines are overbank deposits. Since overbank processes selectively deposit the finest fraction of the sediment load, floodplain deposits do not reflect the competency of streamflow within associated channels, nor do they indicate the calibre of the sediment load. Therefore floodplain deposits represent the lowest gradient, but the nature of the bypassing sediment is unknown. The sequence boundary is placed at the point of maximum retrogradation of facies, for example eolian facies within the floodplain deposits. Since the point of maximum progradation is non-unique, the point of maximum retrogradation may be non-unique too. It is therefore possible that the sequence boundary should be placed at the floodplain – braided stream facies contact. Due to the overall high accommodation setting, this sequence boundary is gradational and difficult to place.

Sequence B-3 comprises a lower 4<sup>th</sup>-order sequence set that progrades from floodplain to gravel-bed braided stream facies, and an upper set that retrogrades to floodplain facies. The gravel-bed braided stream deposits vary in thickness and grain size between sections, and the thickness of floodplain facies is complementary to this variation. Coarse fluvial conglomerate is prominent within section B and floodplain mudstone prominent within section C. This likely reflects the position of the “main” alluvial channel belt, a topographically lower area of greater subsidence and therefore higher accommodation. That section B was the location of greater subsidence is consistent with the greater total thickness of section B, and with paleocurrent measurements from sequences B-3 and B-4 within sections A and C that trend toward section B. With respect to graded profile, the progradation represents an increase in gradient over the course of alluvial accumulation, likely as a response to basin subsidence and coeval marginal uplift. The retrogradation is interpreted to represent infilling of accommodation space, a decrease in the depositional gradient and a culminating phase characterized by a high proportion of sediment throughput.

Sequence B-4 is similar to B-3 except that the conglomerate is much thinner and finer grained. Although the upper part of sequence B-4 is interrupted by minette flows, the implications with respect to graded profile and accommodation are the same.

Sequences containing alluvial fan facies are sub-divided into progradation, aggradational, and retrogradational successions. Within the present framework these are related to increasing, high, and low accommodation and gradient. This approach is



TEXT-FIGURE 12

Fourth-order sequences composed of eolian, playa, and deltaic facies. Section corresponds to section B in text-figs. 10 and 11.

consistent with the findings of Viseras et al. (2003) that recent alluvial fans in: low subsidence settings were characterized by relatively low gradients and progradation; high subsidence settings were characterized by high gradients and aggradation; and very low subsidence settings were characterized by the lowest gradients and retrogradation.

A similar analysis can be applied to the succession of 3<sup>rd</sup>-order sequences as to the succession of 4<sup>th</sup>-order sequences. At Thirty Mile Lake, the succession B-1 to B-4 is overall upward-fining, defining a retrogradational 3<sup>rd</sup>-order sequence set. Sediment flux was exceeded by accommodation, the basin was underfilled, and facies retreated to the basin margin as the sys-

tem was unable to infill the new accommodation space. By implication, closer to the paleobasin margin, though not preserved, sequences B-3 and B-4 would likely have progradation-maximum alluvial fan deposits. Sequence B-5 is coarser grained than sequence B-4, and located at the top of the Baker 2<sup>nd</sup>-order sequence, it marks a progradational top to the succession of third-order sequences, indicating that sediment flux, including volcanic flux, exceeded accommodation at the basin scale likely as a result of decreased subsidence. Although volcanism was active throughout, voluminous minette volcanics virtually blanketed the basin during sequences B-3 and B-4, the period of inferred maximum subsidence and contributed volcanic flux such that the succeeding siliciclastic sequence indicated a basinal overfilled state. The tectonic stage of rifting represented by the Baker 2<sup>nd</sup>-order sequence is thus illustrated by the upward-fining then upward-coarsening succession of 3<sup>rd</sup>-order sequences, indicating increasing rates of accommodation, flood volcanism, subsidence cessation, and finally an overfilled stage overlain by a basin-wide unconformity.

At Thirty Mile Lake contacts between all facies and particularly between sequences are gradational, due to high accommodation in proximity to an inferred basin-bounding normal fault.

### Christopher Island

Baker sequence rocks at Christopher Island have low dips, generally <15°, and the topography is subdued. As a result, the measured thickness of stratigraphic sections is much less than at Thirty Mile Lake. There is however, a sufficient thickness from northwest Christopher Island (text-fig. 10), where the volcanic component is smaller than eastern Christopher Island, to reconstruct a third-order sequence from this paleodepocentral location (text-fig. 11).

