White Channel Gravel alteration revisited

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ABSTRACT

The White Channel Gravel (Pliocene) is the most important gold-bearing unit in the world famous Klondike goldfields of west-central Yukon. It is up to 46 m thick and consists of framework-supported, poorly bedded, slightly muddy sandy gravel that was deposited by braided rivers. Historically, this unit is subdivided into a lower 'white gravel' and an upper 'yellow gravel'. The colour of the white gravel is due to an abundance of quartz clasts and an alteration of the sand-mud matrix that has been referred to as 'leaching' or 'bleaching'. Previous researchers concluded that the alteration is hydrothermal in origin, but a review of this research shows that there is no unequivocal evidence supporting hydrothermal alteration. Petrographic examination of in situ samples from both the white and yellow gravel reveals a depositional fabric and an alteration fabric, although the alteration is better developed in the white gravel. The alteration is reinterpreted as the result of weathering, and particularly diagenesis due to groundwater flow.

RÉSUMÉ

Les graviers de White Channel (Pliocène) constituent l'unité aurifère la plus importante des champs aurifères de la région ouest-centre du Yukon, de renommée mondiale. D'une épaisseur pouvant atteindre 46 mètres, ces graviers sableux légèrement boueux et mal lités furent déposés par des cours d'eau anastomosés. Historiquement, cette unité comprend des « graviers blancs » inférieurs et des « graviers jaunes » supérieurs. La couleur des graviers blancs s'explique par une abondance de clastes quartzeux et par une altération, qualifiée de « lessivage » ou de « blanchiment », de la matrice sable-boue. Des chercheurs avaient conclu précédemment que l'altération était d'origine hydrothermale, mais un examen des résultats de cette recherche révèle qu'aucune donnée non équivoque ne milite en faveur de cette explication. Un examen pétrographique d'échantillons in situ prélevés sur des graviers blancs et des graviers jaunes a révélé une fabrique de dépôt et une fabrique d'altération, l'altération étant plus accentuée dans les graviers blancs. Selon la réinterprétation, l'altération des graviers serait le résultat de la météorisation et plus particulièrement de la diagénèse provoquée par l'écoulement des eaux souterraines.

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INTRODUCTION

The White Channel Gravel is the most important placer gold-bearing unit in the world famous Klondike goldfields. The Klondike goldfields are located in the unglaciated part of west-central Yukon (Fig. 1), and extend from the Klondike River, south to the Indian River (Fig. 2), and from the Yukon River, east to Flat Creek, covering an area of approximately 2000 km^2. Since their discovery over 100 years ago, they have produced an estimated 311 million tonnes of gold, primarily from bench and creek placers that are fluvial in origin and range from Pliocene to Holocene in age (Lowey, 1998, 2001a; McConnell, 1905, 1907). The dominant forcing mechanisms controlling the formation of the placer deposits were isostatically compensated exhumation and climatic change related to the repeated glaciation of the Yukon (Lowey, 2001b,c). Historically, the Klondike goldfields are classified into three levels of gravel with four main units (McConnell, 1905, 1907). The 'high-level' gravel includes the Pliocene age White Channel Gravel, which McConnell (1905, 1907) subdivided into a lower 'white gravel' and an upper 'yellow gravel' (Figs. 3, 4). McConnell (1905, 1907) described the white gravel as being dominated by rounded pebbles and boulders of vein quartz, with minor amounts of schist and gneiss pebbles, all in a compact matrix of 'sericite plates' and angular quartz grains; whereas the yellow gravel consists mostly of flat schist pebbles in a significantly less compact, coarse sandy matrix. Overall, the White Channel Gravel is up to 46 m thick and consists of framework-supported, poorly bedded, slightly muddy, sandy pebble to cobble gravel (Fig. 5). It was deposited by braided rivers such as the paleo-Bonanza and paleo-Hunker creeks (Lowey, 1998).

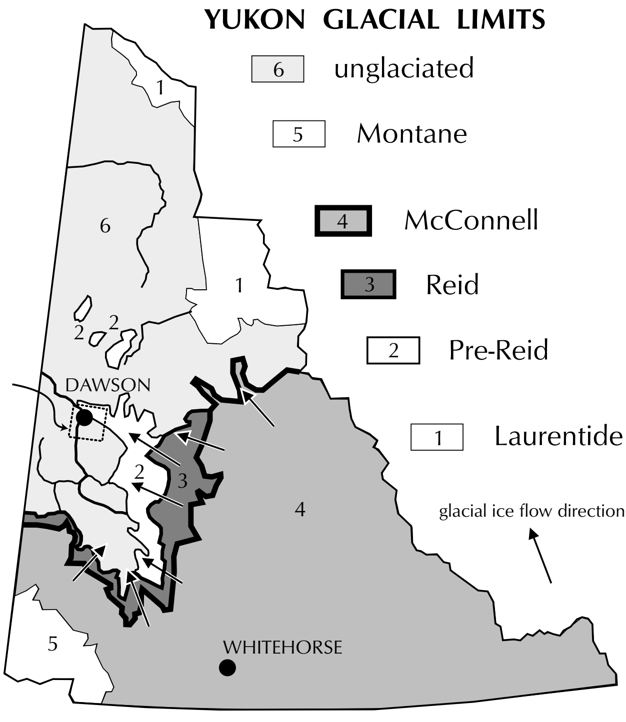

Figure 1. Location map of the Klondike goldfields (box) and Yukon glacial limits (modified from Bostock, 1966; Hughes, 1968).

According to McConnell (1905), the White Channel Gravel was named for its dominant white or light grey colour, which he attributed to the abundance of quartz clasts and an alteration of the sand-mud matrix that he thought was due to the 'leaching of iron'. McConnell (1905, 1907) also recognized that some igneous clasts in the gravel decomposed and crumbled easily when thawed. Tempelman-Kluit (1982) referred to the alteration as 'bleaching' and suggested that it was caused by groundwater. He further suggested that the gold in the gravel had precipitated from the mixing of deep, warm, ascending groundwater with shallow, cool, descending groundwater, and proposed that the gold was 'growing' in the gravel. This prompted a detailed study of the origin of gold in the White Channel Gravel by Dufresne (1987). Dufresne (1987) concluded that the alteration and gold were due to low temperature (i.e., 120-130°C), low

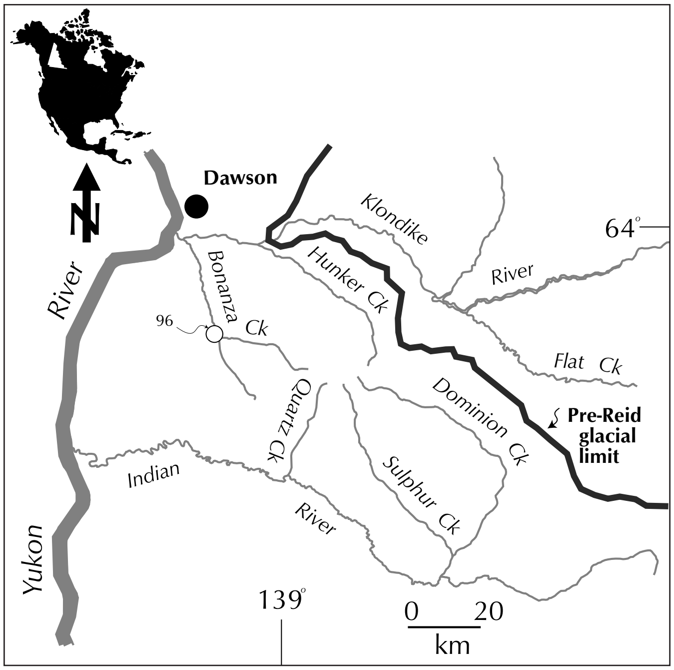

Figure 2. Klondike goldfields, west-central Yukon, and major drainages (96 = 1896, the year and location of gold discovery).

