A four stage evolution of the White Channel gravel: Implications for stratigraphy and palaeoclimates

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ABSTRACT

Although the White Channel gravel (WCG) of the Klondike district, Yukon, contains gold placers which have been exploited for over a century, few sedimentological studies have been undertaken. This study reports a four stage evolution of the WCG, comprising:

i. An initial downcutting period which preferentially retained gold particles on the base of the strath.
ii. An aggradational stage in which gold concentration occurred within sedimentary features.
iii. A lacustrine layer representing a depositional hiatus.
iv. A final, more rapidly aggrading fluvial stage.

Identification of the lacustrine layer has clarified the evolution of the WCG depositional fluvial systems. Architectural element analysis and detailed sedimentological observations have been synthesized to gain a clearer understanding of the spatial variations within the WCG. Additionally, the identification of plant species from pollen within the lacustrine layer provides irrefutable evidence that the Klondike district was at least 7°C warmer during the Pliocene compared to the present.

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INTRODUCTION

The gold placers of the Klondike district, Yukon Territory, Canada, have generated around 90% of the Territory's historic gold production, producing a recorded minimum of 10 million fine ounces of gold (Burke *et al.*, 2005). The 'White Channel gravel' (WCG) found within the drainages of the Klondike district are economically important auriferous high bench gravel deposits. Despite the economic importance of the WCG deposits, only limited study has been undertaken in order to establish their sedimentological and depositional history. A greater understanding of these deposits and their depositional history is desirable if the remaining placers contained within the WCG are to be utilized. Such knowledge will aid in exploration for similar placer deposits, not only within the Yukon, but worldwide. This study introduces a new methodology for recording the sedimentology of the WCG that allows for a greater comprehension of its formation, and presents an initial interpretation of observations made during recent fieldwork in the Bonanza and Hunker Creek drainages. These are the preliminary findings of an on-going study which will continue to characterize materials collected in the field and synthesize field data with information gained from physical modelling of river systems.

THE WHITE CHANNEL GRAVEL

The auriferous high bench WCG deposits studied in the present project are situated within the Klondike River drainage, located within an unglaciated area of west-central Yukon, Canada, immediately south of Dawson City (Fig. 1). The study areas are within the drainages of Bonanza and Hunker Creeks, both of which flow into the Klondike River. The WCG deposits sit uncomformably on the White Channel strath, an eroded bedrock surface composed mainly of Klondike Schist of the Yukon-Tanana terrane, at heights of 10 m to 200 m above the modern creeks (Lowey, 2004). The WCG deposits in Bonanza and Hunker Creeks are locally overlain by loess ('black muck') and colluviums. However, at the confluence of Bonanza and Hunker Creeks with the Klondike River the WCG is both over laid by, and interbedded with, the Klondike gravel, a glaciofluvial outwash deposit related to the pre-Reid glacial retreat (Morison and Hein, 1987). Deposits of the WCG have a length of several kilometres, a maximum width of 1 km, a maximum thickness of 46 m, and are composed predominantly of clast supported gravels with the presence of minor sand and mud horizons (McConnell, 1905; Lowey, 2004). An organic-rich mud, thought to be an overbank deposit, has been recorded within the WCG at Dago Hill on Hunker Creek (Durfresne