Linked facies from proximal to distal are gravel-bed to sand-bed braided stream, floodplain, eolian, playa-mudflat, and shallow lacustrine (Hadlari et al. 2006). Fourth-order sequences in braided stream deposits from Christopher Island are similar to the sand-bed braided stream units from Thirty Mile Lake. Lacustrine bearing 4<sup>th</sup>-order sequences are similar to marine sequences. In text-figure 12, deltaic distributary channel and interdistributary bay deposits are succeeded by delta front turbidites recording relative base level rise. This is succeeded by a prograding delta front, rippled sandsheet, and metre-scale eolian cross-sets that record relative base level fall. The eolian deposits pass upward into playa, eolian, then to fluvial deposits recording another pulse of relative base level rise and fall. These sequences are relatively thin, occurring over 10-15 metres. Thus, 4<sup>th</sup> order sequences that include lacustrine deposits (deltaic or playa) are a function of lacustrine base level fluctuations.

### Third-Order Sequences

The succession of 4<sup>th</sup>-order sequences over a few hundred metres from northern Christopher Island consist of (text-fig. 11): a retrogradational set (TST), culminating at delta front turbidites; a progradational set (HST), with braided stream facies sandstone at the top; another retrogradational set (TST), with a thin basal conglomerate passing through braided stream facies sandstone and overlying eolian sandstone; which passes upward into fluvial sandstone, possibly the upper HST. The 3<sup>rd</sup>-order sequence boundary is an erosional surface at the base of the conglomerate. Across this boundary there is a shift in paleocurrent directions from southwest- to south-directed

(text-fig. 11), indicating a change in the drainage regime likely related to tectonic parameters (cf. Miall 2001). This succession represents two incomplete depositional sequences, which actually constitute a genetic sequence.

### Application of the Terrestrial Sequence Stratigraphic Model

With respect to regional paleocurrent patterns (text-fig. 4) and braided stream, eolian, and lacustrine facies, Christopher Island represents the depocentre of Baker Lake sub-basin and is therefore located at the basinal or nearshore zone in text-figure 2. Although the base of the lower 3<sup>rd</sup> order sequence is not exposed (text-fig. 11), the lower part consists of a retrogradational 4<sup>th</sup> order sequence set of fluvial, eolian, and shallow lacustrine deposits, indicating that SF<A (TST; e.g. text-fig. 2e). Thin delta front deposits record the maximum flooding of the basin. The succession of facies subsequently prograde through eolian and playa facies to sand-bed braided stream deposits, defining a progradational set of 4<sup>th</sup> order sequences indicating that SF>A (HST; text-fig. 2a).