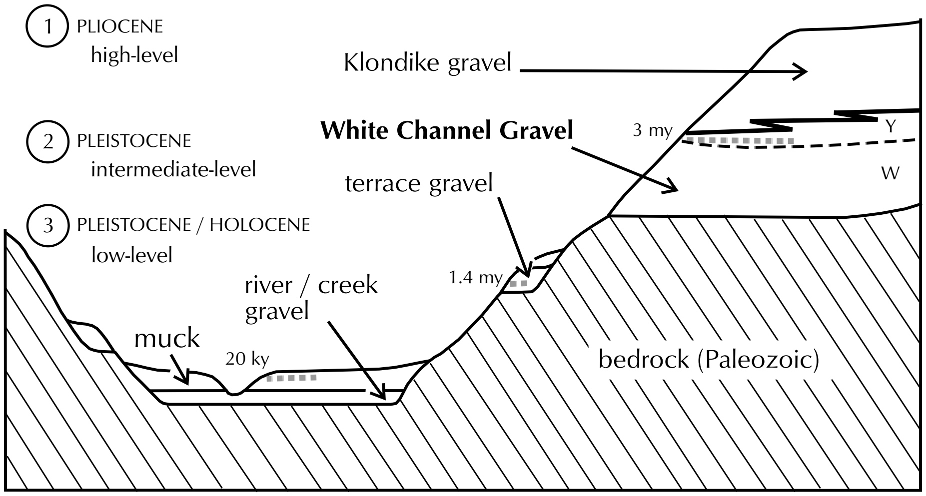

Figure 3. *Schematic cross-section of Bonanza Creek, showing the stratigraphy of the Klondike goldfields; W = white gravel; Y = yellow gravel; 3 my and 1.4 my = age of tephra in million years; 20 ky = age of tephra in thousand years (modified from McConnell, 1905, 1907; Westgate et al., 2000).*

salinity (i.e., 1-2 wt.% NaCl) hydrothermal fluids characteristic of epithermal mineralization. The hypogene alteration proposed by Dufresne (1987) resembles argillic-type wall-rock alteration (Peters, 1987). Dufresne (1987, p. 150) further proposed that "Current gravitational techniques employed in the evaluation and mining of clay-altered White Channel gravel and footwall rocks are vastly inadequate to recover the large amount of fine-grained hydrothermal gold suspected to be present in these units." However, Knight et al. (1994, 1999), using major and minor trace element compositions of gold particles from placer and lode deposits in the Klondike goldfields, determined that "most if not all" of the gold was derived from the lodes, similar to what McConnell (1905, 1907) had reported nearly one hundred years ago.

Perplexingly, Knight et al. (1999) did not discount a hydrothermal origin for the alteration. Instead, they stated (Knight et al., 1999, p. 652) that Dufresne (1987) "demonstrated clearly that the White Channel alteration is the result of ... hydrothermal activity." The statement by Knight et al. (1999) is confusing because the alteration is still considered hydrothermal in origin even though the gold is not. The author has worked on the White Channel Gravel for the last four years, and has observed and described only sedimentary processes (i.e., Lowey, 1998, 1999a,b, 2001a,b,c,d). The purpose of this paper is to review the evidence for and against hyrothermal alteration, present new evidence regarding the alteration from transmitted light petrography, and reinterpret the origin of the alteration in terms of sedimentary processes.

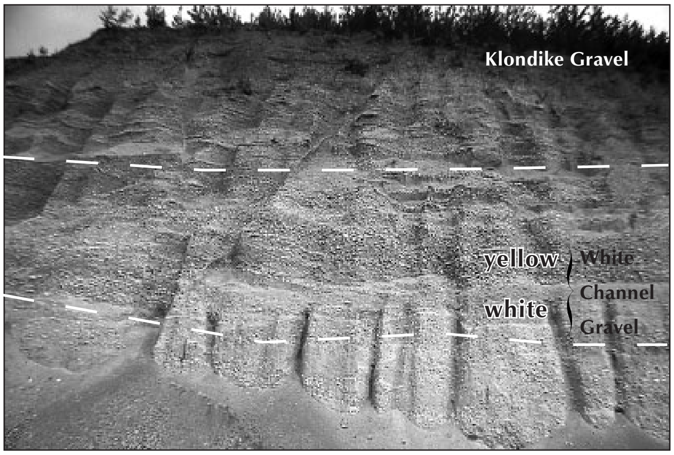

Figure 4. *White Channel Gravel, showing the white gravel and yellow gravel sub-units and the overlying Klondike Gravel, Australia Hill.*

Figure 5. *White gravel, showing the preserved texture, Jackson Hill.*

EVIDENCE FOR AND AGAINST HYDROTHERMAL ALTERATION

Dufresne (1987) presented seven major lines of evidence for hydrothermal alteration of the White Channel Gravel: 1) distribution of the alteration; 2) grain-size analysis; 3) mineralogy; 4) crystallinity of clay minerals; 5) geochemistry; 6) discovery of new veins; and 7) distribution of gold.

DISTRIBUTION OF ALTERATION

Dufresne (1987) classified the degree of alteration as ranging from unaltered (1) to altered (6), and mapped its lateral distribution in the White Channel Gravel and in the bedrock (Fig. 6). He also recognized three alteration zones (i.e., the footwall zone in bedrock, the iron zone in gravel adjacent to bedrock, and the bleached zone in gravel above bedrock) based on their physical characteristics (Fig. 7). Note that both the iron and bleached zones correspond to McConnell's (1905, 1907) white gravel sub-unit, whereas the unaltered gravel corresponds to McConnell's (1905, 1907) yellow gravel sub-unit. Dufresne (1987) suggested that the distribution of the alteration, particularly the three alteration zones, was evidence that it was hydrothermal in origin.