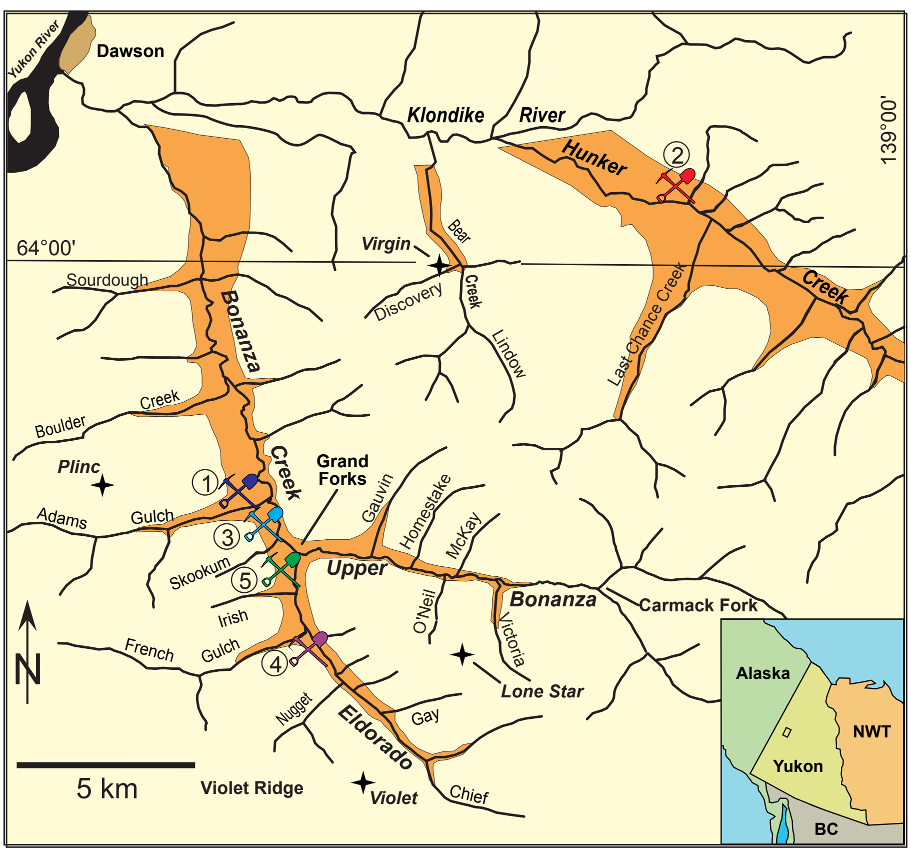

Figure 1. *Map of the study area in the Klondike River drainage with the five study sites marked, adapted from Chapman et al., 2010.*

and Morison, 1985), although no further investigations into it or its organic content were reported. Historically, the WCG has been divided into a lower 'white' and higher 'yellow' units, based on the corresponding colour difference, which was thought to represent separate deposition of the units (McConnell, 1905; 1907). However, later work has proposed that the WCG is one unit with no observed break in deposition and that the colour difference seen within the deposit is a result of staining caused by groundwater percolation (Morison, 1985). The WCG is Pliocene in age, the 'white' unit has been dated between 5 and 3 Ma (based on hornblende $^{40}Ar/^{39}Ar$ dating), whereas a date of 3 Ma was recorded for the yellow unit using glass fission track dating (Lowey, 2004). The overlying Klondike gravel has an age of 2.62 +0.21/-0.17 Ma based on terrestrial cosmogenic nuclide burial ages (Hidy *et al.*, 2013). Lowey (2004) reports that there is no mention of plant or animal remains in current descriptions of the WCG, though fossil pollens and spores have been reported. Fossil pollen samples were used by Morison (1985) to ascribe a Pliocene age to the lower 'white' unit of the WCG, through the presence of *Corylus* within the pollen assemblage and through comparison of the whole flora assemblage (*Abies*, *Corylus, Picea*, *Pinus* and *Poaceae*) with known dated flora assemblages within Alaska (Westgate *et al.*, 2003). However, to date there have been no palaeoenvironmental interpretations of these pollen samples and the current palaeoenvironment model for the north west of the Yukon is based on studies on gravel deposits in neighbouring Alaska (Ager *et al.*, 1994; White *et al.* 1999). These authors suggest a mean annual temperature of 3°C associated with a greater amount of precipitation than currently observed.

The present study focusses on five localities where WCG remains within the Bonanza Creek and Hunker Creek drainages. These localities represent proximal, medial, and distal proportions of the depositional system. The proximal sites are represented by mine sites at French Hill on Eldorado Creek and Gold Hill on Bonanza Creek, medial sites are represented by Cheechako Hill and Adams Hill on Bonanza Creek, and the distal site for this study is at Australia Hill on Hunker Creek (Fig. 1).

