A SPECTROGRAPHIC AND MINERALOGRAPHIC INVESTIGATION OF ALLUVIAL GOLD FROM THE CENTRAL YUKON

A Thesis submitted in Partial Fulfillment of the
Requirements of Bachelor of Science in
the Department of Geology

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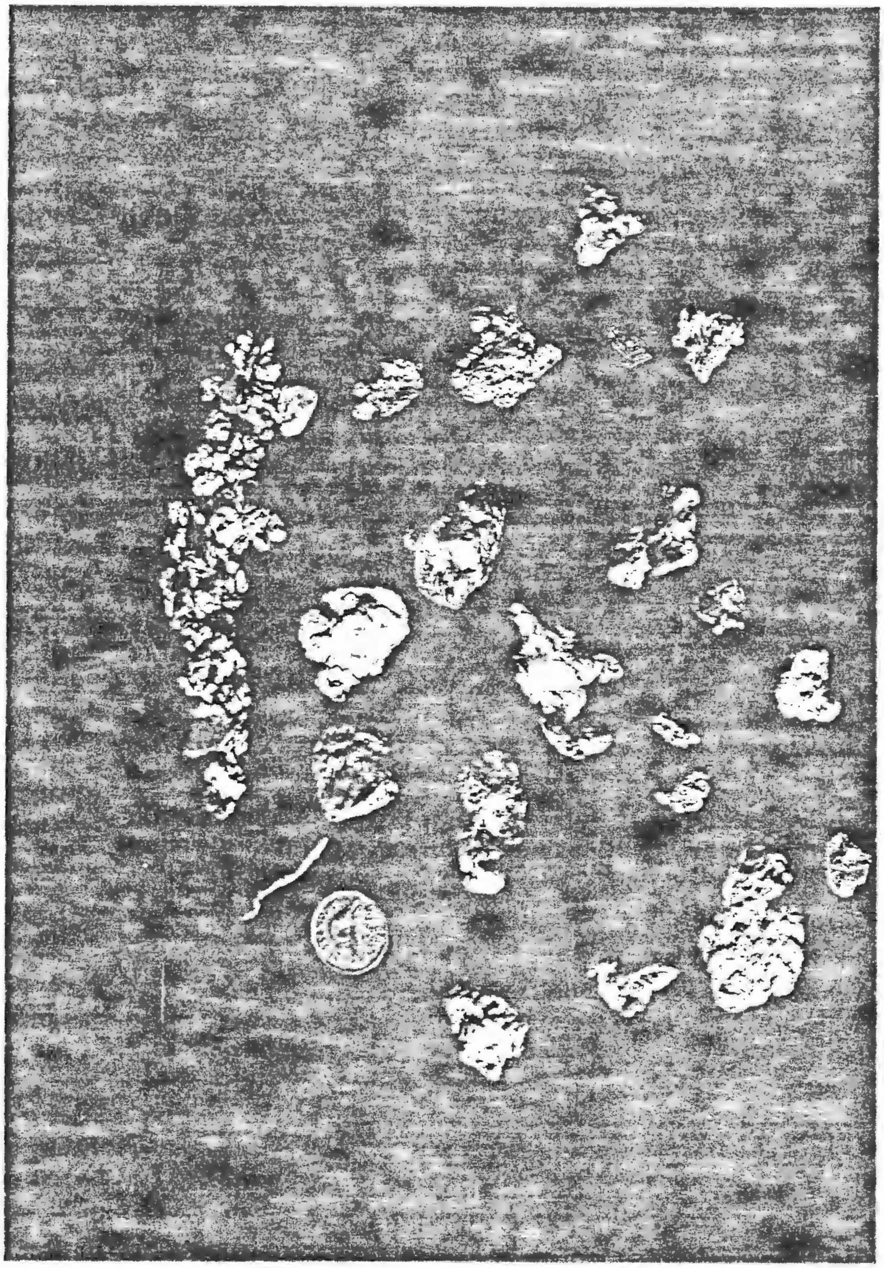
ABSTRACT

With the purpose of determining the usefulness of placer gold as an indicator of metallogenic zones, and of investigating its texture, structure and possible mode of origin, samples of alluvial gold, collected from the Dawson and Mayo districts of the Central Yukon, were studied and discussed. Semi-quantitative spectrographic analyses were made on gold from each locality. Certain assemblages of trace elements, particularly zinc, bismuth, arsenic and antimony, show a characteristic distribution and can often be correlated with the presence of known mineralization in the area. This study suggests that spectrographic analysis of placer gold might be used to indicate metallogenic zones and to aid geochemical methods in delimiting certain areas for careful geological exploration.