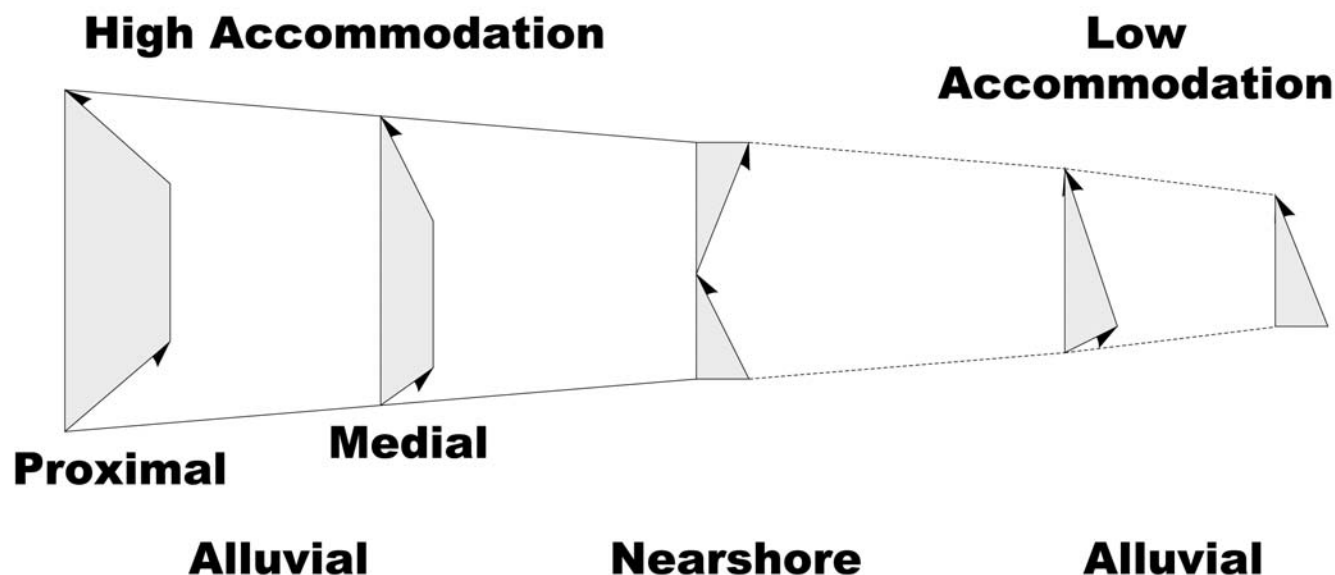
The sequence boundary is at the base of conglomerate, ~5m thick, sharply overlying sandstone (text-fig. 11). This is interpreted to reflect a relative base level fall (e.g. text-fig. 2c) resulting in a basinward migration of the shoreline, subaerial erosion initiating at the old shoreline, and an increase in gradient of the graded profile and thus stream calibre. Alternatively, if relative base level fall resulted in basinward migration of the shoreline at the same gradient as the graded profile then alluvial environments would be characterized by non-deposition. In either case coarse detritus was transported basinward, and when relative base level fall ceased, coarse fluvial deposits were deposited on the erosion surface. Across the sequence boundary, paleocurrent directions change from westerly to southerly (text-fig. 11), this is attributed to renewed subsidence and tilting of the half-graben. The <5m conglomerate is succeeded by sand-bed braided stream deposits, indicating that coarse detritus no longer reached the basin centre, since coarse sediment fractions were deposited upstream as the alluvial plain began to aggrade. The braided stream deposits of the upper 3<sup>rd</sup> order sequence are succeeded by eolian deposits defining a high accommodation, transgressive systems tract. Note that, within the present facies tract, eolian deposits are intimately related to lacustrine deposits, and so the alternation of fluvial and eolian facies can be treated similar to the alternation between fluvial and lacustrine. The top of the upper 3<sup>rd</sup> order sequence is not exposed, but the transition from eolian to fluvial may indicate the transition from transgressive to highstand systems tract.

These two incomplete depositional sequences are inferred to record base level fluctuations with equivalent componentry of marine shelf sequences, namely that of lowstand, transgressive, and highstand systems tracts. Therefore, in limited sections from Christopher Island, at the inferred depocentre of Baker Lake sub-basin, a third-order sequence has the same architecture as nearshore sequences in other basins, including rift basins (Embry 1989; Changsong et al. 2001; Benvenuti 2003). These 3<sup>rd</sup>-order pulses of accommodation are attributed to subsidence via normal faults that bounded the half-graben, in essence a “tectonic cyclothem” *sensu* Blair (1988).

### Aniguq River

The Aniguq River study area is located at the northwestern margin of the Baker Lake sub-basin (text-fig. 4), where the Baker 2<sup>nd</sup>-order sequence is ~500m thick (Rainbird and Hadlari 2000; Rainbird et al. 2003). A volcanic-dominated section consists of





TEXT-FIGURE 13

Architectural comparison of sequence forms from the basin depocentre to the basin margin. High accommodation alluvial settings with high sediment flux are characterized by thick sequences and upward-coarsening to upward-fining successions. Low accommodation alluvial sequences are predominantly upward-fining with a sharp or erosional base. A mixed alluvial-lacustrine depositional sequence typically has an upward-fining to upward-coarsening character, consisting of lowstand, transgressive, and highstand systems tracts.

K-feldspar porphyry tuff at the base succeeded by minette flows (text-fig. 6). A sedimentary-dominated, laterally equivalent section consists of conglomerate and sandstone that interfingers with the volcanic succession (text-fig. 6). This latter section is segmented by strike-slip faults along the course of the Aniguq River, but there is sufficient outcrop to discern the lower unconformity overlying crystalline basement, the upper unconformity between the Baker and Whart sequences, and unconformities within the Baker sequence that bound 3<sup>rd</sup>-order sequences. Unconformity interpretations are based on calcrete horizons and regolith developed upon interbedded volcanic flows (Rainbird et al. 2003). The locations of these unconformities, with respect to 100 m-scale coarse-fine alternations interpreted as 3<sup>rd</sup>-order sequences, are below conglomerate units that fine upward to sandstone. This is similar to alluvial 3<sup>rd</sup>-order sequences described elsewhere (Westcott 1993; Shanley and McCabe 1994; Olsen et al. 1995; Plint et al. 2001; Atchley et al. 2004).