ORGANIC-RICH MUD HORIZON

An organic-rich mud horizon was found at French Hill (Eldorado Creek), Cheechako Hill, and Adams Hill (Bonanza Creek). The mud layer is black to dark black-brown in colour, 3 mm to 6 mm thick, and is laterally extensive when seen in outcrop. It was only observed within a small exposure at French Hill, in an outwash gully within the gravel face. At Adams Hill, there is evidence to suggest that this layer has been partially eroded and re-deposited within a sand horizon at approximately the same stratigraphic level, as the sand horizon contains fragments of organic mud. The organic-rich horizon typically overlays an inorganic mud that is 10 to 15 cm thick, light grey in colour, and varies from massive to finely laminated. Overlying the organic-rich horizon is a second inorganic mud layer with a similar grey colour, laminated to massive, and 11 to 14 cm thick, which in turn is overlain by a sequence of bedded sand, which is overlain by the upper unit of the WCG. The sand is observed at both Cheechako Hill and Adams Hill where they are 2 m and 30 cm in thickness respectively, containing beds that exhibit cross-bedding and trough cross-bedding, and have grain sizes that range from very fine sand to granular but have a mean grain size of medium coarse sand.

Analysis of the organic-rich horizon reveals a large quantity of diatoms, observed together with heavily fragmented ancient plant material. The presence of diatoms suggests that the horizon is aquatic in origin (Smol and Stoermer, 2010). The samples also contain an array of fossil pollen (Fig. 2). *Abies*, *Corylus, Picea*, *Pinus* and *Poaceae* have all been found that match those in samples from the WCG (Westgate *et al.*, 2003). In addition to this, *Alnus*, *Betula*, *Campanula*-type, Cyperaceae, Ericaceae, *Ilex,* Liguliflorae-type*, Quercus*, *Salix*, and *Sphagnum* have all been found within the organic-rich mud horizon, giving a detailed insight into the flora present during its deposition in the Pliocene. This initial analysis suggests the flora assemblage represents a cold needleleaf forest (taiga) biome, more taxonomically diverse than the modern high latitude forests and comparable to those reported from Circle, Alaska (Ager *et al*., 1994). One sample shows a high Cyperaceae content, indicating the possibility of a local sedge swamp being present at the time of deposition. The flora assemblage found within the organic-rich mud horizon indicates that the study area was much warmer than today, with an estimated mean annual temperature of 3°C, in comparison to the Klondike region's present mean annual temperature of -4°C (Environment Canada, 2013), and would have also experienced greater precipitation than today. These pollen samples are important because understanding of Late Pliocene vegetation in Canada is currently restricted to islands in the Arctic Sea (Salzmann *et al*., 2008). This means that the global state-of-the-art Late Pliocene vegetation reconstruction previously relied on

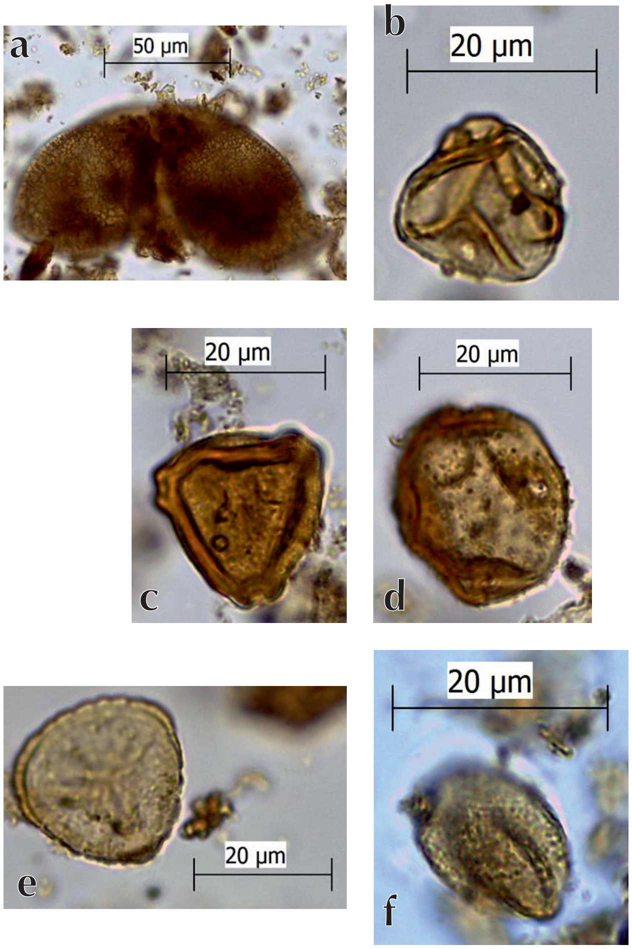

Figure 2. *Examples of the fossil pollen found within the organic-rich mud horizon. Pollen are as follows: (a) = Pinus; (b) = Alnus; (c) = Betula; (d) = Campanula-type; (e) = Sphagnum; and (f) = Quercus.*

predictions from an Alaskan vegetation model to cover much of Canada (Salzmann *et al.,* 2008). The organics preserved within this horizon in the WCG will provide data to ground-truth this region of the current global vegetation reconstruction used in the PlioMIP (Pliocene Model Inter-comparison Project), which aims to improve our understanding of terrestrial ecosystem dynamics during the most recent geological warm period.

