Anatomy of a Late Jurassic Gilbert-type delta in basal strata of the Tantalus Formation, Whitehorse Trough, Yukon

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ABSTRACT

Most chert-pebble conglomerate units within the Late Jurassic to mid-Cretaceous Tantalus Formation were deposited in shallow, deep and meandering gravel-bed rivers. However, the presence of large-scale angle of repose foresets of large- to small-pebble conglomerate, with distinct down-slope termination in laminated mudrocks, indicates that at least some >5 m foresets were formed by episodic flood-controlled progradation of a small river-dominated lobate delta. Architectural analysis of exposures at the Whitehorse Coal deposit, 26 km south-southwest of Whitehorse, indicates periodic rapid progradation into a small lake that was at least 6 m deep. Thinning and downlap of some foreset units indicate shifting location of topset distributary channels. Down-slope transition of gravel foresets into thin sub-horizontal beds of massive and graded sandstone and pebbly sandstone suggests that the foresets were inertia-dominated. Deformation of bottomset beds is directly related to foreset progradation over under-compacted lacustrine clays.

RÉSUMÉ

La plupart des unités de conglomérat avec cailloux de chert comprises dans la Formation de Tantalus du Jurassique tardif au Crétacé moyen ont été déposées dans les lits de gravier de cours d'eau à méandre peu profonds ou profonds. Cependant, la présence de lits frontaux très inclinés de conglomérats avec gros à petits cailloux et distinctes terminaisons aval dans des argiles laminaires indique qu'au moins certains des lits frontaux de plus de 5 m ont été formés par progradation épisodique déterminée par les crues dans un delta dominé de petits cours d'eau. L'analyse architecturale d'affleurements au gisement de charbon de Whitehorse, situé à 26 km au sud-sud-ouest de Whitehorse, révèle une progradation périodique rapide dans un petit lac dont la profondeur était d'au moins 6 m. L'amincissement et la surface basale de certaines des unités de lits frontaux indiquent un déplacement des défluents ayant déposé les lits sommitaux. Vers l'aval une transition des lits frontaux de gravier vers de minces couches sub-horizontales de grès massif et granoclassé et de grès caillouteux indique que l'inertie dominait les lits frontaux. La déformation des lits de fond est directement reliée à la progradation des lits frontaux sur des argiles lacustres sous-compactées.

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INTRODUCTION

The stratigraphy and sedimentology of the Tantalus Formation is being examined as part of a larger program to evaluate the hydrocarbon potential of the Whitehorse Trough (Long, 2005; Lowey, 2004, 2005; Lowey and Long, this volume). Sections were measured and samples collected in 2005 and 2006 for petrographic and geochemical analysis to determine the stratigraphic framework, geotectonic significance, sedimentology, age and provenance of the formation.

This paper deals specifically with exposures of the Tantalus Formation at the Whitehorse Coal deposit (McConnell, 1901; Cairnes, 1908; Cockfield and Bell, 1926, 1944; Fyles, 1950; Wheeler, 1961; Hart and Pelletier, 1989; Bremner, 1988; Hart and Radloff, 1990; Hunt, 1994; Hunt and Hart, 1994; Hart, 1997; Cameron and Beaton, 2000), located on the southern flank of Mount Granger, 26 km south-southwest of the city of Whitehorse (Fig. 1). Goodarzi and Jerzykiewicz (1989) indicate that the coals within this deposit have been subject to both regional and contact metamorphism. They recorded reflectance values of up to 3.81 in samples adjacent to felsic dykes, and suggested that this indicates that a medium- to low-volatile bituminous coal had been coked at a temperature of around 600°C. Later studies by Beaton *et al.* (1992), Hunt and Hart (1994), and Cameron and Beaton (2000), found that the coal is typically anthracite, or meta-anthracite, with maximum vitrinite reflectance of 1.65 to 5.62. Intrusion of felsic dykes into exposures at Mount Granger led to the local development of natural coke and peperite, with fluidized magma invading the coal (Fig. 2).