#### *Application of the Terrestrial Sequence Stratigraphic Model*

With respect to graded profile and accommodation, the coarse base to the 3<sup>rd</sup>-order sequences is interpreted to record an increase in depositional gradient at the basin margin as it responded to basin subsidence as in text-figure 3.2e. The upward-fining trend is inferred to record a decrease in depositional gradient due to basinward infilling of AS. The development of unconformities within the Baker sequence at Aniguq River, in contrast to their absence at Thirty Mile Lake at the southeastern basin margin, is attributed to location on the hinged side of the half-graben and therefore less accommodation. This is further indicated by the thinner Baker 2<sup>nd</sup>-order sequence at Aniguq River (~500m vs. >2000m at Thirty Mile Lake.), and the accordingly scaled thickness of 3<sup>rd</sup>-order sequences (~100-150m vs. 400-600m at Thirty Mile Lake; text-fig. 6).

There are 4 sequences at Aniguq River and probably 5 at Thirty Mile Lake (text-fig. 6). According to the volcanic stratigraphy, from the base, the second sequence at Aniguq River correlates to sequence B-3 at Thirty Mile Lake. This indicates that deposition did not occur initially at the hinged margin, but proceeded as the basin expanded; and therefore the B-1/B-2 conformable sequence boundary transforms into an unconformity toward Aniguq River that onlaps the basal unconformity east of Aniguq River.

## DISCUSSION

### **Fourth-Order Sequences**

Third-order sequences are composed of sets of 4<sup>th</sup>-order sequences. Lacustrine 4<sup>th</sup>-order sequences, 5-15m thick preserved at the inferred basin depocentre (text-fig. 12), directly record base level fluctuations. Sequences of this scale have been observed in other extensional basins (e.g. Changsong et al. 2001; Benvenuti 2003) and are generally attributed to fault-subsidence. For example, high-resolution seismic data from the Rukwa Rift in Tanzania identified wedge-shaped lacustrine sequences, 6 to 65m thick, some bounded by angular truncations, and therefore attributed to pulses of fault activity (Morley et al. 2000).

It is possible that 4<sup>th</sup>-order alluvial sequences are correlative (text-fig. 9), recording fluvial infilling of accommodation increments generated by basin-margin normal-fault-induced subsidence. Infilling of this accommodation would then record a decrease in gradient as new accommodation was filled, resulting in the upward-fining succession. The tops of alluvial sequences indicate a stage of sediment bypass, suggesting the reinstatement of a graded profile. Deposition or incision will occur if a change takes place, such as autogenic infilling of basal AS, which will result in a further upward-fining trend as part of the same sequence, or renewed subsidence and the initial

tion of new lacustrine and alluvial sequences. Blair (2000) observed bedding discordance over intra-fan unconformities bounding 5–10 m intervals of upward-fining alluvial fan deposits, and concluded that fault activity had periodically caused a down-drop of the fan thus prompting renewed aggradation.

This proposition should be considered with caution, because lateral shifting in an alluvial setting is an abrupt and episodic process that will necessarily lead to successive self-similarly stacked stratal packages. Thus the fluvial system will aggrade in punctuated units as accommodation is more gradually filled within the lacustrine system. It is therefore possible that the alluvial plain is in a state of constant aggradation throughout the accommodation increment recorded by 4<sup>th</sup>-order lacustrine sequences, and that the 4<sup>th</sup>-order alluvial sequences are simply a product of channel tract aggradation/avulsion processes.

It is also possible that a combination of channel aggradation-avulsion and accommodation-gradient processes contributed to the development of 4<sup>th</sup>-order alluvial sequences. Krapez (1996) postulated that 4<sup>th</sup>-order sequences from an Archean strike-slip basin represent relatively short-term processes that were chaotic composites of intrinsic (systemic redistributions of energy) and extrinsic (climate change or tectonic factors) rhythms, which is compatible with the previous discussion. Considering the number of factors (e.g. local faulting, aggradation-avulsion, or discharge variations as a function of climate) and thus the uncertainty involved, one-to-one correlation of fourth-order sequences between nearshore and proximal alluvial settings from this study is equivocal, in addition to exceeding the dataset for the Baker Lake Basin. Since the vertical succession of 4<sup>th</sup>-order sequences occurs over a larger scale than lateral channel switching processes, 4<sup>th</sup>-order sequence sets should yield reliable SF/A relations relevant to the trends upon which these units were superimposed.