The White Channel Gravel is not restricted to Bonanza and Hunker creeks. It also occurs along Dominion Creek, Quartz Creek and the Indian River (Lowey, 1998, 1999a,b; McConnell, 1905, 1907). Hence, the distribution of the gravel is widespread, indicating that the alteration is regional in extent. In addition, the degree of alteration in the White Channel Gravel along Bonanza and Hunker

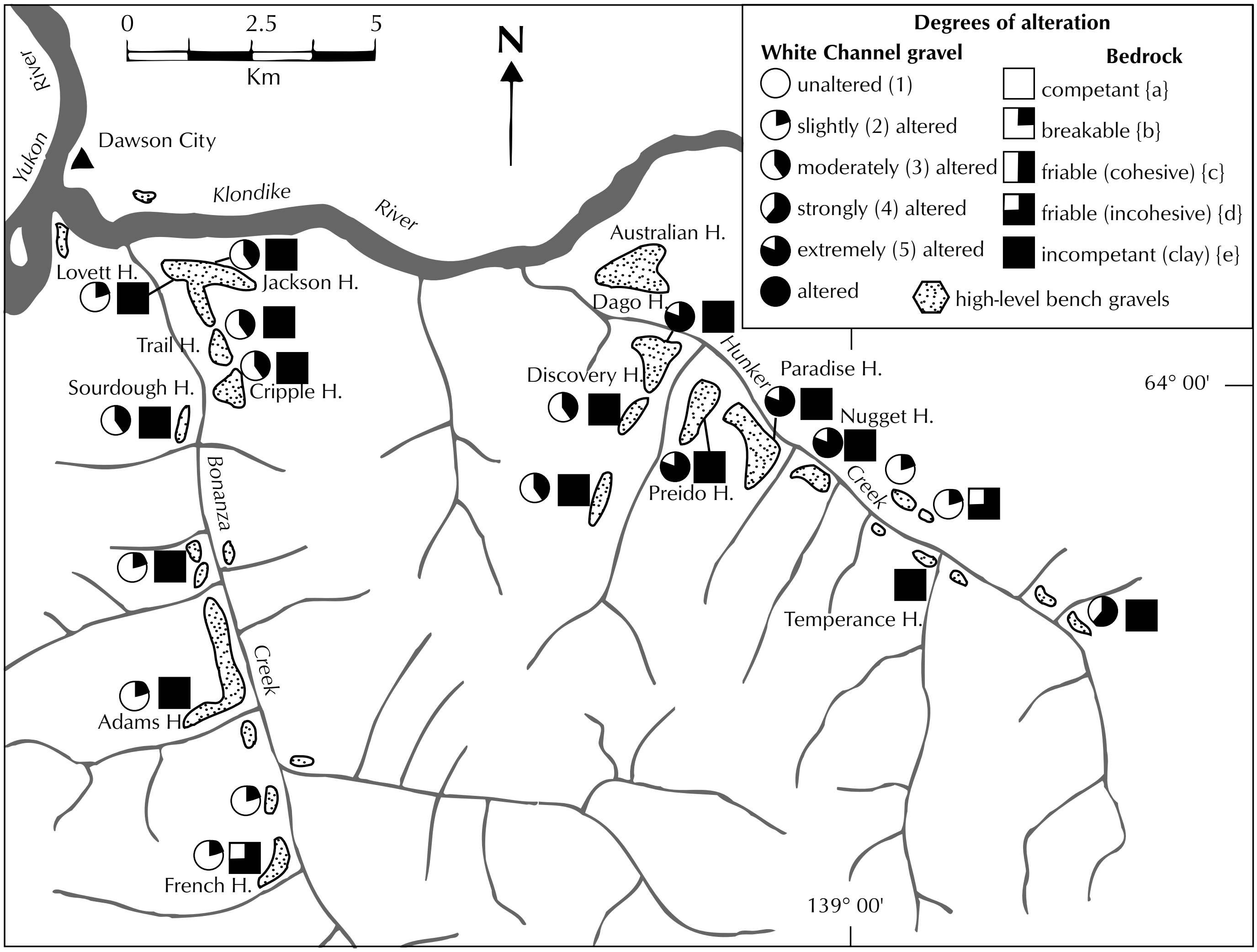

Figure 6. *Map showing the degree and distribution of alteration in the White Channel Gravel and bedrock (modified from Dufresne, 1987, Figure 2.5). H = Hill.*

creeks tends to increase downstream, indicating that groundwater flow may be an important process in the formation of the alteration. With regards to the three alteration zones, note that Figure 7 is an idealized, schematic section (modified from Dufresne, 1987), and the author could not find the three zones vertically juxtaposed in the field during placer deposit mapping.

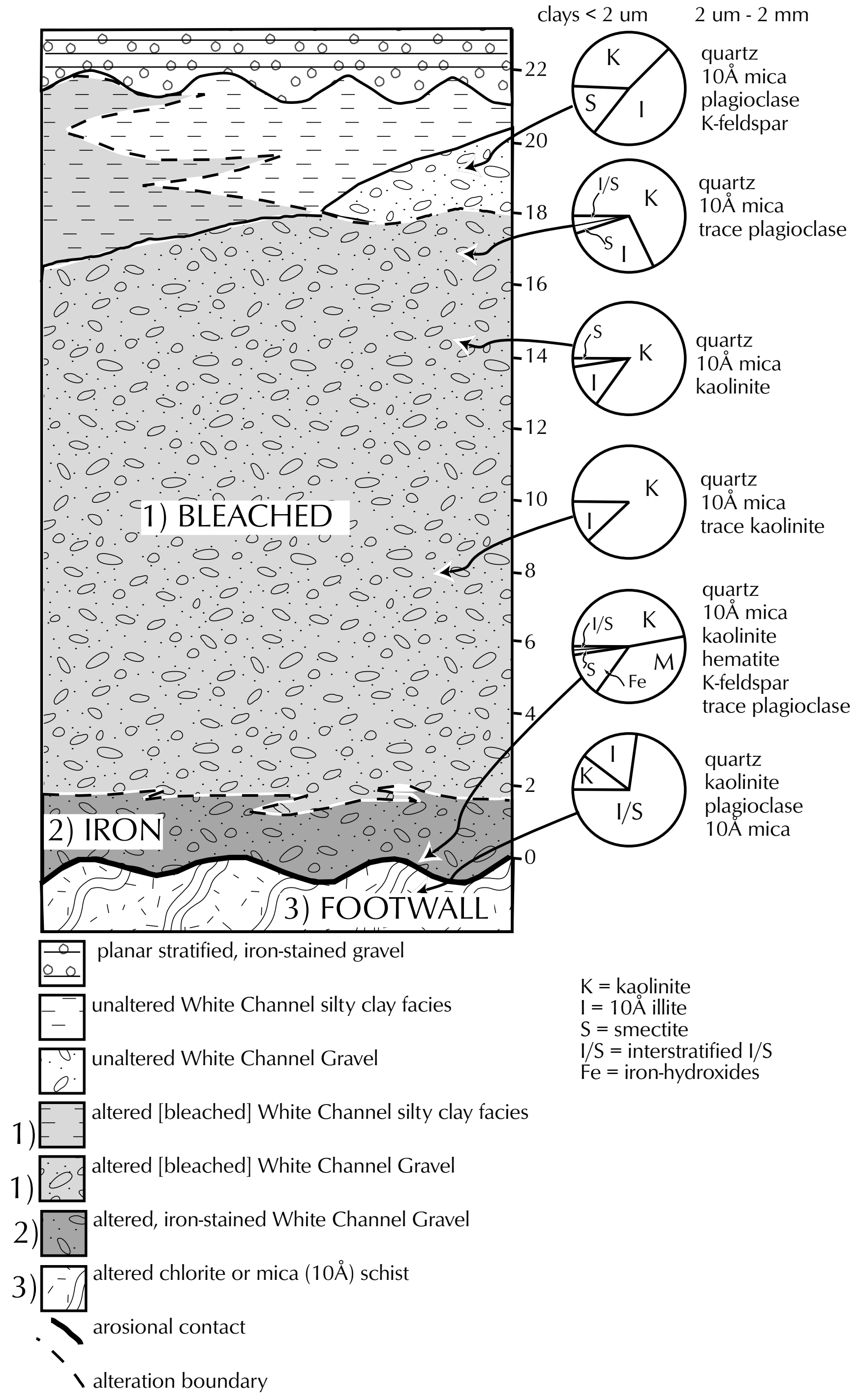

Figure 7. *Schematic diagram of the White Channel Gravel, displaying the three alteration zones and clay mineralogy (modified from Dufresne, 1987; Figure 2.8).*

GRAIN-SIZE ANALYSIS

The grain-size distribution of gravel samples was determined using standard hydrometer analyses (Dufresne, 1987). Based on this technique, Dufresne (1987, Table 2.1) demonstrated that there was more clay in the iron and bleached zones (i.e., 6-14 wt.% and 5-14 wt.%, respectively) than in the unaltered gravel (i.e., 2 wt.%), and concluded that this was evidence that the clay was due to post-depositional alteration.