Figure 2. *Peperite (white and grey flecks, top right) and natural coke (black) produced by intrusion of a felsic porphyry dyke (left and lower right) into water-saturated medium- to low-volatile bituminous coal, Mount Granger, Whitehorse. Age of the dyke is not known.*

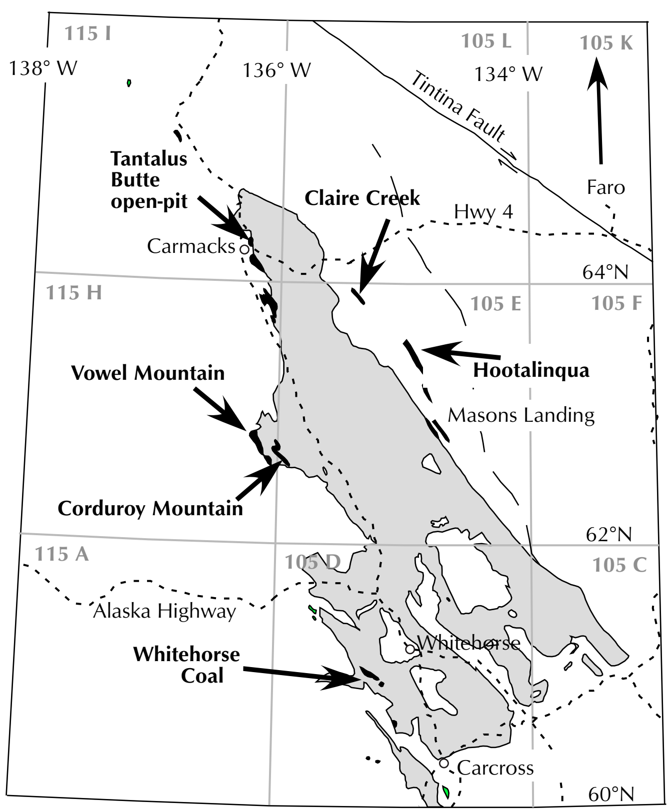

Figure 1. *Distribution of the Late Jurassic to mid-Cretaceous Tantalus Formation (black) within the Whitehorse Trough. Strata of the underlying Lewes River and Laberge groups are shown in grey.*

SEDIMENTOLOGY OF THE TANTALUS FORMATION

The Tantalus Formation represents the youngest unit within the Whitehorse Trough (Tempelman-Kluit 1984; Hart, 1997; Lowey, 2004). It is dominated by chert-pebble conglomerate, with minor sandstone, mudstone and coal. Past investigations demonstrate that most of the conglomerates were deposited in shallow (<3 m) and deep (>3 m) gravel-bed braided rivers, with some thicker composite sets representing deposits of meandering gravel-bed rivers (Long, 1986, 2005; Lowey, 1984).

Deep (>3 m) gravel-bed river deposits have been identified at Hootalinqua and Corduroy Mountain (Fig. 1),

Figure 3. *Thickness of gravel foresets (formed as DA elements) provides minimum depth estimates of 3 m for some rivers at Tantalus Butte (left; staff is 1.5 m long) and >4 m for rivers at Hootalinqua (right).*

where channels may have been several kilometres wide (Long, 2005). In many cases, the minimum depth of these rivers can be estimated from the maximum size of planar cross-stratification formed by avalanching at the downstream end of compound braid bars (DA element of Miall, 1985). As bar tops are typically eroded by later fluvial action, the preserved thickness of these downstream accretionary elements underestimates true maximum flow depth (Fig. 3).

Twelve-metre-thick lateral accretion (LA) sets in exposures at Claire Creek indicate deposition in meandering gravel-bed rivers (Fig. 3; Long 1986, 2005). The composite nature of lateral accretion sets is confirmed by the presence of isolated packages of cross-stratified sandstone and lenticular gravel units in which paleoflow indicators are at a high angle to the slope of the set boundaries (Fig. 4).