### Third-Order Sequences

Geochronologic data from the Baker 2<sup>nd</sup>-order sequence are sparse (Rainbird et al. 2006), however crude division of the net time (ca. 50 m.y.) by the minimum number of 3<sup>rd</sup>-order sequences (5) suggests that they span approximately 10 m.y. They occur across the Baker Lake sub-basin from conformities to correlative unconformities, and also between sub-basins across the greater Baker Lake Basin (Hadlari 2005). Stratigraphic analysis indicates that they record pulses of accommodation and infilling by the sedimentary system. The succession of 3<sup>rd</sup>-order sequences documents the tectonic history of the basin, and thus these regional pulses of subsidence are basin-filling rhythms in the genetic sense (Embry 1989; Krapez 1996).

Third-order sequences from the Baker 2<sup>nd</sup> order sequence comprise a spectrum of forms from depocentral lacustrine-bearing at Christopher Island, to low accommodation alluvial sequences at Aniguq River, to high accommodation alluvial sequences at Thirty Mile Lake. The present data set for the Baker Lake sub-basin does not enable direct correlation of these sequences, but speculation with respect to a model can perhaps be tested against similar basins for which seismic data and/or extraordinary outcrop are available.

As indicated from other extensional basins, depositional sequences from more basinal settings are similar to marine shelf sequences with respect to high and low accommodation systems tracts (Embry 1989; Changsong et al. 2001; Benvenuti 2003), consisting of retrogradational to progradational compo-

nents separated by maximum flooding surfaces, and bounded by erosional surfaces. More proximal alluvial sequences have an overall upward-fining character with a lower section that may initially coarsen upward. In low accommodation settings these sequences are bounded by erosional surfaces, as exemplified by paleosols at Aniguq River. Even more proximal alluvial sequences in high accommodation settings, such as at Thirty Mile Lake, which contain alluvial fan facies deposited adjacent to inferred basin-margin normal faults, have a thicker progradational base and aggradational centre. If we consider that these sequences represent a continuum from the centre to the margin of the basin (text-fig. 13), then we can explore the factors that produce this trend. It is not intended that specific sequences be correlated, but that the forms from different locations be compared.

With respect to a unified sequence model (text-fig. 14), below the sequence boundary, proximal and medial locations record the lowest gradient facies (e.g. floodplain) and are generally characterized by a relatively high proportion of sediment bypass (text-fig. 14b) if not erosion (text-fig. 14c). Nearshore locations are characterized high SF/A and lake contraction through infilling with detritus (text-fig. 14b,c).