The abundance of clay (the grain size) does not imply a secondary origin — the clay could be detrital in origin and related to deposition: Dufresne (1987) reported one sample from 'overbank sediments' of the unaltered gravel that contained 31 wt.% clay. Note that Dufresne (1987) confuses the grain-size definition of clay with the mineral definition of clay. In addition, only the sand-mud matrix was sampled and all grains larger than 2 mm were screened off (Dufresne, 1987). Sampling only the matrix of the gravel (and ignoring the framework or gravel-sized fraction) results in a 'relative abundance', which changes if the framework component of the gravel is included. For example, assume that one sample of gravel contains 70% gravel (framework), 24% sand, 2% silt and 4% clay, and that another sample contains 91% gravel, 6% sand, 1% silt and 2% clay. Obviously, the first sample contains more clay. However, by recalculating the weight percentages using only the sand, silt and clay fraction (i.e., ignoring the framework or gravel-sized fraction), the first sample appears to have less clay (i.e., 13%) compared to the second sample (i.e., 22%). Dufresne's (1987) sampling method is thus biased: the results show only variability within a sample and not between samples. Unfortunately, this sampling bias affects most of the other lines of evidence Dufresne (1987) puts forward for hydrothermal alteration.

Table 1 summarizes the results of three particle-size analyses of the White Channel Gravel. The gravel samples were collected using proper sampling methods and were analysed using standard sieve and hydrometer techniques. Note that the absolute or actual amount of clay in the various gravel sub-units is ≤1%, much less than the maximum 14% in the gravel sub-unit that Dufresne (1987) reported.

MINERALOGY

The mineralogy of the gravel samples was determined using standard X-ray diffraction analyses (Dufresne, 1987). Based on this technique, Dufresne (1987, Table 2.2, 2.3, 2.4) demonstrated that, in the <2 µm fraction, there was more kaolinite in the iron and bleached zones (i.e., ~65% and ~70%, respectively) than in the unaltered gravel (i.e., 41%), but that there was less illite in the iron and bleached zones (i.e., ~30% and ~27%, respectively) than in the unaltered gravel (i.e., ~41%). He also calculated the abundance of several other minerals in the <2 µm fraction (e.g., smectite and mixed illite/smectite) and in the <2 mm fraction (e.g., muscovite, feldspar, chlorite, kaolinite, hematite and goethite). Dufresne (1987) concluded that the iron and bleached zones were characterized by extensive secondary clay mineral development, which he attributed to hydrothermal alteration.

The mineralogy results are based on the relative abundance of clay-sized grains in the matrix, and as it was pointed out previously, Dufresne's (1987) sampling method is biased. In addition, the abundance of the various minerals was calculated from X-ray diffractograms, and the resulting percentages are only semi-quantitative (Hardy and Tucker, 1988). Dufresne (1987) also assumes that all of the <2-µm-sized clay minerals are secondary in origin (hence, the 10 Å phyllosilicate minerals in the <2-µm fraction are referred to as illite rather than muscovite). Note that similar clay mineral assemblages have been found in the pre-Reid, Wounded Moose paleosol (Foscolos et al., 1977) and in the 'clay cliffs' of Whitehorse, Yukon (Mougeot, 1994).

CRYSTALLINITY OF CLAY MINERALS

The crystallinity of minerals was based primarily on the 'Hinckley crystallinity index' of kaolinite (Dufresne, 1987), which is derived from the 1İ0 and 11İ peaks on diffractograms (Hinckley, 1963). Based on this technique, Dufresne (1987, Table 2.2, 2.4) obtained kaolinite crystallinities of 1.03 for the footwall zone, 1.3 and 1.59 for the iron zone, 0.53, 0.59 and 0.61 for the bleached zone, and <0.3 for unaltered gravel. He concluded that the high crystallinity of kaolinite in the iron zone indicates that it is hydrothermal in origin.

The Hinckley crystallinity index provides a value indicating only a 'relative degree of crystal perfection' and not what caused it (Hinckley, 1963). Hinckley (1963) reported crystallinity index values ranging from 0.25-1.5 for very pure, detrital kaolinite. In addition, the Hinckley crystallinity index is not widely used because it is influenced by the presence of quartz, feldspar, iron oxides and other clay minerals (Aparico et al., 1997), all of which are present in the White Channel Gravel, especially Dufresne's (1987) iron zone.

GEOCHEMISTRY

The geochemistry of the gravel samples was based on whole rock analyses of major and minor trace elements (Dufresne, 1987). These analyses revealed an apparent depletion in certain oxides (i.e., Fe_20_3, Mg0, Na_20 and K_20) in the bleached zone, which Dufresne (1987, Table 2.1) concluded was due to hydrothermal alteration.

Again, the geochemistry results are based on only the relative abundance of the matrix, which limits their

Table 1. *Particle-size analysis of the White Channel Gravel, Australia Hill, Klondike goldfields, Yukon.*

SUB-UNIT	SAMPLE NUMBER	% GRAVEL >2 mm	% SAND <2 mm >0.0625 mm	% SILT <0.0625 mm >0.0039 mm	% CLAY <0.0039 mm
yellow	GL98-08B	80.5	17.3	2.0	0.2
white	GL98-08A	73.9	20.8	4.6	0.7
iron-stained	GL98-09A	70.1	24.3	4.6	1.0

applicability. In addition, the depletion of the oxides could be due to other processes, such as weathering. Also, if it is assumed that the geochemical results are applicable, then they can be statistically tested to determine if they are significant. When using geochemical results expressed as major oxides for sediments, it is often convenient to calculate a 'chemical index of alteration', or CIA: high CIAs indicate greater chemical weathering [CIA= (100 Al_20_3)/(Al_20_3+Ca0+ Na_20+K_20), Fairchild, et al., 1988]. Using Dufresne's (1987, Table 2.5) data, the unaltered gravel (three samples) has a mean CIA of 71.5, with a standard deviation of 4.8; whereas the bleached zone gravel (eleven samples) has a mean CIA of 79.0, with a standard deviation of 6.0. Testing the difference between these means with a t-test (based on independent samples, Bluman, 1992) reveals a calculated t-statistic of -2.27. This value lies outside the critical region of ±4.303 (based on two degrees of freedom and a 95% confidence interval), indicating that there is not enough evidence to support the claim that the CIA of the unaltered gravel differs from the CIA of the bleached or altered gravel.