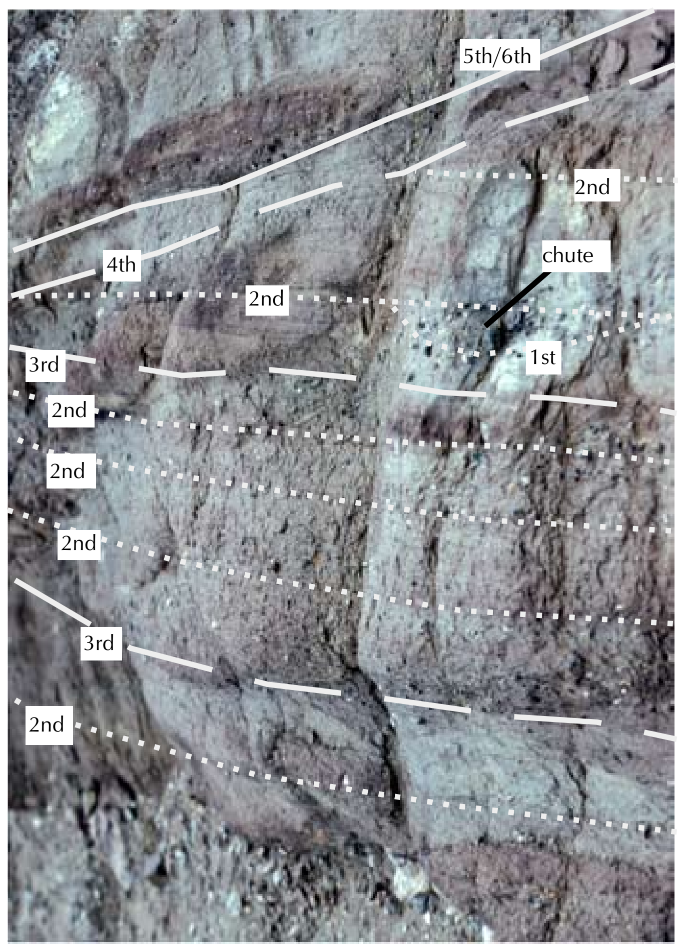

Figure 4. *Composite gravel and gravelly sandstone units forming lateral accretion (LA) elements in a large-scale gravel-dominated point-bar in the Tantalus Formation at Claire Creek. Note limited preservation of overbank elements and preservation of isolated lenses of gravel oriented at right angles to the slope of the bar-form (chute deposits).*

Fine-grained, massive to weakly laminated mudstones, and organic-rich mudstones with abundant slickensides were deposited in overbank and floodplain settings. The high ash content of many of the associated coals (16-76%: Cameron and Beaton, 2000) suggests that these were also deposited in a floodplain, or floodplain swamp environment, subject to frequent clay input during floods. Thin, stacked sandstone sheets in this setting represent both levee and splay deposits (Fig. 5a,b). Channel-fill sandstone units are rare, and represent deposits of small high-constructive anastomosed and single-channel streams. Composite macroforms, with inclined sheets of mudstone and sandstone, exposed in the lower part of the test-pit at the Whitehorse Coal site, were deposited in mixed, sandy-muddy, meandering streams (Fig. 5c).

Given the preponderance of fluvial deposits within the formation, it is tempting to interpret all large-scale gravel foresets as either accretionary sets, formed at the downstream end of longitudinal braid bars (DA elements of Miall, 1985), or if gently inclined, lateral accretion elements from the margins of braid bars, side-bars or