CURRENT DEPOSITIONAL MODEL FOR THE WHITE CHANNEL GRAVEL

The current proposed mode of deposition for the WCG involves continuous deposition by shallow gravel-bed braided river systems in the palaeo-creeks (Morison, 1985; Morison and Hein, 1987; Lowey, 2004; 2006). Morison and Hein (1987) divided the river systems into a crudely braided proximal system with a few main channels, and a medial to distal setting with well-defined braided sequences composed of channels and low relief bars. These authors also proposed that the upper 'yellow' unit was deposited in a less energetic fluvial regime. This depositional model has been developed by four sedimentological studies: Morison (1985), Morison and Hein (1987) and Lowey (2004, 2006), which have collectively applied three different lithofacies schemes to examine the WCG. Lithofacies schemes divide a deposit into a series of homogeneous components based on factors including structure, grain size, and texture that can be observed through the entirety of the deposit. Once a lithofacies scheme has been developed, it allows for stratigraphic sequences through the deposit to be recorded, enabling discussion and interpretation of the formation and evolution of the deposit. The first lithofacies scheme developed for the WCG (Morison, 1985) divided the deposit into 14 individual facies, the majority (80%) of these being gravel based. This approach was adapted and simplified by Morison and Hein (1987) who reduced the number of facies to nine through the combination of related units. Lowey (2004; 2006) used a single lithofacies scheme comprising eight facies types based on the ideas of Miall (1978). All of these lithofacies schemes have several features in common. Clast-supported gravels are a dominant feature present in two or more facies, either massive or containing crude planar or cross bedding, representing bars within the depositional environment. These lithofacies schemes were used to produce stratigraphic sections and panels of the deposits, allowing for the sedimentology of the WCG to be recorded and interpreted.

Nevertheless, the use of stratigraphic sections has its limitations within these deposits, primarily because they do not capture the wide range of variation that can occur laterally within a single exposure. Even when several sections are prepared within the same exposure, it is frequently challenging to characterize the sedimentary features and to cross-correlate them. When panels have been produced in an attempt to capture any spatial variation within an exposure (Lowey, 2004), the use of a lithofacies scheme has resulted in large areas being recorded as a single lithofacies, with none of the internal structures of the exposure being recorded. This means that, within the existing literature, details of variation within the sediments are not wholly represented. The stratigraphic sections and panels that have been produced also provide little information on the sizes of the bars and channels within the braided river system that laid down the WCG, and any variation within them over the period of deposition.

ARCHITECTURAL ELEMENT ANALYSIS

This study introduces the use of an alternative methodology of recording the sedimentology of the WCG deposits. Architectural element analysis has been successfully used in a number of studies (*e.g.*, Ashworth *et al.*, 1994; 1999; Peakall *et al.*, 1996) to record the varying depositional niches within a gravel deposit, such as gravel bars, channels, and overbank deposits (Fig. 3). This technique records the sedimentology of an entire exposure, as opposed to a single transect represented by a stratigraphic sequence, easily recognising and recording spatial variations within a deposit. The architectural elements represent those seen within modern gravel bed braided river systems (*e.g.*, Ashworth *et al.*, 1999; Bridge and Lunt, 2009). The use of this method has provided data on the relative sizes of bars and channels within the river system that deposited the WCG. This method is also beneficial as it allows comparison of the WCG deposits with modern river systems, other ancient river systems, and experimentally produced model river systems. In the field, this method was implemented on 16 exposure faces over the five study sites. The sedimentary architecture was recorded onto detailed scaled photos of the outcrop, facilitating element shape, size, and inter-relationship to be precisely documented.