DISCOVERY OF NEW VEINS

Dufresne (1987) reported that the footwall zone contained three types of previously unrecognized veins: 1) Type 1 - quartz; 2) Type 2 - carbonate and quartz; and 3) Type 3 - clay iron oxide and amorphous silica. Fluid inclusion data from Type 1 and 2 veins revealed homogenization temperatures ranging from ~90-300°C, and 0-4.6 wt.% NaCl (Dufresne, 1987). Using these results, Dufresne (1987) concluded that the veins were emplaced during the alteration by ascending hydrothermal fluids, which resulted in epithermal gold mineralization in the bedrock and altered gravel.

The age of the veins is unknown and they only 'appear' to be related to the alteration (Dufresne, 1987). In addition, Dufresne (1987, p. 82) stated that the veins have been observed at most hills in the Klondike goldfields, but that the "vein occurrences are usually rare, with erratic distribution and extent." One would expect that the veins should be more common and predictable in distribution and extent if they caused the regional alteration observed in the White Channel Gravel. Also, Knight et al. (1999) demonstrated that the gold in the gravel was mainly derived from mesothermal quartz veins: that is, the gold in the gravel is detrital or placer gold and did not originate through precipitation of hydrothermal fluids.

DISTRIBUTION OF GOLD

McConnell (1907, p. 220) observed that the "greater part of the gold in the hill and creek gravels occurs on or near bedrock, either in the lower four to six feet (1.2-1.8 m) of gravel or sunk for some distance in the bedrock itself." He (McConnell, 1907, p. 221) noted also several exceptions to this general rule, such as at Dago Hill where a "considerable enrichment takes place at a point sixty feet (18 m) above bedrock," and at Paradise Hill where the "main gold zone here is in many places not found on bedrock, but at elevations of from three to twelve feet (0.9-3.7 m) or more above it." McConnell (1905, p. 105) concluded that there is "little doubt that the Klondike gold, or the greater part of it, at least, is detrital in origin, and has been largely derived from the auriferous quartz veins cutting the older schists." However, he (McConnell, p. 106) suggested that a "small percentage may have been precipitated from water carrying gold in solution," citing as evidence a boulder from the Sixtymile River placer area, the upper surface of which was partially covered with dendritic gold.

McConnell's comments were interpreted by Dufresne (1987) as evidence for a hydrothermal origin of the gold, and because Dufresne (1987) thought that the alteration was related to the gold mineralization, he concluded that the alteration was also hydrothermal in origin. In addition, Dufresne (1987) based his interpretation on personal communications with two placer miners (i.e., Mike Stutter and Benny Warmsby) and on a student completing a Master thesis on the White Channel Gravel (i.e., Steve Morison). According to the two placer miners (who provided calculations of gold grade), the bleached zone gravel contains higher concentrations of gold than the unaltered gravel (Dufresne, 1987, p. 67). Unfortunately, there is no information on how the calculations were done or what the calculations are based on. Also, Morison (Dufresne, 1987, p. 67) suggested that the distribution of gold in the altered gravel is atypical and "contrasts distinctly with the normal distribution of placer gold in unaltered gravel," but Morison does not explain its variation from 'normal'.

The distribution of gold in the Klondike goldfields was discussed by McConnell (1907). He reported that the distribution partly depended on the underlying bedrock: bedrock underlying the White Channel Gravel is more decomposed (i.e., clay-rich) than that under gravel along Bonanza and Hunker creeks. Excessive clay in the bedrock prevents gold from descending further (i.e., into fractures), thereby allowing its concentration at the gravel-bedrock contact (McConnell, 1907). The slight enrichment of gold above bedrock in the White Channel Gravel at Dago Hill was attributed by McConnell (1907) to the development of a 'clayey stratum' or false-bedrock, which prevented the gold from settling further through the gravel. Similarly, the enrichment of gold above bedrock in the yellow gravel of the White Channel Gravel at Paradise Hill was due to the more 'compact nature' of the white gravel, which resulted in gold being concentrated at the white gravel/yellow gravel contact (McConnell, 1907). Also, as it was pointed out previously (i.e., in the Introduction and in the section Discovery of New Veins), gold in the White Channel Gravel is detrital in origin and so Dufresne's (1987) reasoning that 'if the gold is hydrothermal in origin, then the alteration is too,' is no longer valid.

NEW EVIDENCE FROM TRANSMITTED LIGHT PETROGRAPHY

There appears to be no compelling evidence for hydrothermal alteration, but perhaps by looking at the texture of the White Channel Gravel, it may be possible to recognize an alteration fabric and distinguish this from a depositional fabric. Carrigy and Mellon (1964), Dickinson (1970), Moraes and De Ros (1990), Pettijohn et al. (1987), Thomas (1983), and Wilson and Pitman (1977) present criteria for distinguishing between depositional and alteration textures based on observations of thin sections. A total of 32 undisturbed gravel samples were collected from the White Channel Gravel (including both the white and yellow gravel sub-units and the iron-stained gravel) by carefully excavating 'cylindrical' mounds of gravel and saturating these with epoxy resin. After the epoxy hardened, the samples were removed and sent to Vancouver Petrographics Ltd., where they were made into oversized thin sections and off-cuts (which were stained for potassium feldspar). The thin sections were subsequently examined with a petrographic microscope.

DESCRIPTION OF FABRIC

Representative photomicrographs displaying the observed fabric are presented in Figures 8 and 9. Figure 8a is a view in plane light of the white gravel, showing the wide range in grain size from pebbles to sand, silt and clay. Note that the silt-clay groundmass has a turbid or cloudy colour. Figure 8b is the same view in crossed polars, showing a vein-quartz pebble and angular quartz grains 'floating' in a groundmass of degraded muscovite and possibly illite. In a study of the heavy minerals in the Klondike area, Gleeson (1970) reported that 'muscovite' was present in all gravel samples from the goldfields. The muscovite was thought to be a mixture of 'hydromica' (i.e., illite), sericite and muscovite, and ranged from < 1 to 81% in the fine sand fraction (Gleeson, 1970). Figure 8c is a view in plane light of the white gravel, showing the angular quartz grains surrounded by the cloudy groundmass. Figure 8d is the same view in crossed polars, showing degraded muscovite between the angular quartz grains. Note that the sample displays very little porosity. Also observed in the white gravel were slightly bent muscovite grains, very mildly squished labile grains, local microcline grains, well developed 'books' of kaolinite, and undifferentiated illite/smectite.

Figure 9a is a view in plane light of the yellow gravel, showing the wide range in grain size from pebbles to sand, silt and clay. Note the erratic distribution of limonite and that the silt-clay groundmass has a less turbid or cloudy colour than in the white gravel. Figure 9b is the same view in crossed polars, showing a vein-quartz pebble, angular quartz grains and muscovite grains that are not as degraded as those in the white gravel. Also observed in the yellow gravel were slightly bent muscovite grains, very mildly squished labile grains, many microcline grains, local plagioclase grains, and undifferentiated kaolinite/illite/smectite. Figure 9c is a view in plane light (approximately 5 mm wide) of iron-stained gravel, showing the wide range in grain size from pebbles to sand, all surrounded by hematite and probably goethite. Figure 9d is the same view in crossed polars, showing a vein-quartz pebble, angular quartz grains and muscovite surrounded by hematite and probable goethite.