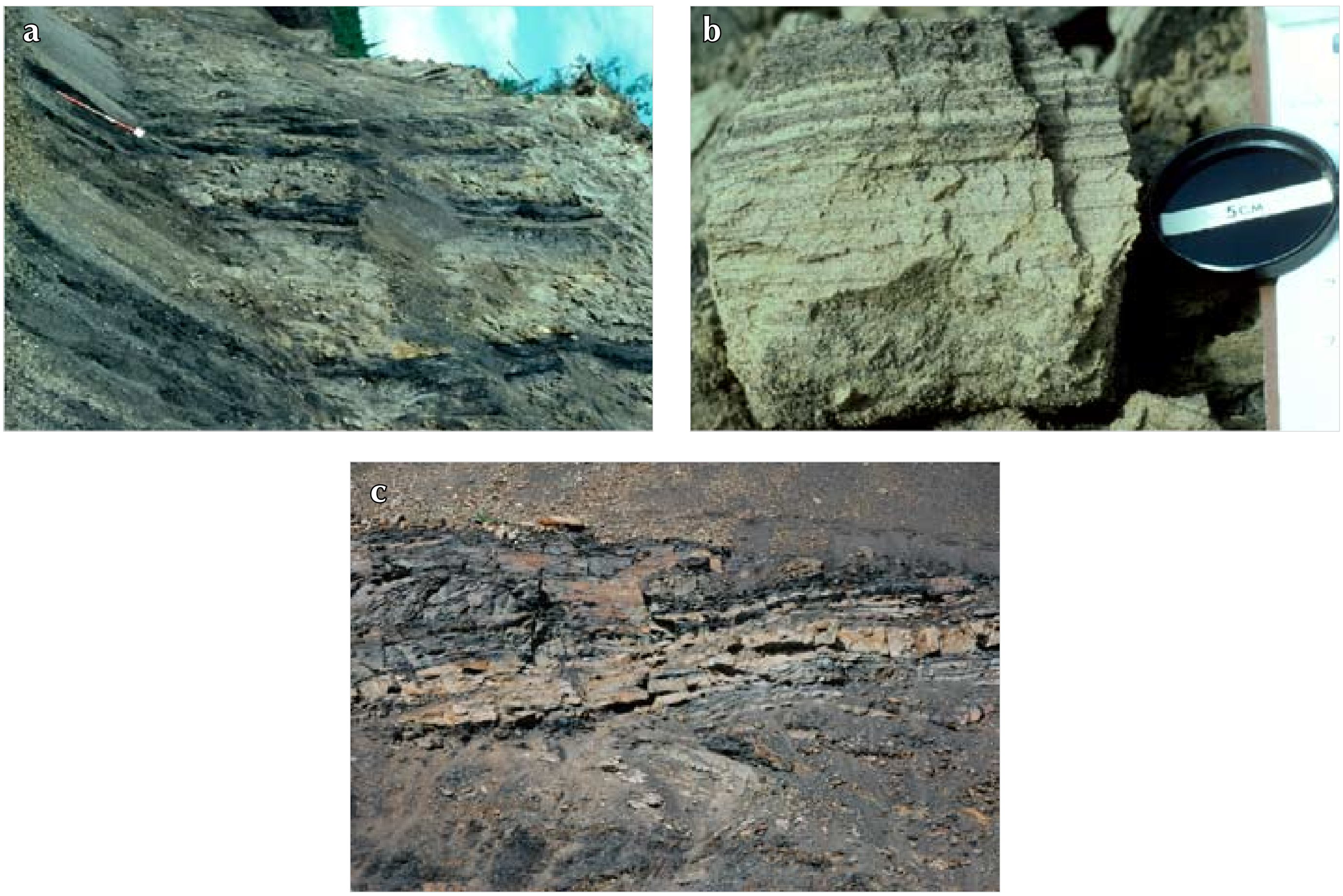

Figure 5. (a) *Overbank levee (dark) and splay (light) deposits in the Tantalus Formation at Tantalus Butte open pit, Carmacks. Staff is 1.5 m long.* ***(b)*** *Detail of splay deposit in the Tantalus Formation at the Tantalus Butte open pit. Note abundance of reworked organic detritus in the upper part of the sample. These 'coffee-grounds' reflect reworking of woody organic debris from levee deposits during flood events in both meandering and high-constructive fluvial systems.* ***(c)*** *Exposure of a fine-grained meandering stream channel deposit (inclined strata in lower part of photograph) in the test-pit at Whitehorse Coal, near Mount Granger. LA surfaces consist of alternating flat- and ripple-laminated sandstone, and silty, organic-rich mudstone. Prominent semi-continuous sandstone units (with mudstone partings) above the channel represent splay deposits; massive to weakly bedded organic-rich mudstones (with abundant slickensides) above and below the sandstone units represent overbank floodplain deposits. Main coal seam at this location is immediately below this photograph. Width of photograph is about 10 m.*