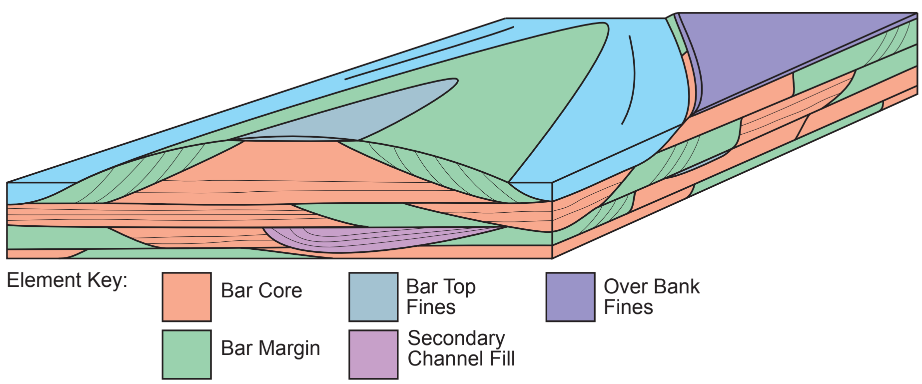

Figure 3. *The White River, Yukon, Canada; an example braided river system similar to that which deposited the White Channel gravels. The lower figure is a generic block model diagram of the architectural elements that are present within a braided river system (block model represents the circled red cross section line).*

The architectural element scheme utilized for the WCG is adapted from Ashworth *et al.* (1999), whose work examined the deposits of the Ashburton River, Canterbury Plains, New Zealand. This new scheme is composed of seven main elements (Fig. 3), descriptions of which are listed below. Due to the nature of working on both active and inactive mine sites, the size and exposure of the mine face outcrops vary from site to site.

WHITE CHANNEL GRAVEL ARCHITECTURAL ELEMENT SCHEME AND ANALYSIS

The WCG is analysed using seven architectural elements (examples illustrated in Fig. 3 and Fig. 4)

A. *Bar Core:* Coarse grained, laterally extensive gravel sheets that can be massive to laminated, typically lacks internal structure, but may contain low angle cross bedding. Predominantly clast supported gravel with moderate to poor sorting, however, some fining up may be seen. Bar cores are tabular with erosional bases and represent primary channel fill. Bar cores may laterally grade into bar margins and may be overlain by bar top fines. This is a primary element within the WCG.