A mineralographic study was made on mounted and polished specimens of gold, by etching the surface with aqua regia to show significant textures. Features observed and discussed were dendritic intergrowths, the mutual arrangement of crystal aggregates, as well as zoning and twinning within crystal boundaries. Factors related to the origin of placer gold, such as oriented microcrystals,



Frontispiece - Coarse alluvial gold from the White Channel Gravels of Discovery Hill, Hunker Creek. Note wire, hopper-shaped crystallized sample, and gold intergrown with quartz.

redeposited surface gold, and foreign inclusions are described. From the investigation, it was concluded that alluvial gold originated by denudation of quartz veins rather than by precipitation from stream waters.

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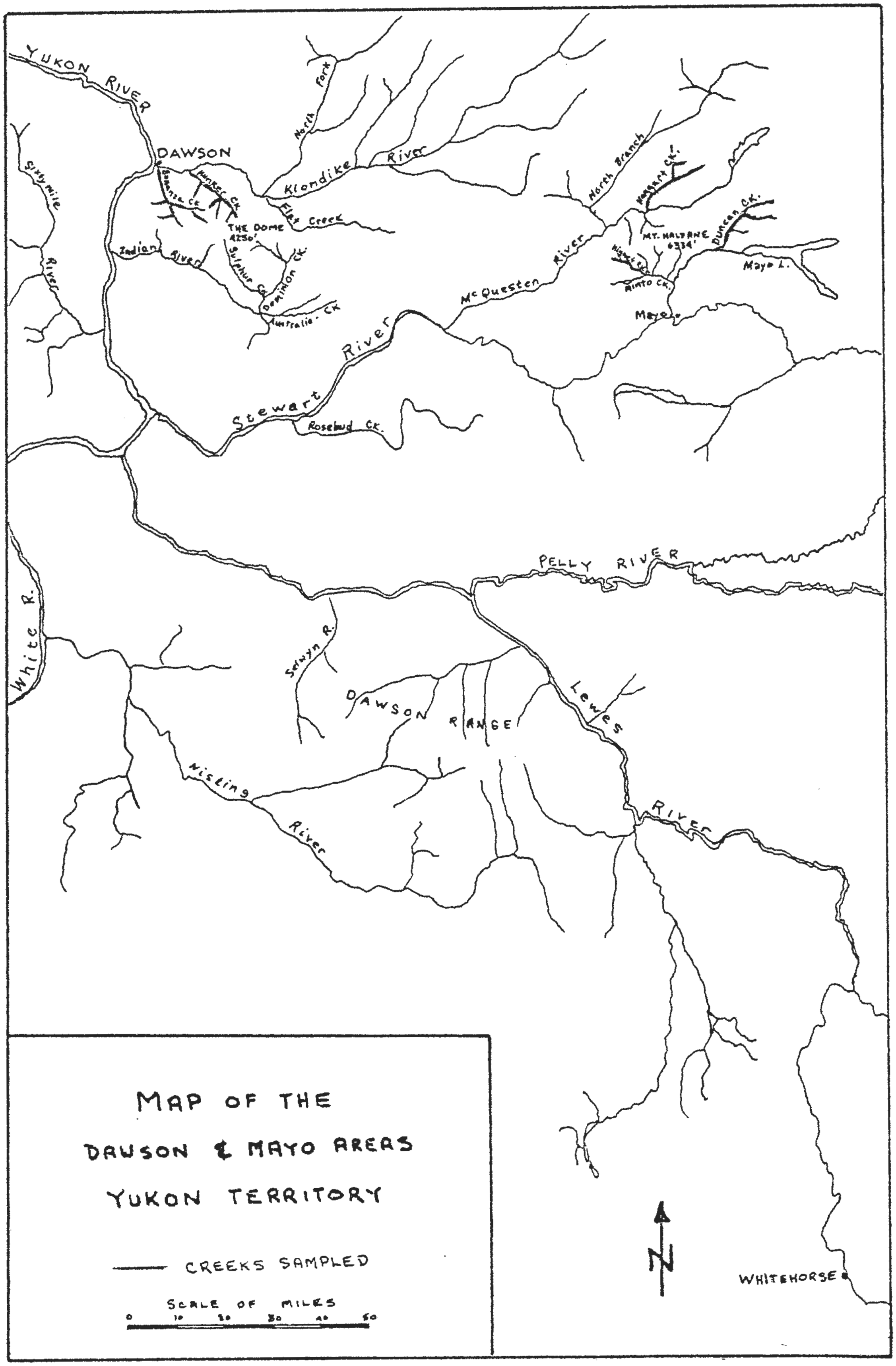