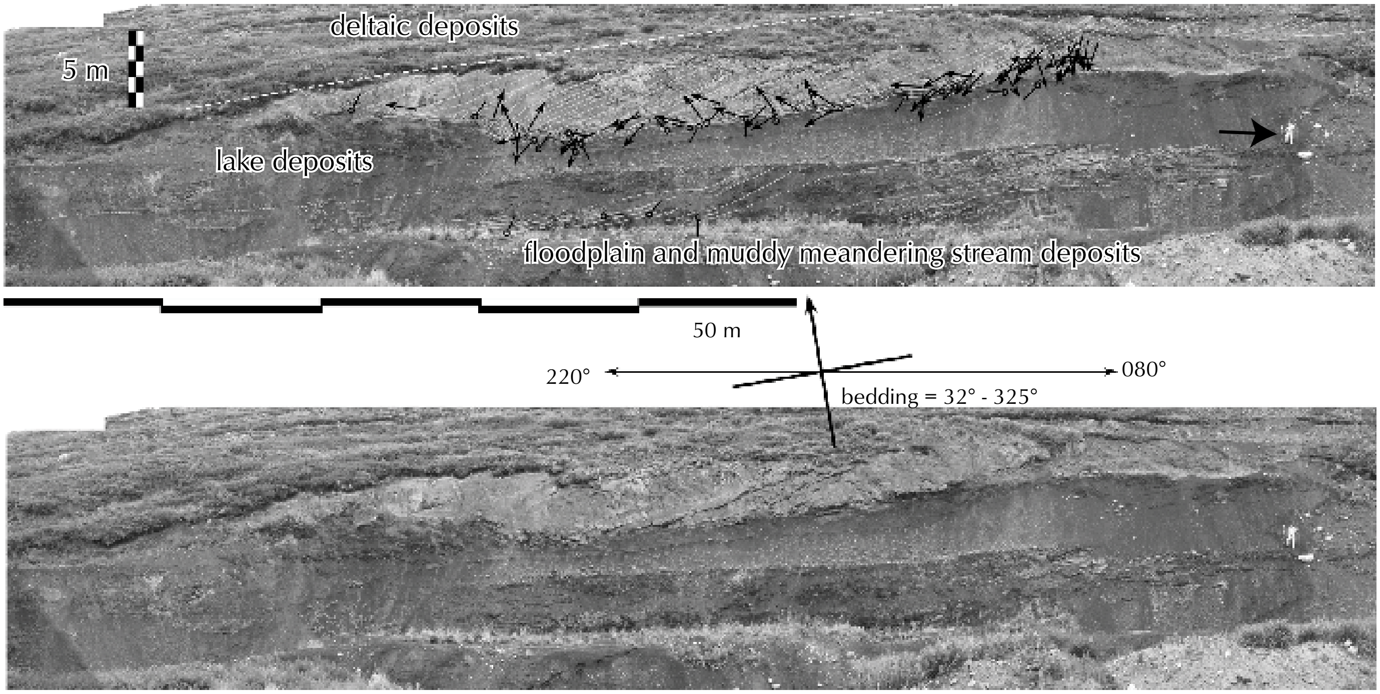

Figure 6. *Large-scale gravel foresets exposed in the test pit at the Whitehorse Coal site near Mount Granger. Upper diagram shows main surfaces bounding depositional elements. Person on right for scale.*

meander-bends (LA elements). This would be a mistake as large-scale foresets exposed at the Whitehorse Coal deposit, behind Mount Granger, were formed as foresets of a Gilbert-type delta which prograded into a small fresh-water lake.

Architectural analysis of the exposure in the coal pit (Fig. 6) indicates that the delta was lobate, with minor shifts in the distributary mouth position, indicated by downlap of some foreset laminae. In this diagram, primary orientation data has been corrected for structural dip of the outcrop, and presented so that arrows (foresets) and pins (bed surfaces) pointing away from the observer are up, and those pointing down indicate slopes (flow) towards the observer (*cf.* Long *et al.*, 2000).

The average inclination of 52 (dip-corrected) foreset elements is 27° (Fig. 7a), with dip decreasing slightly from crest to toe. Mean paleoflow direction was to the southwest (Fig. 7b). Foreset elements are typically 20 to 170 cm thick (average 70 cm), and tend to thin and fine slightly down-dip. Amalgamated foreset packages are 1 to 1.7 m thick. Within these packages, sub-elements typically consist of clast-supported medium-pebble conglomerate (granule to large pebble), with lesser amounts of large