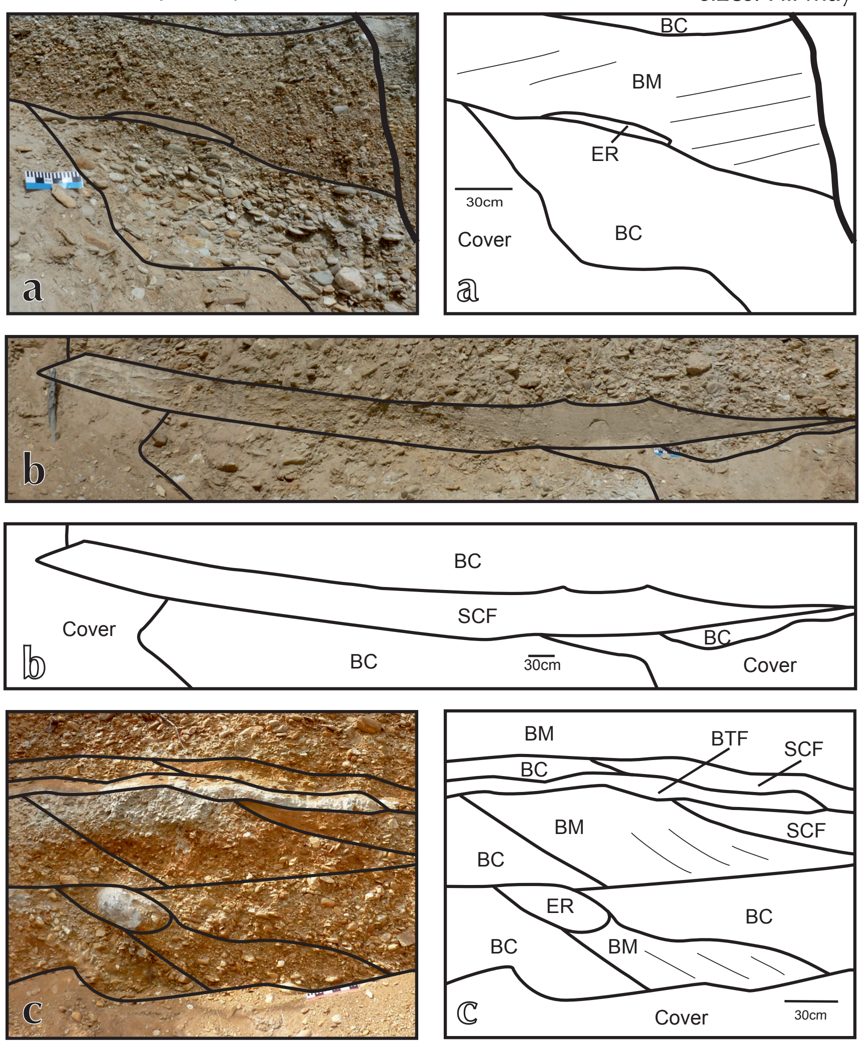

Figure 4. *Examples of the architectural elements seen within the White Channel gravels: (a) and (b) from Adams Hill and (c) from Cheechako Hill. Labels on figure are as follows: BC = Bar Core; BM = Bar Margin; BTF = Bar Top Fines; SCF = Secondary Channel Fill; OBF = Overbank Fines; and ER = Erosional Remains.*

B. *Bar Margin:* Coarse grained, although generally finer than bar cores, with lenses of finer grained material sometimes present. Largely cross-bedded and moderate to well sorted. Bar margins are tabular with erosional bases, but not as laterally extensive as bar cores. Bar margins may laterally grade into bar cores, may be overlain by bar top fines, and represent primary channel fill.

C. *Bar Top Fines:* Fine grained sheets of sand and silt that may be laterally extensive but are often eroded into discontinuous horizons. Bar top fines are found as thin beds overlying bar cores and bar margins. They are preserved only in relatively low energy conditions.

D. *Secondary Channel Fill:* Coarse gravel to fine sand in grain size and may be homogeneous or a mixture of sizes. Fill may be massive or show a range of internal stratification including grain size sorting that may be observed both laterally and vertically. Channel fills possess arcuate erosional bases which may contain a coarser lag deposit in the bottom of the channel fill. These fills represent the infilling of channels that have cut through the bar complexes within the braid plain of the ancient fluvial system.

E. *Overbank Fines:* Mud deposits that may be massive or laminated and in some cases may contain clasts (present as matrix supported gravel). They generally produce relatively tabular deposits which vary in size, dependent on subsequent erosion.

F. *Sand Horizon:* Coarse to fine grained sands which may contain granule to small pebble sized lags at their base. Sands are tabular when extensive lateral preservation has been achieved and may possess erosional bases. Sands may be planar, cross- or trough cross-bedded and can contain fining sequences.

G. *Erosional Remnants:* Areas where the initial depositional environment cannot be identified due to their small size within the outcrop and, therefore, a lack of distinguishing features.

The discovery of the organic layer provides the opportunity to study discrete depositional systems within the WCG, allowing for the palaeo-sedimentary systems evolution to be established. At the Cheechako Hill site the architectural element composition and element sizes (Table 1) can be compared for the upper and lower units. In the lower unit, all the elements present (with the exception of the erosional remains) are larger than in the upper unit based on mean height and width measurements. An example of this are the bar cores in the upper unit having an average width of 2.9 m compared to 4.5 m of the lower unit. Bar cores are the dominant sedimentary characteristic in both units (68% of total exposure), comprising a larger percentage of the sediment in the lower unit (74% of exposure) than the upper unit (58% of exposure). However, the upper unit contains a larger proportion of preserved bar margins, (27% versus 18% of exposure in the lower unit) and contains more fine sediment in the form of bar top fines and overbank fines, both of which are absent from preservation within the lower unit. This indicates that the braided river system that deposited the WCG was initially a larger river system with a low aggradation rate, which produced large gravel bars (Table 1) that were largely erosive as they migrated and stacked. In this environment, previously deposited bar top fines were removed by the succeeding fluvial flows. Fine sediment, muds and sands, immediately above this layer indicates the presence of a much smaller river system which preceded the reinstatement of gravel transport and deposition. In the upper unit, the smaller element sizes coupled with the preservation of fine sediment is interpreted as indicating the presence of a fully developed river system that was smaller and more highly aggradational than that which deposited the lower unit. This enhanced aggradation prevented the extensive reworking seen in the lower unit. This sequence can also be observed within the architectural element composition and element sizes of Adams Hill (Table 2).