INTERPRETATION OF FABRIC

Transmitted-light microscopy reveals a depositional fabric characterized by quartz grains 'floating' in a matrix of allogenic muscovite (degraded) and possibly illite. In addition, an alteration fabric is evident, characterized by mild compaction and the formation of a 'pseudomatrix' due to the precipitation of authigenic kaolinite, limonite and hematite, and possibly illite, smectite, and goethite, and probably the recrystallization of detrital clay minerals. Precipitation and recrystallization has also resulted in a reduction in the porosity of the White Channel Gravel. Hence, the fabric is due to deposition and alteration, although the degree of alteration is greater in the white

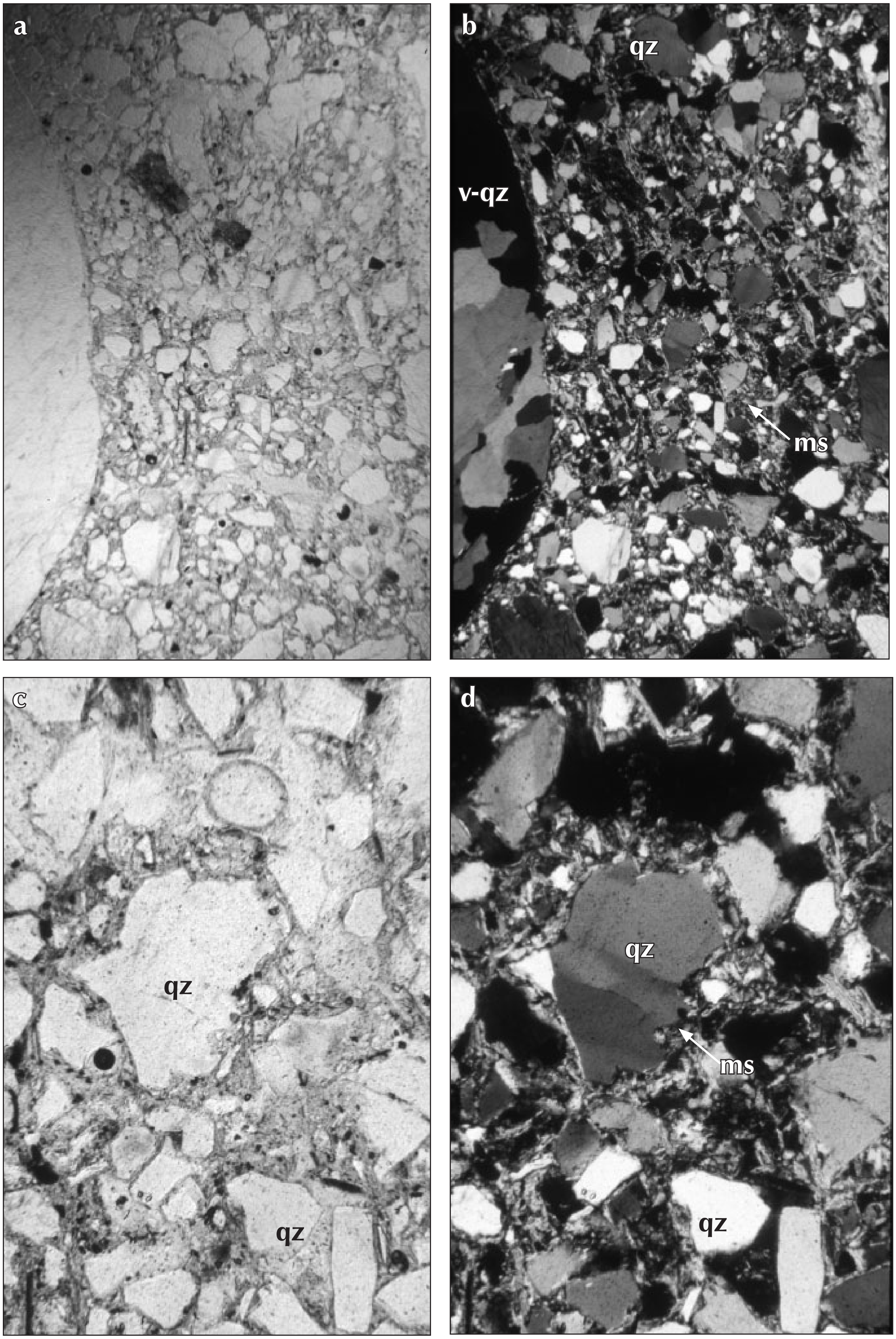

Figure 8. *Thin-section photomicrographs of the white gravel. (a) wide range in grain size from pebbles to sand, silt and clay with the silt-clay groundmass displaying a turbid or cloudy colour (view approximately 5 mm wide, plane light); (b) vein-quartz pebble (v-qz) and angular quartz (qz) grains 'floating' in a groundmass of degraded muscovite (ms) and possibly illite (view approximately 5 mm wide, crossed polars); (c) angular quartz grains surrounded by the cloudy groundmass (view approximately 1.4 mm wide, plane light); (d) degraded muscovite between the angular quartz grains (view approximately 1.4 mm wide, crossed polars).*