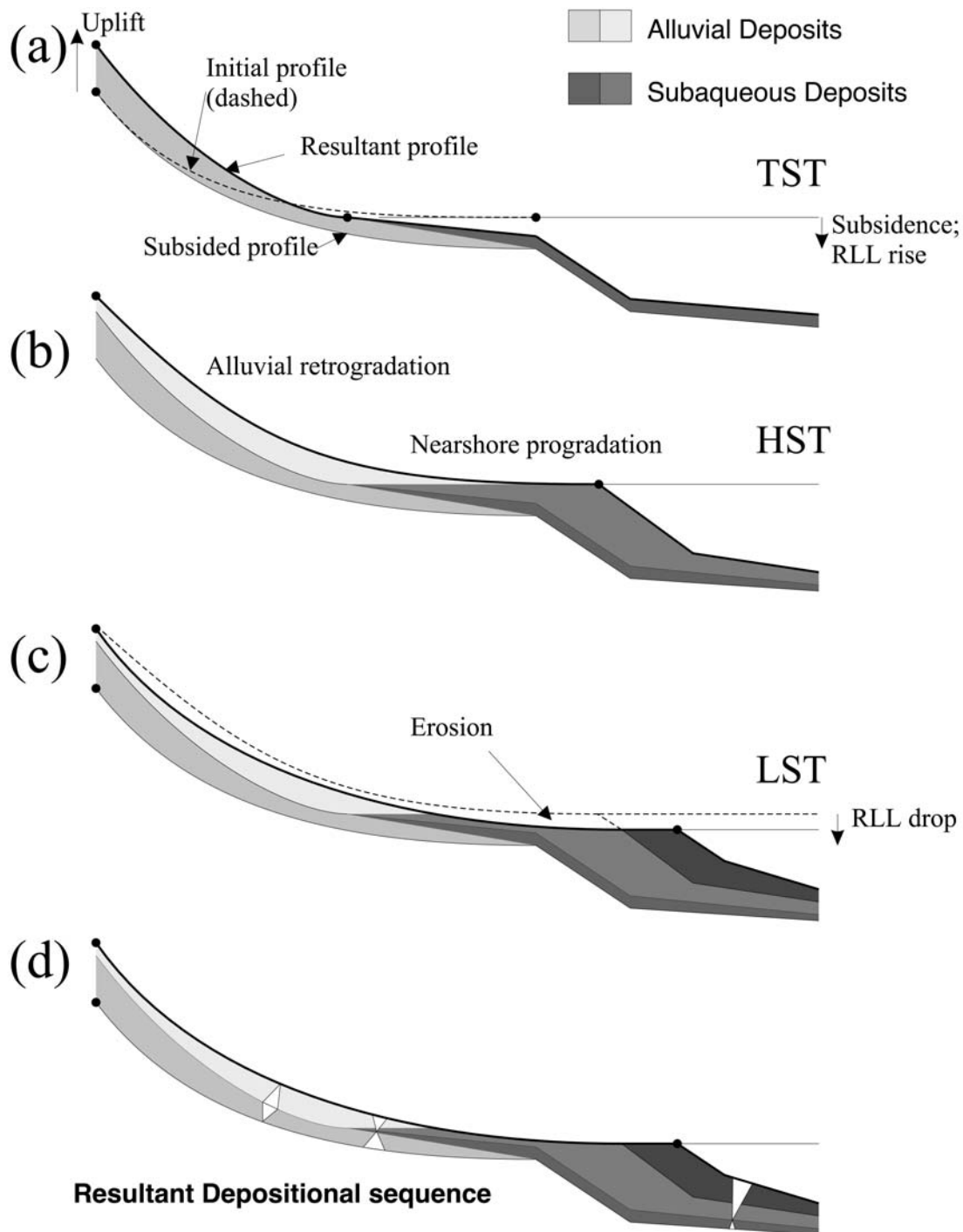
The base of a 3<sup>rd</sup> order alluvial sequence is conformable in high accommodation settings and unconformable in low accommodation settings. In areas of high accommodation, initiation of accommodation in proximal locations resulted in an increase in gradient during alluvial accumulation, and thus a progradation of facies and increase in grain size (text-fig. 14a). This also occurred in medial locations, although the rate of accumulation is presumed to have been less since the gradient-response to accommodation is expected to begin near the sediment source, effectively localizing deposition upstream. In basinal locations, renewed accommodation and fluvial deposition was initially marked by deposition of gravel. This lag is overlain by finer deposits indicating that coarse sediment no longer bypassed proximal locations. As accommodation increased and lake expansion occurred, basinal facies retrograded, and this was recorded by upward-fining (text-fig. 14a).

With increasing rates of accommodation, at proximal locations a maximum gradient determined by boundary conditions may be achieved, which would lead to an aggradational succession. In basinal settings, relative base level rose and lake expansion approached a maximum, equivalent to the maximum flooding surface in the marine realm.

As accommodation decreased, new accommodation space was filled and old accommodation space began to be filled. In proximal locations this led to a decrease in gradient, retrogradation of facies and decrease in grain size. Rates of alluvial accumulation also decreased, and therefore more sediment was available for transport into basinal locations. This also occurred in medial locations, a decrease in gradient and retrogradation of facies, and lower rates of deposition. With minimal subsidence, as the basin infills and the margins denude, the grade of sediment supply if not the flux is expected to decrease, thereby accentuating the rate of proximal and medial retrogradation. As the locus of deposition migrated basinward, the lake contracted and nearshore facies prograded, resulting in a nearshore upward-coarsening succession that completed the depositional sequence (text-fig. 14b).

Subsequent upland erosion and relative base level fall may lead to alluvial and nearshore erosion (text-fig. 14c).

# Alluvial sequence evolution



TEXT-FIGURE 14

Resultant depositional sequence with respect to alluvial and nearshore locations. (a) Initial conditions of graded profile intersecting base level. Concurrent source uplift and basin subsidence result in an increase in alluvial gradient and a relative base level rise. Alluvial deposits coarsen-upward and nearshore deposits fine-upward during this phase. (b) Cessation of subsidence/uplift leads to a high proportion of alluvial sediment throughput and nearshore deposition, resulting in nearshore progradation, net alluvial gradient decrease and therefore alluvial facies retrogradation. The alluvial system may still build upward through deposition to match source uplift, or if caught up, source erosion may contribute to a further decrease in alluvial gradient. (c) Alluvial erosion and relative base level fall may contribute to establishment of a widespread erosional surface. (d) Resultant stratigraphic signatures are upward-coarsening to –fining in alluvial settings, upward-fining to –coarsening in nearshore settings, and upward-coarsening dominated in deeper, basinal settings. LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract, and RLL = relative lake level (base level). Shades of light and dark are used to differentiate deposits between successive time intervals, light shades are alluvial deposits and dark shades are lacustrine deposits.