Table 1. *Architectural element frequency and size data from the Cheechako Hill site.*

		Number of elements	Exposure (%)	Mean Height (m)	Mean Width (m)
Bar Core	Total	37	68	0.45	3.83
	Lower	21	74	0.47	4.51
	Upper	16	58	0.44	2.93
Bar Margin	Total	19	21	0.4	2.65
	Lower	8	18	0.43	3.25
	Upper	11	27	0.37	2.21
Bar Top Fines	Total	2	<1	0.11	1.8
	Lower	0	-	-	-
	Upper	2	1	0.11	1.8
Secondary Channel Fill	Total	15	9	0.26	2.15
	Lower	8	9	0.31	2.22
	Upper	7	9	0.2	2.07
Overbank Fines	Total	1	1	0.36	3.35
	Lower	0	-	-	-
	Upper	1	3	0.36	3.35
Erosional Remains	Total	5	<1	0.18	0.51
	Lower	1	<1	0.13	1.46
	Upper	4	1	0.19	1.52

HISTORY OF THE WHITE CHANNEL GRAVEL

The study demonstrates that there are two distinct phases of WCG deposition, separated by a system shut-down characterized by the rapid abandonment of a high-energy braided river system, and the development of a lake or swamp. The WCG below and above this stratigraphic marker are fundamentally different in nature. Architectural element analysis demonstrates that the lower WCG was formed by a large braided river system, associated with a relatively low aggradation rate. In contrast, the upper WCG is a smaller channel system with a considerably higher aggradation rate that results in the preservation of a greater percentage of the deposits. While dating of the WCG is limited, this analysis indicates that the lower WCG unit represents a much greater proportion of the total time of deposition, compared to the upper WCG unit.

Table 2. *Architectural element frequency and size data from the Adams Hill site.*

		Number of elements	Exposure (%)	Mean Height (m)	Mean Width (m)
Bar Core	Total	39	62	0.95	4.13
	Lower	19	59	0.97	4.54
	Upper	20	66	0.94	3.79
Bar Margin	Total	25	26	0.77	3.18
	Lower	12	25	0.67	3.79
	Upper	13	27	0.86	2.61
Bar Top Fines	Total	3	<1	0.29	1.48
	Lower	0	-	-	-
	Upper	3	1	0.29	1.48
Secondary Channel Fill	Total	9	11	0.68	4.73
	Lower	6	16	0.69	5.79
	Upper	3	4	0.65	2.6
Erosional Remains	Total	9	1	0.22	1.1
	Lower	4	<1	0.14	0.86
	Upper	5	2	0.29	1.48

The bipartite nature of the WCG, separated by fine grained, mud-rich sedimentation, and an organic-rich lacustrine horizon, suggests that a major event took place at this interface. At the WCG-bedrock interface there is very coarse gravel that represents a phase dominated by erosion into the bedrock prior to significant aggradation. Above this coarse basal gravel, there is no obvious decline in the gravel size or architectural element size with time in the lower WCG until the abrupt transition into the muddy sediments. This section examines the possible mechanism for the abandonment of coarse grained gravel deposition.

Large tectonic events involving the back tilting of the braided river system would have led to a reduction and eventual elimination of down-valley slope. Such an interpretation would fit with the development of a lake that was at least 5 km in length, which would not normally form in a system characterized by relatively steep gradients. An isolated phase of tectonism, during an otherwise reportedly tectonically quiet period (Duk-Rodkin *et al.,* 2001), would have been required to alter the braided river system, as mentioned, and allow for the formation of a lake. Given the regional setting of the deposit this tectonic phase may be related to the Tintina Fault, north of the study area, or the St. Elias orogeny to the south. Alternatively, damming of the river could have occurred, either by landslide, perhaps associated in turn with seismicity, or by an ice dam further down the system. In both cases, the development of a lake behind the dam would lead to a marked backwater effect, and any resultant gravity deposition would have been restricted to the head of the lake. However, analysis of the flora suggests that the climate at this time was relatively warm and consequently an ice dam is improbable. The marked difference between the channel systems represented by the lower and upper WCG does suggest, however, that some fundamental change has occurred to the system across this condensed section. This in turn militates against the suggestion of a landslide induced dam, since these are typically ephemeral events on a geological time scale, and would not be expected to lead to any significant re-organization of the system.