MAP OF THE
DAWSON & MAYO AREAS
YUKON TERRITORY

INTRODUCTION

The search for ore deposits in the Yukon Territory, particularly in the Keno Hill area, has increased immensely over the last few years. At present, though many major mining companies have interests in the district, production comes only from United Keno Hill's mine-mill complex on Galena and Keno Hills and from many placer gold operations in the Klondike and Mayo areas, a substantial part of which is controlled by the Yukon Consolidated Gold Corporation.

Owing to very poor outcrop, geochemistry as a prospecting tool has been used extensively in explorations both by mining companies and government, with primary emphasis placed on soil and silt sampling. With the object of contributing to this search, the author carried out spectrographic and metallographic analyses on thirteen samples of alluvial gold from the Mayo and Dawson regions, collected during the summer of 1964. The specimens included both nuggets, coarse flakes and fine dust from placer operations which were visited while in the employ of the Geological Survey of Canada.

By means of spectrographic analyses of the gold and semi-quantitative tabulation of minor elements contained, the writer hoped to suggest the presence of metallogenetic zones in the Mayo and Klondike districts (two areas having well known mineral deposits). The work was carried out in a similar manner to that of H. V. Warren and R. M. Thompson[1] in so far as trace elements, where found in anomalous amounts, were construed as evidence of possible lode deposits in the area. A discussion of known mineralization in each of the sampling localities was therefore included, in order to check the reliability of the use of minor elements in gold as "pathfinders" to ore deposits.

The second part of the thesis consisted of a metallographic study made on sixteen polished sections of gold, with the object of adding any information possible to that already known on microstructures of alluvial gold. By means of etching with aqua regia, crystal arrangements and zoning, as well as foreign inclusions in the specimens were studied and interpreted, while attention was also given to aspects of the investigation which might provide evidence for the ultimate origin of placer gold.

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[1] H. V. Warren, and R. M. Thompson, Minor Elements in Gold. Economic Geology, vol. 39, No. 7, pp. 457-471. Nov. 1944.

ACKNOWLEDGEMENTS

I would like to sincerely thank, J. M. Atcheson, I. C. Bremner, A. T. Fry and L. Hogg, who contributed samples for the study. I would also like to thank my adviser,Dr. R. M. Thompson of the University of British Columbia, Department of Geology for his assistance in spectrographic and X-ray analyses, Dr. R. W. Boyle of the Geological Survey of Canada who suggested the thesis topic, and Dr. J. R. Lund of the University of British Columbia, Metallurgy Department, who allowed me free use of metallographic equipment and aided in interpretation of microstructures.

GEOLOGIC HISTORY

The geomorphic erosion cycle which brought about the placer concentration of gold in the Central Yukon has been explained by D. D. Cairnes.[2] In the Late Tertiary as as a result of uplift of the Yukon Plateau, an erosion cycle was initiated which led to downcutting of deep valleys. The long duration of degradation resulted in

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[2] D. D. Cairnes, Report on the Mayo Area, Yukon. Geological Survey, Department of Mines, Summary Report 1915, pp. 10-37.

development of mature stream deposits consisting primarily of rounded quartz gravels. The quartz, with its associated deposits of placer gold, originated from erosion of auriferous veins cutting the Pre-Cambrian Klondike Schist.