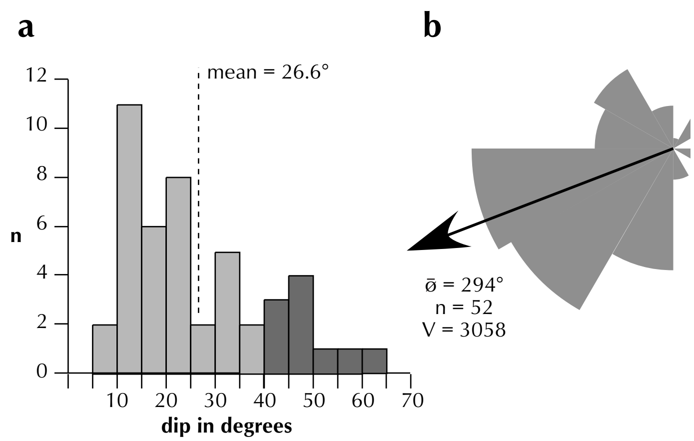

Figure 7. (a) *Histogram of foreset dips. Values over 40° exceed the angle of repose for medium gravel.* ***(b)*** *Rose diagram of foreset dip directions. ø̄ = vector mean; n = number of observations; V = variance.*

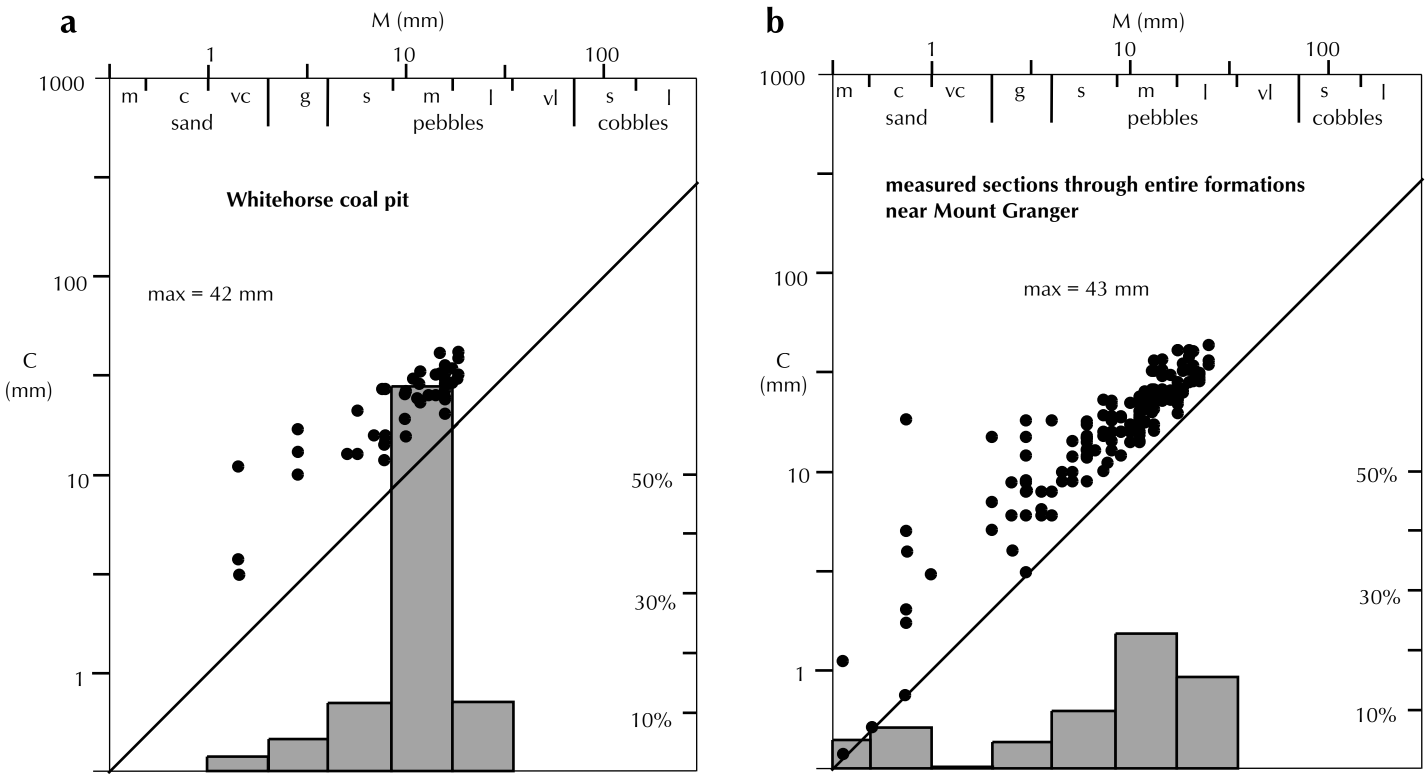

Figure 8. *Comparison of maximum (C) and medium (M) grain-size in delta foreset units in* ***(a)*** *the Whitehorse Coal pit and* ***(b)*** *in measured sections in the same area, indicating strong overlap of populations. Histograms show volumetric percentages of conglomerate grades recorded in each of these sections. Sandstone component of the deltaic section may be underestimated.*