From the analysis provided above, a tectonically induced change appears the most likely (although it is noted that this hypothesis is inconsistent with that of Duk-Rodkin *et al.* (2001)). The new model suggested here proposes that the condensed section between the lower and upper WCG, represented by the fine grained sediment, was the product of a period of significant tectonic activity leading to the back tilting and ultimate abandonment of the braided river system. After a period of lacustrine activity, a new braided river system (the upper WCG) prograded over the lake deposits, but as a smaller system. The higher aggradation rate suggests that more accommodation space was available, presumably related to the re-grading of the down valley slope leading to significant localized aggradation rates.

IMPLICATIONS OF FLUVIAL SYSTEM SHUTDOWN FOR PLACER-LODE RELATIONSHIPS

The hypothesis of a four stage evolution for the WCG has implications for studies of placer-lode relationships. Placer mining activities generally concentrate on processing the lowest stratigraphic levels in the WCG and it is generally accepted that the highest gold grades are found at the bedrock contact. This observation is consistent with a prolonged erosional phase in which gold particles accumulated in bedrock imperfections, while most other clasts were swept through the system. The preservation of sedimentary architecture above this horizon indicates that the fluvial system then switched to an aggradational regime, during which gold particles could not penetrate down to the bedrock gutter. The sedimentary architecture of the lower WCG unit suggests the concentration of gold continued within a slowly aggrading system that processed a large amount of material, selectively retaining the coarse gold particles, therefore, producing high gold grades. In contrast, the placers which formed above the organic-rich layer accumulated in a rapidly aggrading system, and consequently gold grades are relatively low. However, the presence of gold within these sediments shows that particulate gold continued to enter the fluvial system, either as a consequence of on-going erosion of *in situ* gold mineralization or through the continued influx of elluvial gold. The analysis of the placer evolution, described above, suggests that the placer gold grades are primarily a function of the sedimentary environment rather than an indication of variation of gold grade within an eroding orebody. The gold-rich paystreaks at the base of the WCG probably contained only a fraction of the total gold eroded from the source, and consequently current estimates of the original size of the hypogene source may be under represented.

CONCLUSION

The detailed studies of the WCG presented above has established four stages of development. The initial stage involved downcutting and formation of a gold placer through winnowing in an aggressive fluvial regime. A second stage is defined by a change to an aggradational system, although gold placer formation continued within this sedimentary environment. A third stage, defined by an organic-rich mud horizon is interpreted as a lacustrine environment, established during a hiatus in deposition that was succeeded by a fourth stage, in which gravels aggraded rapidly in a new fluvial system.

The discovery of a widespread organic-rich mud horizon that acts as an important stratigraphic marker horizon has enabled the division of the WCG into a lower and an upper unit. Consideration of the size of the lake suggests that the most likely cause of formation is tectonic activity within the area rather than an ephemeral surficial control such as a landslide or ice dam. The newly established units of the lower and upper WCG both display some key differences that reflect changes in the depositing river system. The difference in architectural element sizes between the two units indicates that the lower unit was deposited by a larger river system than the upper unit. Consequently, the early river system would have been able to concentrate coarse gold more effectively than its later counterpart. Architectural analysis has also shown that the lower unit was deposited in an environment with a much lower aggradation rate than the upper unit, which would facilitate a higher degree of gold concentration within the sediments. Conversely, the upper unit underwent less reworking which may result in differing variations in gold grade through the lower and upper parts of the WCG section.

The gold present at the base of the WCG accumulated while most other material was transported away. Almost certainly, some gold was removed at the same time and, consequently, the gold present in the placers probably under represents the amount eroded from the original sources.

The study of the pollen within the organic-rich mud horizon has facilitated reconstruction of the Pliocene palaeo-flora. The species present indicate that the average annual temperature was at least seven degrees warmer than at present. These palaeo-flora data provide independent validation of data generated using state-of-the-art Late Pliocene global vegetation reconstructions, which are used in Pliocene climate modelling.

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