In an ensuing period of upwarping, followed by glaciation, many of these rich accumulations were destroyed. However, some remained untouched as the high level White Channel Gravels of the Klondike (see Plate 1) and as benches (remnants of higher channels) in the Mayo region. The gravels of present day stream beds, enriched in gold by reconcentration of earlier detritus, were found to be most extensively mined today.

GEOLOGIC SETTING AND DESCRIPTION OF PLACERS[3]

Klondike District

In the Dawson area, quartz occurs plentifully as discontinuous veins and lenses in schist. Scanty mineralization, including pyrite, chalcopyrite, galena, magnetite and native gold, is present in the quartz.

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[3] L. H. Green, and C. I. Godwin, Mineral Industry of the Yukon Territory and Southwestern District of Mackenzie, 1962. Geological Survey of Canada, Paper 63-38.

Plate 1
White Channel Gravels located on Cripple Hill, Bonanza Creek

Bonanza Creek, the most important gold-bearing water course in the Klondike, was sampled at three locations (see Figure 1). At the mouth of Victoria Gulch on Upper Bonanza, smooth flakes of gold with few nuggets are found (sample 1). At the head of the gulch, gold-quartz veins were mined on the Lone Star Property, and several thousand dollars in gold recovered before the mine was

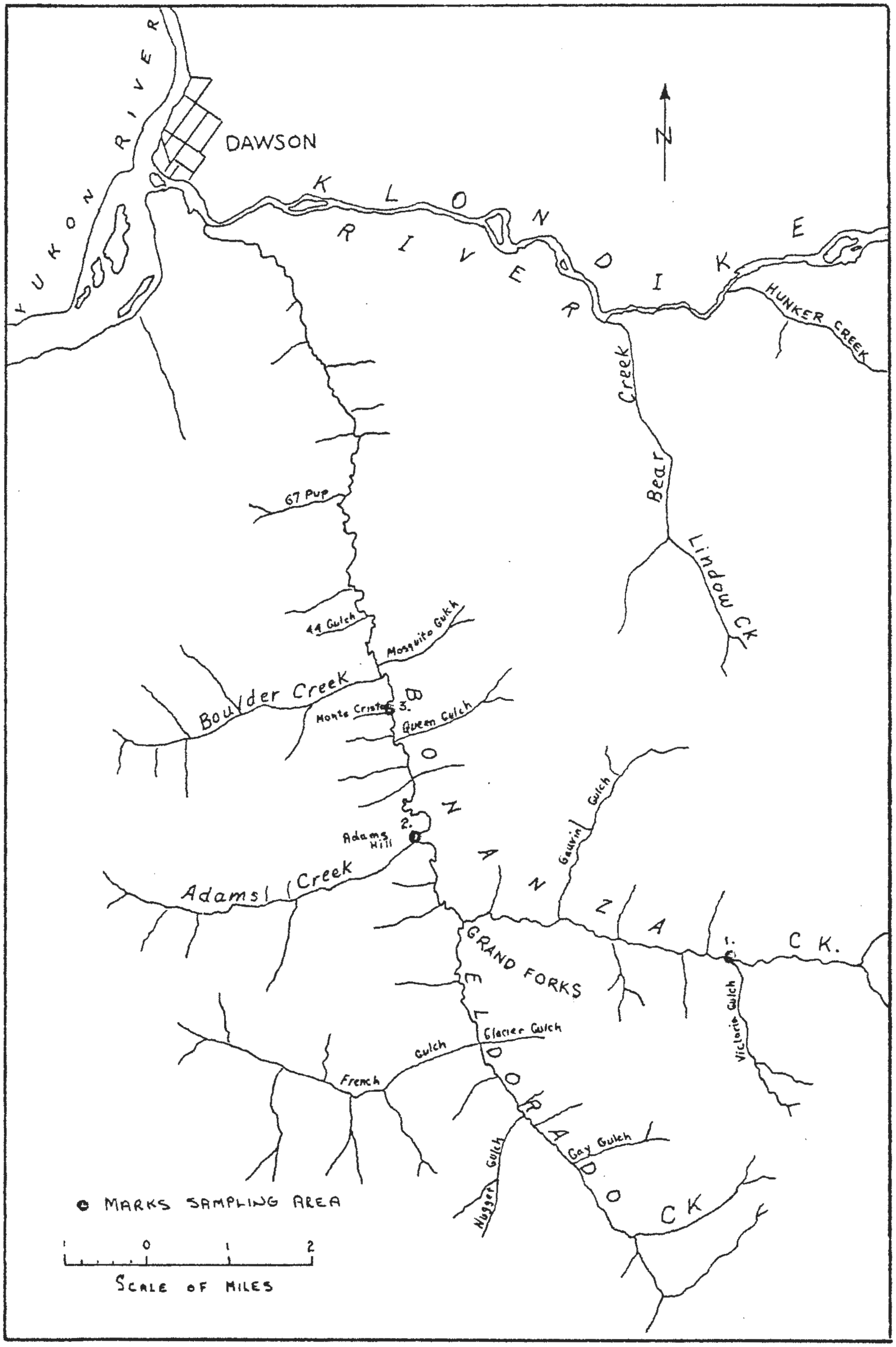

Figure 1. Bonanza Creek, Klondike Gold Fields.
(After McConnel, 1900)

closed down. On Adams Hill, gold in the form of well worn coarse flakes, (sample 2) is removed from the White Channel Gravels by hydraulic means. From Monte Cristo Gulch, gold is in the form of flattened to irregular coarse flakes (sample 3a). A significant number of flakes were seen to be comprised partly of gold and partly of a grey malleable metal (sample 3b).

Hunker Creek, six miles above Bonanza, (see Figure 2) contains more White Channel gravels than any other stream in the district. Samples collected from Dago Hill, Goldbottom and Preido Hill (samples 4, 5 and 6) -- all located near the Hunker-Goldbottom junction on Hunker Creek, typically consisted of fine to coarse flakes. Below Goldbottom, a specimen from an unknown locality on Hunker Creek was obtained (sample 7). Finally, from the White Channels of Discovery Hill, located on Lower Last Chance Creek, a sample of fine and coarse flakes (assaying about 700 fine) as well as very angular, crystallized and dendritic nuggets was obtained (sample 8). The frontispiece of gold from Discovery Hill is remarkable for its hopper-shaped crystals and impregnation of quartz fragments. Heavy minerals in concentrates include silver, magnetite, ilmenite, cassiterite, monazite and zircon.

<u>Mayo District</u> (see Figure 3)