pebble, small pebble and granule conglomerate (Fig. 8a). The size distribution is remarkably similar to the values obtained from measured sections through the whole formation near Mount Granger (Fig. 8b) suggesting that these are genetically linked. Maximum grain size in both data sets is 42 to 43 mm (large pebble grade).

Lower ends of foresets either terminate abruptly against bottomset mudstones (Fig. 9a,b), or prograde a few decimetres to metres into pro-delta mudstones (Fig. 9c,d,e) with rounded or snub-nosed terminations (Fig. 9f). Soles of some units have distinct grooves (Fig. 9d). Some of the grainflow units show evidence of gravitational sinking into underlying bottomset muds, and are in places deformed by overlying foreset gravels (Fig. 10).

INTERPRETATION

Large-scale gravel foresets exposed in the Whitehorse Coal pit are best interpreted as deposits of a classic steep-sloped Gilbert-type delta, which prograded into a shallow fresh-water lake in an intermontane basin setting. The similarity of grain-size distributions in the foresets and associated fluvial strata (Fig. 8) indicates that the deposit reflects progradation of a large-scale fluvial system into a small lake, and is not a local high-gradient fan-delta with a point-sourced fluvial system. The delta appears to more closely resemble the deeper water, inertia-dominated, type B model of Postma (1990), with shifting or multiple distributaries. Gravel-dominated Gilbert-type deltas typically have foreset slopes over 20° (Gilbert, 1885, 1890; Postma *et al.*, 1988; Sohn *et al.*, 1997). The dip of foresets in sand-dominated Gilbert-type deltas may be as high as 24 to 27°, and in gravel-dominated systems can be 30-35° (Nemec, 1990). The average 27° dip recorded in this study (Fig. 7) falls between these two extremes. A

***Figure 9.** **(a)** Central part of exposure showing grouped (0.7-1.7 m thick) packages of gravel foresets, separated by sandy layers (third-order surfaces), that probably mark individual flood seasons (width of view = 8.5 m). **(b)** Detail of foreset toes, showing three packages related to seasonal flood events. **(c)** Detail of sand beds at base of foresets that are tangential to underlying bottomsets. This indicates these units were deposited from grainflows, initiated by over-steepening of upper foreset slopes by grain-fall processes. **(d)** Linear grooves (sole marks) at base of large pebble grainflow on foreset bed (width of view = 80 cm). **(e)** Snub-nosed bed of medium pebble conglomerate emplaced at toe of foreset, overlain by massive sandstones of similar grainflow origin. **(f)** Isolated large pebble in sparsely pebbly sandstone of grainflow origin.*

***Figure 10. (a)** Load cast and tool marks at base of sandstone grainflow. **(b)** Multiple sandstone grainflow units interbedded with bottomset mudstones and deformed beneath a gravel lobe at the base of a later grainflow unit. **(c)** Large-scale deformation of bottomset beds beneath prograding gravel foresets. **(d)** Graded granular sandstone unit interbedded with bottomset mudstones, showing load and flame structures.*

total of 21% of the dips recorded are greater than 40°, which is close to or above the static angle of repose for gravel in water, and so the slopes may have been over-steepened by later gravitational processes.