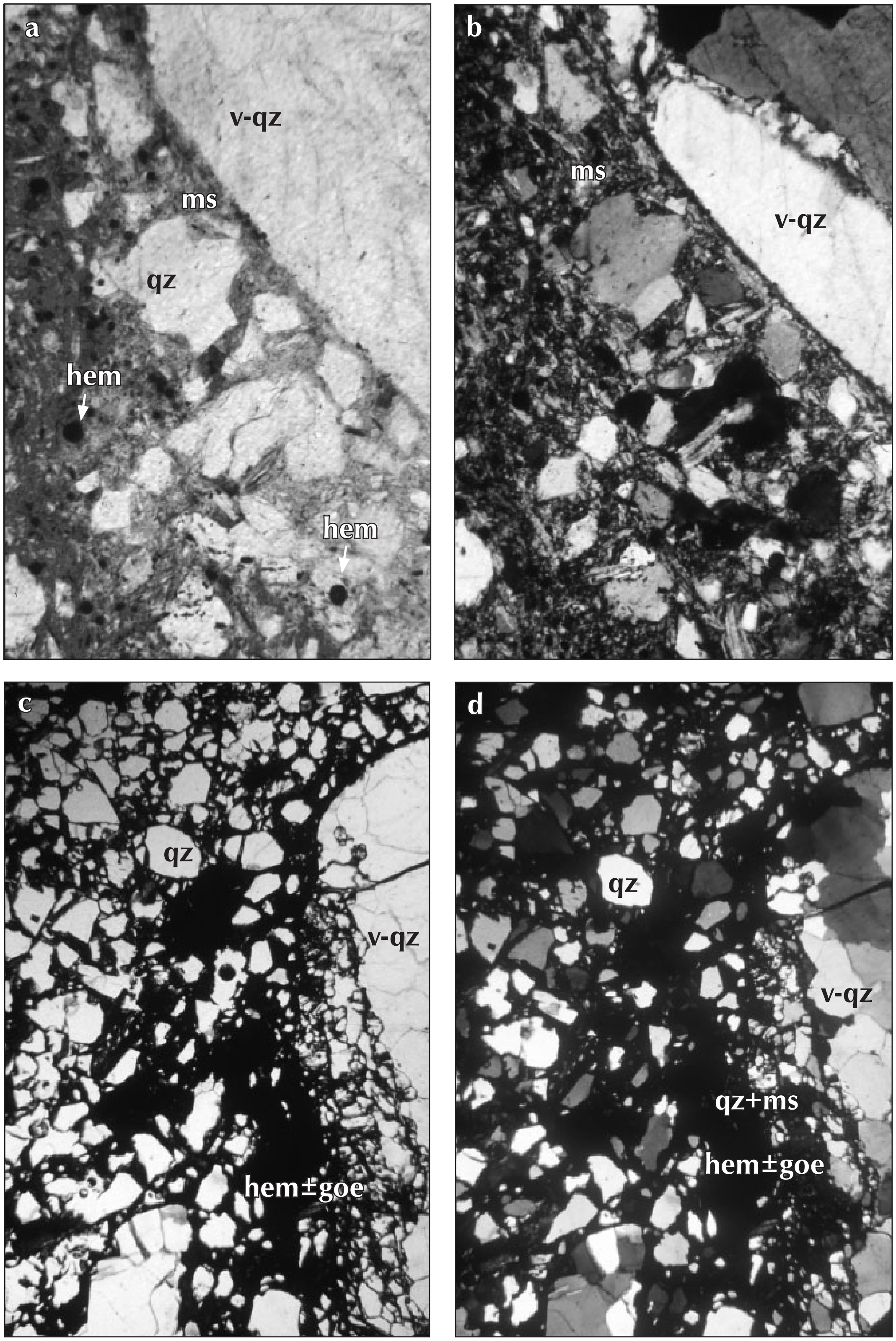

Figure 9. *Thin-section photomicrographs of the yellow gravel: (a) wide range in grain size from pebbles to sand, silt and clay, with an erratic distribution of hematite (hem) and a silt-clay groundmass that has a less turbid or cloudy colour than in the white gravel (view approximately 5 mm wide, plane light); (b) vein-quartz pebble (v-qz), angular quartz grains (qz) and muscovite grains (ms) that are not as degraded as those in the white gravel (view approximately 5 mm wide, crossed polars). Thin-section photomicrographs of the iron-stained gravel: (c) wide range in grain size from pebbles to sand, all surrounded by hematite (hem) and probably goethite (goe) (view approximately 5 mm wide, plane light); (d) vein-quartz pebble, angular quartz grains and muscovite surrounded by hematite and probable goethite (view approximately 5 mm wide, crossed polars).*

gravel than in the yellow gravel. The alteration can be explained as a combination of weathering and diagenetic processes. Diagenesis refers to "all chemical, physical, and biologic changes undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surficial alteration (weathering) and metamorphism," (Bates and Jackson, 1987); it includes "compaction, cementation, authigenesis, recrystallization, inversion, replacement, dissolution and bioturbation" (Boggs, 1987). According to Morrow and McIlreath (1990), it is not possible to assign unique ranges of temperature and pressure conditions to diagenesis, although it is generally accepted that diagenesis is characterized by temperatures of 0-300°C and pressures of 0.1-10 MPa. Surprisingly, diagenesis has not been mentioned in any previous research on the geology of placer deposits in the Klondike goldfields, particularly those studies examining the alteration or sedimentology of the White Channel Gravel (i.e., Dufresne, 1987; Dufresne and Morison, 1985; Dufresne et al., 1986; Froese, 1997; Milner, 1976; Morison, 1985; Morison et al., 1998; Tempelman-Kluit, 1982). The degree of alteration observed in the White Channel Gravel is classified as early diagenesis (i.e., characterized by changes occurring during burial to a few metres and temperatures not 'appreciably' exceeding 25°C; Berner, 1980), rather than the more advanced late diagenesis (i.e., characterized by deeper burial and higher temperatures; Thomas, 1983; Tucker, 1981).

REINTERPRETATION OF ALTERATION

Figure 10 presents a schematic diagram of paleo-Bonanza Creek, showing how weathering and diagenesis produced the alteration observed in the White Channel Gravel. Clay minerals can originate in at least the following five ways:

1) The Klondike goldfields (and most of west-central Yukon) are mainly underlain by Paleozoic metasedimentary (i.e., Klondike Assemblage and Nasina Assemblage) and meta-igneous rocks belonging to the Yukon-Tanana Terrane, and minor amounts of altered ultramafic rocks that are assigned to the Slide Mountain Terrane (Mortensen, 1990, 1996). This area is thought to have been a mature, subdued landscape by Miocene time, which underwent a period of uplift and erosion in the Pliocene (Tempelman-Kluit, 1980). Common bedrock lithologies throughout the goldfields include schist, gneiss and quartzite, which contain abundant muscovite, biotite, chlorite and feldspar (Mortensen, 1996). These minerals alter during weathering to clay minerals such as illite, smectite, vermiculite and kaolinite (Blatt, 1992; Bloom, 1969; Grim, 1968; Velde, 1985), all of which were probably produced during the long period of weathering

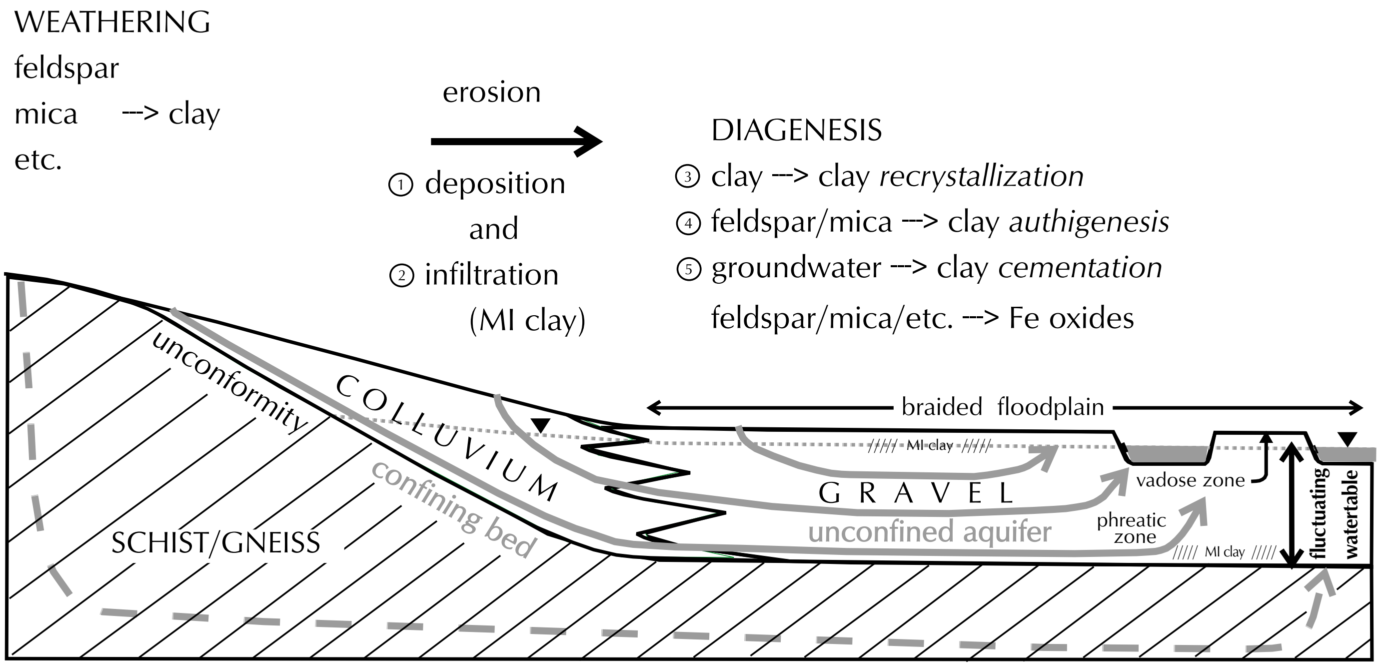

Figure 10. *Schematic diagram summarizing the origin of alteration in the White Channel Gravel, Klondike goldfields, Yukon; MI = mechanically infiltrated; = water table.*

required to develop the subdued Miocene landscape. During subsequent uplift and erosion in the Pliocene, the clays may have been transported and deposited as allogenic clay minerals with other sediments to form the White Channel Gravel. This long period of weathering followed by uplift and erosion may also explain the formation and distribution of tors throughout the goldfields (Easterbrook, 1993). In addition, Johnson and Meade (1990), and Morton and Hallsworth (1999) have shown that further weathering of sediment occurs during periods of alluvial storage on floodplains, which may have resulted in additional clay minerals being produced.