In the Dublin Gulch-Haggart Creek area,

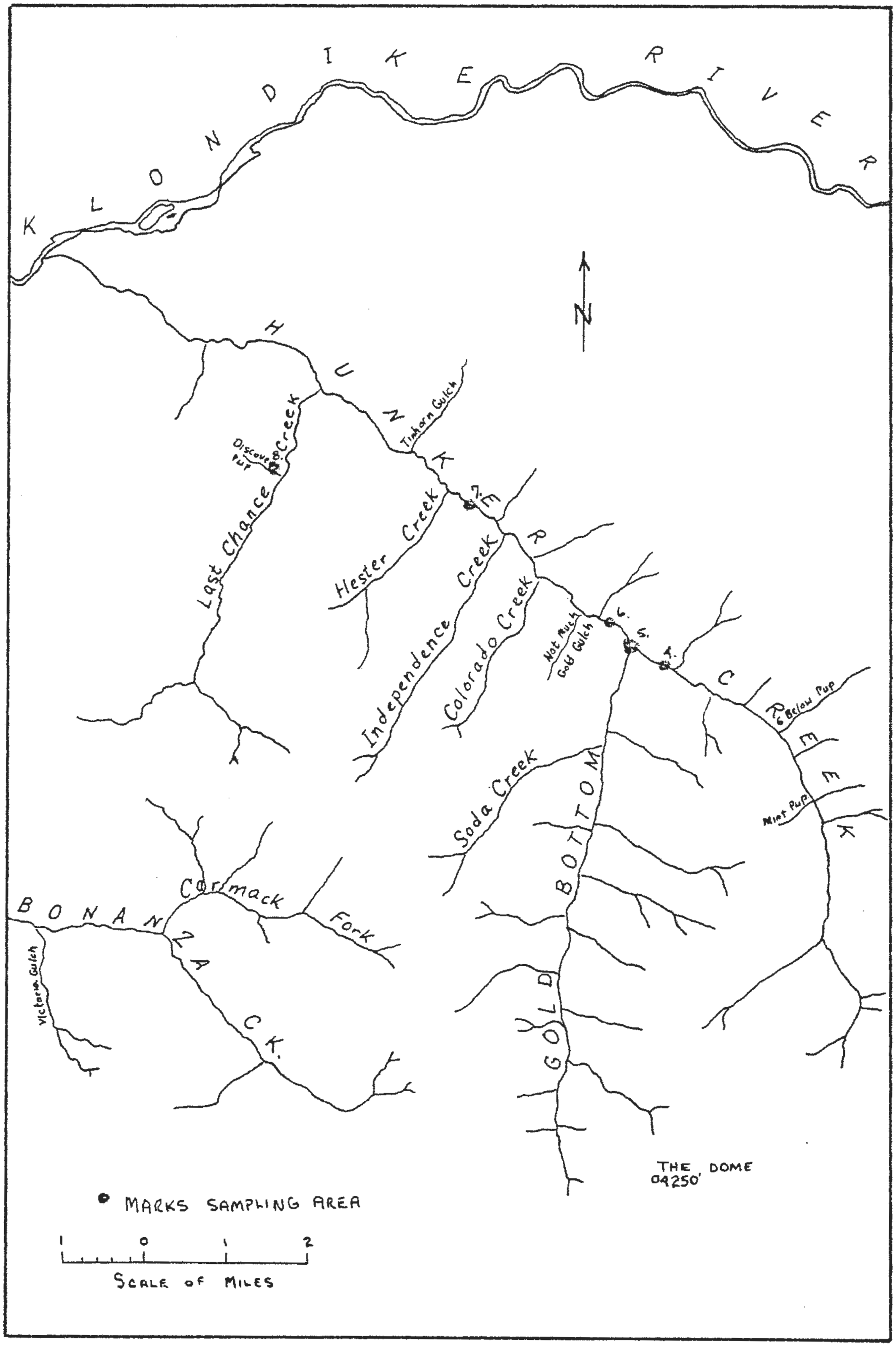

Figure 2. Hunker Creek, Klondike Gold Fields.
(After McConnel, 1900)

Pre-Cambrian schists, quartzites and minor limestones predominate and are intruded by Mesozoic granitic stocks. Gold values averaging .5 oz./ton with less than 1 oz./ton silver are found in quartz-arsenopyrite veins usually located near the schist-intrusive contact. Scheelite, recovered as a placer concentrate from Dublin Gulch, has been found in place in only minor amounts. Generally it forms crystals up to .5 inches long in otherwise barren quartz veins cutting pegmatite zones in the intrusives, or is found as scattered flecks in the adjacent diopside skarns. Jamesonite-stibnite-sphalerite veins, with or without silver, are situated in the Haggart Creek drainage basin. Cassiterite has been found in place at the Haggart-Dublin junction. Characteristic heavy minerals are magnetite, wolframite, hematite, ferberite, arsenopyrite, cassiterite (well crystallized), jamesonite, bismuth, galenobismutite and bismuth tellurides.[4] Gold from Dublin Gulch is typically rough and wiry (sample 9) with nuggets up to 1 ounce comprising 10% of the total. In contrast, gold from Haggart Creek is well worn and few nuggets are found.

The drainage basin of Duncan Creek contains the rich Keno Hill - Galena Hill ore deposits of essentially

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[4] A. E. Aho, Mineralogy of Some Heavy Sands of the McQuesten River Area, Y. T. Unpublished B.A.Sc. Thesis, University of B. C., 1949, pp. 18-21.