In coarse-grained Gilbert-type deltas, the character of foresets is directly influenced by flow inertia, and the relative density of the sediment-laden river water compared with lake water (Orton and Reading, 1993). In friction-dominated distributaries of gravel-bed systems, where the river-water density is similar (homopycnal) to that of the lake water, the flow will expand and coarse material will accumulate rapidly from turbulent suspension immediately below the brink-point by grain-fall processes (Kleinhans, 2005). If the river water is buoyant (hypopycnal), coarser material is expected to fall out close to the brink-point, with progressively finer material accumulating further from the distributary mouth. This would produce low-gradient foresets, with tangential lower contacts and a marked coarsening-upwards tendency, not seen in these deposits. Tangential lower contacts would also be expected if river waters were denser than lake waters (hyperpycnal flows). In this case cold-water underflows or sediment-laden flash-flood waters would flow down the foreset slope as dilute-sediment gravity flows, to produce abundant normally and/or inverse-graded units (Postma and Roep 1985; Nemec, 1990; Postma, 2001).

In friction-dominated homopycnal systems, inertial forces may propel individual pebbles over the brink-point, so that they roll down the foreset under the influence of gravity. Collision with other grains during down-slope transport can transfer kinetic energy and trigger avalanching of other grains. In most cases, rapid sedimentation by grain-fall processes on the upper part of the foreset will cause this to rapidly become over-steepened, fail and cause a grainflow (Kleinhans, 2005). Kinetic sieving, where coarser material overrides finer material during grainflow, should result in inverse coarse-tail grading. This is not readily apparent in foresets in the Whitehorse Coal pit. This may be due to the uniformity of gravel populations delivered to the delta front, and a general deficiency of sand-sized material in the rivers that form the Tantalus Formation. Alternatively, the absence of marked inverse coarse-tail grading in the foresets may be related to the scale of individual grainflow events. Kleinhans (2005) found that in flume experiments small-scale grainflows initiated on the upper part of foreset slopes exhibit inverse coarse-tail grading, but did not travel to the toe of the slope. He found that, in thicker flows, friction at the base of the larger grainflow dragged the top of the underlying deposit down-slope, and flows continued to the base of the slope. For small-sized (sand and granule) material, this could lead to concentration of coarser material at the base of the slope.

Post-depositional slope failure does not appear to be an important process on the delta deposit studied. In deep-water Gilbert-type deltas, load-induced slope failure can cause remobilization of foreset material in the form of sediment gravity flows (Postma 1990; Nemec, 1990; Orton and Reading, 1993; Postma and Roep 1985; Sohn *et al.*, 1997). This should produce tangential toe-set beds, with graded and ungraded turbidite and debris-flow-like beds prograding over bottomset beds. Most foreset beds in the Whitehorse Coal pit exposures come to an abrupt stop at the base of the slope, or prograde only a short distance over bottomset beds, consistent with deposition as grainflows (Fig. 9, 10). Only one graded, granular sandstone unit of possible low-density turbidite origin was observed (Fig. 10d). Down-slope sediment failure should also produce slump-scars and syn-sedimentary faults on, and in the upper parts, of foresets (Nemec, 1990). These are not present in the deposits studied.

Deformation of bottomset mudstones beneath gravel foresets was caused by sediment loading (Fig. 10a,d), and not by shallow rotational sliding of delta front sediments, as suggested by Postma *et al.* (1988). Minor mudstone laminae on foresets are too discontinuous to represent significant permeability barriers.

Sand- and granule-dominated foresets tend to be isolated from gravel foresets and may indicate minor floods, or falling-stage flood conditions near third-order surfaces (Fig. 9a,b). The 0.7-1.7-m thick sinusoidal packages between third-order surfaces probably represent individual flood events or amalgamated products of seasonal floods (Mastalerz, 1990). This might indicate that strata exposed in the pit (Fig. 6) accumulated over at least 20 to 25 years. The presence of downlapping packages of laminae within these foreset elements suggest that the position of distributary channels shifted from time to time.

CONCLUSIONS

The presence of large-scale, steeply dipping foresets, above and grading laterally into mudrocks in the Tantalus Formation at the Whitehorse Coal site are best interpreted as a product of shoal-water Gilbert-type deltas that were fed by a fluvial distributary system with closely spaced, highly mobile bed-load channels feeding the delta as a line source (Type B – deeper water Gilbert-type model of Postma, 1990). Progradation of the delta-front took place over a number of flood seasons, each of which produced downlapping packages of foreset strata, and are capped by finer material near the delta toe. There is no evidence for flash-flood induced progradation, such as marked inverse grading of foresets (Postma *et al.*, 1988; Postma, 2001); hence distributary channels were probably characterized by flood events with moderate discharge (Postma, 2001).

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