There are a few notable implications of this model:

1) A perspective on floodplain deposits as minimum-gradient, minimum accommodation facies within alluvial successions, which is opposite to the model of Wright and Marriott (1993).

Wright and Marriott (1993) suggested that preservation of floodplain fines is a result of rapid aggradation of the alluvial plain. To accumulate a significant amount of fine-grained floodplain sediment, associated channels must have not traversed these locations – implying that channels were relatively stable and that their locations were long-lived (e.g. Aslan et al. 2005).

Now if an aggrading river primarily deposits its load within-channel (otherwise channel deposits would be rare and floodplain deposits the norm) then a rapidly aggrading channel would quickly rise above surrounding areas and therefore be more likely to avulse. Thus high aggradation rates should be accompanied by frequent channel switching events, thereby aggrading the alluvial plain through channel-aggradation. This is not consistent with the model of Wright and Marriott (1993).

An alternative view of floodplain preservation would be that channels or channel tracts are relatively stable in their location due to low rates of aggradation. This allows for thick deposits of laminated fines to accumulate in adjacent areas through overbank flooding. This describes a fluvial system characterized primarily by a high proportion of sediment throughput, whereby most of the sediment load is transported through channels with little deposition. Aggradation of the alluvial plain occurs primarily when water discharge exceeds the capacity of the channel system, but even after these events the channel system does not change location, suggesting that there is no gravitational impetus for a lateral channel shift to occur. Thus, the floodplain and the channel aggrade a *comparable* rate. The result is selective deposition of the finest sediment fraction, and bypassing of an unknown quantity and grain size of sediment, allowing for transport of sand and gravel to locations downstream from the floodplain.

2) With respect to clastic wedge inundations of basinal settings, an upward-fining trend at the top of alluvial sequence, and the indication from the nearshore sequence that new and old accommodation space is being filled: as the locus of deposition migrates basinward and distal locations aggrade, the gradient of the graded profile decreases and alluvial facies migrate headward / sourceward. Accordingly, as a clastic wedge approaches basinal locations, the sourceward reaches of that wedge are characterized by a decreasing gradient and facies therefore retreat sourceward, resulting in a proximal alluvial upward-fining succession and a coeval upward-coarsening succession in the subaqueous basin.

3) In lower accommodation regimes, for example on the hinged margin of a half-graben (Aniguq River), the progradational base of the alluvial sequence is thinner than in high accommodation regimes. Thus with lower levels of accommodation, alluvial accumulation therefore responds primarily to basinal infilling of existing accommodation space, punctuated by brief increases in gradient corresponding to new, low-magnitude accommodation. Positive feedback between accommodation and sediment flux (coupled uplift/subsidence) is expected, leading to low rates of sediment flux. Since the alluvial deposits at Thirty Mile Lake are interpreted to have been deposited during an underfilled stage, headwall erosion did not lead to erosion on

the alluvial plain. But at the less underfilled (but perhaps overfilled due to volcanic flux) Aniguq River location, sourceward erosion led to erosion of the alluvial plain, promoting regolith development and a sharp break in facies.

4) Although not demonstrated in the Baker Lake Basin due to the lack of deep basin deposits, the opposite gradational character of sequences between proximal and distal is noted to be similar to the gradational trend across the shelf to basin facies boundary, and is an extension of this trend. Major basinal accumulations occur during RLL highstand/lowstand when high proportion of sediment bypasses alluvial and nearshore shelfal locations, but basinal locations are characterized by low to non-deposition during RLL rise as the locus of deposition migrates sourceward. Proximal alluvial accumulation is minimal during lowstand as a high proportion of sediment bypasses basinal and/or nearshore locations. Uplift and subsidence lead to increasing alluvial gradients and accumulations, whereas facies transgression characterizes nearshore locations and focuses deposition sourceward. Decreasing accommodation leads to progradation of nearshore facies, source denudation and lower alluvial gradients and accumulations. Therefore, over an accommodation cycle the locus of deposition migrates from basin to source and back through nearshore to basin.