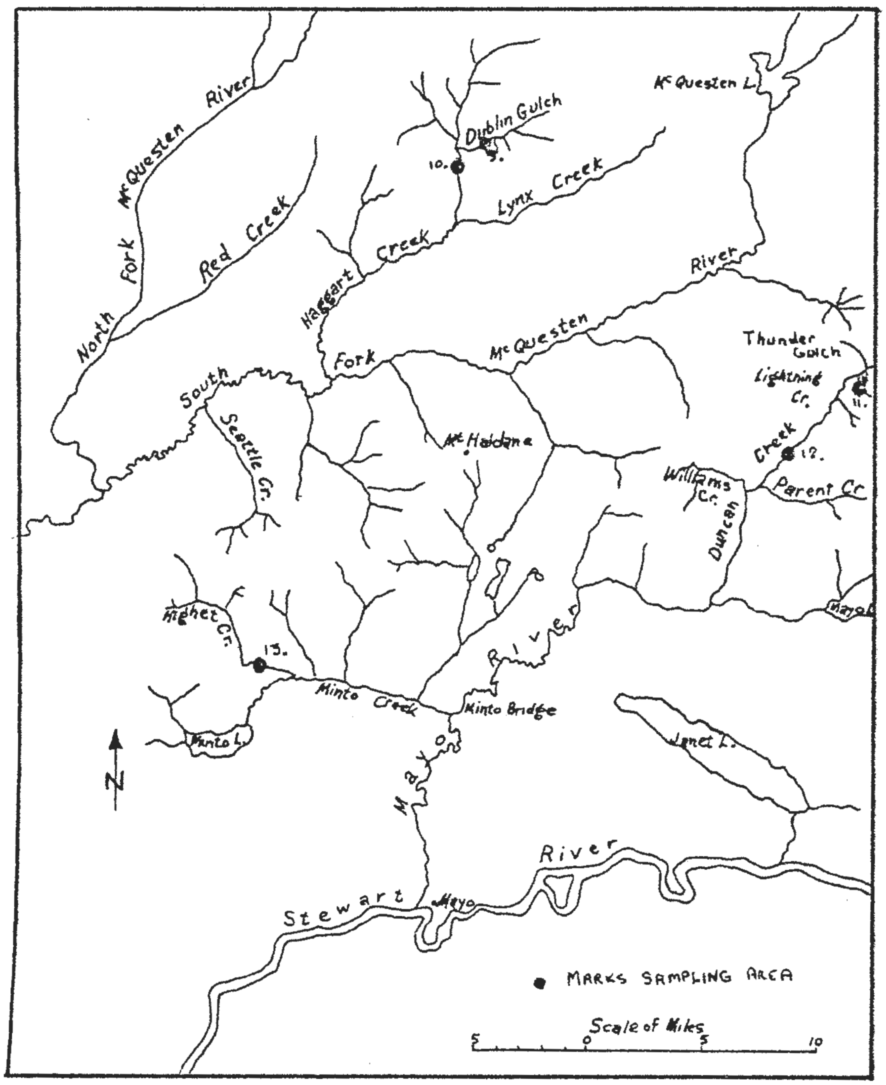

Figure 3. Haggart, Duncan and Highet Creek Systems, Mayo Area. (Geological Survey of Canada, 1915)

tetrahedrite, sphalerite, galena, and silver minerals. Duncan Creek, having both auriferous pre-glacial and glaciofluvial deposits, is characterized by markedly platy flakes of gold (sample 11). From Thunder Gulch, a small tributary of the Lightning-Duncan Creek System, well rounded nuggets and coarse flakes are recovered (sample 12).

Highet Creek, which enters Minto Creek about ten miles north-west of Mayo, contains well worn, coarse gold (850 fine) with nuggets commonly up to three-quarters of an ounce (sample 13). Magnetite, hematite, scheelite, cassiterite, arsenopyrite, bismuth, joseite, stibnite, and ferberite are typical heavy minerals.[5]

SPECTROGRAPHIC ANALYSIS

Procedure

All samples were carefully checked with the binocular microscope and grains chosen for analysis appeared free of mechanically included impurities and of iron oxide staining. Mercury was in no instance used for separation of the gold from other heavy minerals. Analyses were made however, of samples with obvious inclusions for comparative

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[5] Aho, op. cit., pp. 8-11.

purposes. With a Medium Hilger Quartz Spectroscope, a series of narrow tangent strips were exposed on Eastman Kodak Spectrographic Plates,Type II-F,to give successive spectra of: (a) iron (from Hilger's "spec pure" iron electrodes)-- 3 seconds; (b) the gold sample -- 3 seconds and 20 seconds; (c) the R. U. standard (giving the sensitive arc lines of 50 elements) -- 10 seconds.