2) The seepage of muddy water through gravel alluvium may result in the deposition of mechanically infiltrated clays (Moraes and De Ros, 1990). Mechanically infiltrated clays tend to be concentrated within the vadose zone (due to the evaporation of infiltrated water), within the water table (due to a decrease in the velocity of percolating water in the phreatic zone) and above impermeable barriers, such as bedrock-gravel contacts (due to the filtering of clay particles above barriers in the phreatic zone, Moraes and De Ros, 1990). During floods, the White Channel Gravel floodplain would have been repeatedly inundated with muddy water that enhanced the formation of mechanically infiltrated clays. In addition, the White Channel Gravel represents a water table aquifer, or unconfined aquifer, that is confined to the relatively impermeable bedrock walls of the valley. Hence, the floodplain water table, which is closely associated with the river stage, changes as groundwater flow through the aquifer varies (Fetter, 1988). According to Moraes and De Ros (1990), fluctuations in the water table can result in the formation of subhorizontal clay-rich zones that may or may not cut across sedimentary structures. These zones, which correspond to former positions of the water table, can be relatively narrow (i.e., centimetres) or thick (i.e., up to tens of metres), depending on the length of time the water table was maintained at a particular level (Moraes and De Ros, 1990). Dufresne (1987) described similar clay-rich zones that occur above the gravel-bedrock contact and which transect primary sedimentary structures, but he interpreted these zones as evidence of ascending hydrothermal fluids.

3) Once deposited, allogenic and mechanically infiltrated clay minerals may recrystallize. This diagenetic process mainly involves a change in size (usually an increase) or shape of mineral crystals, without significant changes in composition (Boggs, 1987).

4) Other allogenic minerals (such as feldspar, mica and chlorite) deposited with the White Channel Gravel may undergo diagenetic alteration to authigenic clay minerals (i.e., kaolinite, illite and smectite), similar to the weathering process described previously. Depending on their abundance, these new minerals may or may not act as a cement in the White Channel Gravel (Boggs, 1987).

5) New clay minerals (particularly kaolinite) may have precipitated from interstitial pore water and circulating groundwater as diagenetic pore filling cement (Boggs, 1987). Groundwater flow would have been enhanced by the large differences in hydraulic conductivities (i.e., the capacity of sediment to transmit water) between the White Channel Gravel and the underlying bedrock. This may have resulted in a concentration of groundwater flow near the gravel-bedrock contact, which could account also for the formation of the iron oxide cement at this contact, (i.e., Dufresne's [1987] 'iron zone'). The iron for the cement was most likely supplied by intrastratal solution of detrital silicate minerals such as hornblende, chlorite, and biotite, as well as detrital magnetite and pyrite (Tucker, 1981). In addition, iron oxide can be seen precipitating at the bedrock-gravel contact at almost every exposure of the White Channel Gravel and other gravel units throughout the Klondike Goldfields.

There is no evidence that groundwater flowing within the White Channel Gravel aquifer was hot or even warm, and most shallow groundwater has temperatures of <30°C (Berner, 1971; Fetter, 1988; Heath, 1983), implying that the various diagenetic processes responsible for the alteration in the White Channel Gravel would have taken considerable time to occur. Although the age of the white gravel is only loosely constrained to a post-Miocene and pre-Late Pliocene age (~5-3.3 Ma, based on paleomagnetism and paleobotany), the yellow gravel is Late Pliocene in age (~3.3-2.6 Ma, based on glass fission track argon ages of two tephras, Westgate at al., 2000). Hence, the higher degree of alteration observed in the white gravel (i.e., greater degradation of muscovite and a greater amount of authigenic kaolinite), as compared to the yellow gravel, may be due to the older age of this sub-unit. Smith et al. (1986) found a direct relationship between age and clay content of paleosols, with the older paleosol (i.e., Wounded Moose) containing a greater amount of kaolinite than the younger paleosol (i.e., Diversion Creek). In addition, climate is considered the most significant long-term control of weathering, and therefore the type of clay minerals produced during weathering is thought to reflect the climate at the time they formed (Easterbrook, 1993; Grim, 1968). Generally, kaolinite is characteristic of more temperate and humid climates, whereas smectite is characteristic of warm to subhumid climates (Berner, 1971; Foscolos et al., 1977; Smith et al., 1986). Hence, the abundance of kaolinite in the white gravel may also be due to a more temperate and humid climate at the time of its formation. Due to the greater amount of clay in the white gravel, the mining of this sub-unit may result in a slightly greater impact on water quality and effluent discharge than mining other, younger gravel units.

Although a sedimentary origin for the alteration observed in the White Channel Gravel cannot be proven, May (1994) suggested that the presence of certain iron minerals provides a method of distinguishing hydrothermal alteration from weathering: siderite and iron-rich dolomite apparently indicate low temperature hydrothermal alteration, whereas hematite and goethite are supposedly more characteristic of weathering. The White Channel Gravel contains no authigenic siderite or iron-rich dolomite, but it does contain abundant hematite and goethite in Dufresne's (1987) iron zone, which indicates that the alteration is not hydrothermal in origin. In addition, Longstaffe (1984) used oxygen-isotopic compositions of clay minerals to distinguish authigenic from allogenic clays (i.e., authigenic clays, which were mostly kaolinite, have $\delta^{18}O<+16$ SMOW, whereas allogenic clays, which were mostly illite, have $\delta^{18}O>+16$ SMOW). However, Hutcheon (1983, 1990) cautioned that for most sediment, it is practically impossible to physically separate the authigenic from the allogenic clays.

CONCLUSIONS

Dufresne (1987) has not demonstrated clearly that the alteration observed in the White Channel Gravel is hydrothermal in origin: there is no unequivocal evidence supporting hydrothermal alteration. The alteration is reinterpreted as a result of weathering and particularly diagenesis due to groundwater flow. In addition, there is no 'hidden' epithermal gold deposit in the gravel or in the bedrock. The reinterpretation of the alteration as the product of sedimentary processes has the following implications and applications: 1) for the past ~20 years, the alteration had been incorrectly referred to as hydrothermal alteration without any compelling evidence; 2) it appears that the older the gravel, the greater the degree of alteration (i.e., it takes time for weathering and diagenetic processes to operate); 3) the alteration provides information on paleoweathering and paleoclimate; and 4) mining-altered (i.e., older) gravel has a slightly greater impact on water quality and effluent discharge (i.e., authigenic clay is more abundant in the white gravel than in the yellow gravel).

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