## Second-Order Sequence

If the succession of 3<sup>rd</sup> order sequences is treated from a basinal perspective, then the trend of retrogradational to progradational represents high to low accommodation phases. Thus, the basin history is illustrated by the upward-fining then upward-coarsening succession of 3<sup>rd</sup>-order sequences, indicating increasing rates of accommodation, flood volcanism, subsidence cessation, and finally an overfilled stage overlain by a basin-wide unconformity. This is comparable to the framework outlined by Prosser (1993): the upward-fining succession would be equivalent to the rift initiation and rift climax stages; and the upward-coarsening cap is equivalent to the immediate post-rift stage.

On the hinged side of the basin (Aniguq River) the succession is predominantly progradational with unconformities/paleosols developed at sequence boundaries reflecting the low tectonic accommodation. On the opposite side of the basin (Thirty Mile Lake), the succession has a larger retrogradational component, and sequence boundaries are gradational facies boundaries reflecting the high level of tectonic accommodation.

The Baker second-order sequence records the formation of a half graben rift basin at approximately 1833 ±3 Ma (Rainbird et al. 2006) and its subsequent infilling before diagenesis at 1785 ±3 Ma (Rainbird et al. 2002). This is equivalent to a primary, approximately 45 Ma, second-order sequence as defined by Krapez (1996; 1997).

## CONCLUSION

An alluvial sequence stratigraphic model is derived through modification of existing non-marine sequence stratigraphic concepts. Alluvial accommodation space is based upon the graded profile, a topographic profile defined by a graded stream connecting a sediment source to a subaqueous basin. Sedimentary facies are incorporated by considering common characteristics of streams: downstream-fining; downstream decrease in slope; and gradient dependency of stream types. It is suggested that if conditions of sediment supply and discharge are considered boundary conditions specific to individual basins, then rel-

ative facies changes can be interpreted with respect to basin dynamics. Because sedimentary basins are an expression of tectonic setting, accommodation is presumed to be driven primarily by coupled source uplift and basin subsidence, which have feedback effects on sediment supply, sediment flux, and along-stream and end-of-stream deposition. The interpretation of alluvial successions is therefore based on grain size and alluvial facies with respect to the effect of tectonic accommodation on the graded profile. Within this context, the model is able to rationalize previously published alluvial and nearshore sequence forms, specifically an inversion of grain size, within a coherent flexible framework. Within this model, the transition between proximal alluvial and nearshore environments appears to be like the facies boundary between shelf and basin with respect to facies evolution and sediment accumulation.

This model is applied to the non-marine, Paleoproterozoic Baker Lake Basin during a stage of intracontinental rifting represented by the Baker 2<sup>nd</sup> order sequence. The basin is interpreted to have been a half-graben with alluvial fans at the margins transversely feeding a longitudinal drainage system of braided streams that culminated at a depocentre composed of eolian and lacustrine facies. Measured sections from three locations within the basin provide stratigraphic signatures from the lacustrine depocentre, the low accommodation hinged margin, and the high accommodation margin adjacent to the master normal fault.

The ca. 1.84-1.78 Ga, 2<sup>nd</sup> order Baker Sequence comprises a retrogradational succession of 3<sup>rd</sup> order sequences, flood volcanism, and progradational top. This indicates increasing rates of accommodation, flood volcanism, and subsidence cessation equivalent to the stages of rift initiation, rift climax, and immediate post-rift, respectively. Third-order sequences are correlated to a basinwide tripartite volcanic succession and are composed of ~100-500m thick progradational, aggradational, and retrogradational 4<sup>th</sup> order sequence sets. These basin-filling rhythms represent basin-scale accommodation accompanying pulses of normal faulting during development of a half-graben.

### Three types of third order sequences have been identified:

1) mixed fluvial-shallow-lacustrine sequences which are retrogradational-progradational in form, composed of high accommodation, transgressive systems tract-equivalent deposits and low accommodation, highstand systems tract-equivalent deposits;

2) high accommodation proximal-alluvial sequences that record the graded profile response to subsidence, which are characterized by a high accommodation, progradational or aggradational base and a low accommodation, retrogradational top; and

3) lower accommodation alluvial sequences that have a less pronounced progradational base and therefore generally fine-upward and display paleosol horizons near the sequence boundary.

Fourth-order sequences, ~5-15m thick, are composed of sedimentary units representing small-scale base level (lake level) fluctuations possibly related to fault-displacements combined with autogenic alluvial processes.

Because the Baker Sequence was deposited in a hydrologically closed non-marine basin, the effects of sea level can be dis-

counted. Therefore m.y.-scale sequences of 2<sup>nd</sup> and 3<sup>rd</sup> order can be confidently attributed to tectonic processes.

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