Three samples of gold from a single locality, differing in weight by not more than .0006 grams, were arced at 10, 15 and 20 seconds respectively to test the effect of exposure time. The variations had no significant influence on the intensities of spectral lines and therefore, fluctuation in exposure time was not regarded as a source of error. By comparison of lines in the sample with those of iron and R. U. standards, minor elements present in the placer gold could be accurately determined. Hilger's Spectrographic Charts along with several reference texts,[6] proved valuable in identifying spectral lines.

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[6] W. R. Brode, Chemical Spectroscopy. John Wiley and Sons Inc., New York. 1933.
G. R. Harrison, Massachusetts Institute of Technology Wavelength Tables. John Wiley and Sons Inc., New York. 1939.
J. W. Ryde and H. G. Jenkins, Sensitive Arc Lines of 50 Elements. John Mathey and Co. 1961.

Results of Analyses

Results of analyses are tabulated semi-quantitatively (see Table 1) for comparative purposes only. Estimation of trace amounts was made by comparison of lines in the gold sample with that in the R. U. spectrum. Elements showing lines much stronger than the corresponding R. U. were classed as strong (S), those approximately equal to the R. U. as medium (M), and those much weaker, as faint (F), with minor variations within groups shown by addition of suffixes (+) and (-).

As with the work of Warren and Thompson, the elements silica and magnesium with minor aluminum and calcium were not reported, as their presence was probably in the form of trapped gangue minerals or as minor impurities in the electrodes.

In agreement with the work of Warren and Thompson, the author believed that most of the trace elements listed were chemically combined with the gold. The former workers supported their view in light of such findings as: (1) iron was present in gold whether from an iron rich or iron poor deposit; (2) bismuth and lead with traces of tellurium are commonly associated with gold in the Cariboo Mining Division. However, gold was taken from mines in which traces of only one of the elements were found. As Rose and Newman stated,[7] "Gold is occasionally alloyed with iron, bismuth, lead, mercury, tin, antimony, palladium and rhodium."

In three cases, however, a study of polished sections showed the presence of mechanically included minerals. In the case of Discovery Hill, a dendritic nugget contained several rhombs and prisms of arsenopyrite (see plate 2). However neither in a section of five other flakes nor in the spectrographic analyses, was arsenic detected. From Dublin Gulch, a large number of angular arsenopyrite fragments were present in the gold (see plate 3). In this case, the association was supported by field evidence of gold-arsenopyrite-quartz veins found in the area. Either shearing movements while in place or hammering in the stream bed caused fracturing of the arsenopyrite and the granulation of the gold surrounding it as can be seen in Plate 3.

The third occurrence of an included mineral was found in a section from Thunder Gulch. It was identified as jamesonite, by an X-ray powder photograph.

The writer agreed with both the work of Warren and

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[7] T. K. Rose and W. A. C. Newman, The Metallurgy of Gold. Charles Griffin and Co. Ltd. 1937, p. 91.

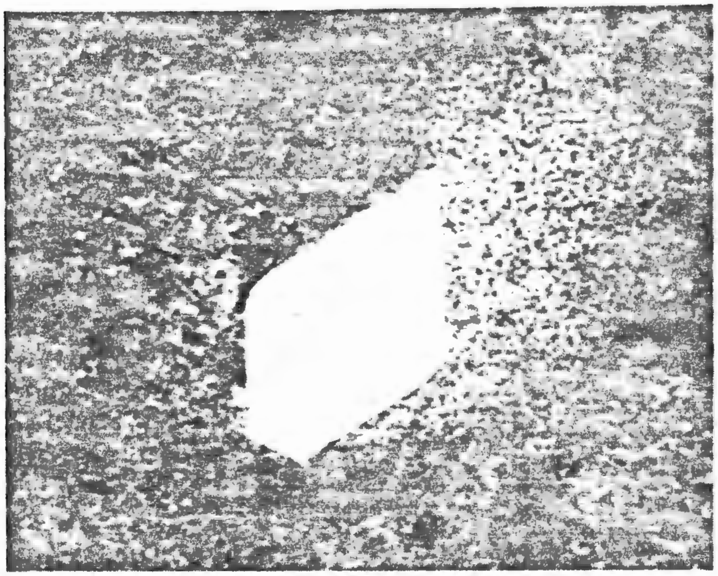

Plate 2
Euhedral rhombic crystal of arsenopyrite, shown after etching. Discovery Hill, Hunker Creek. (700 x)

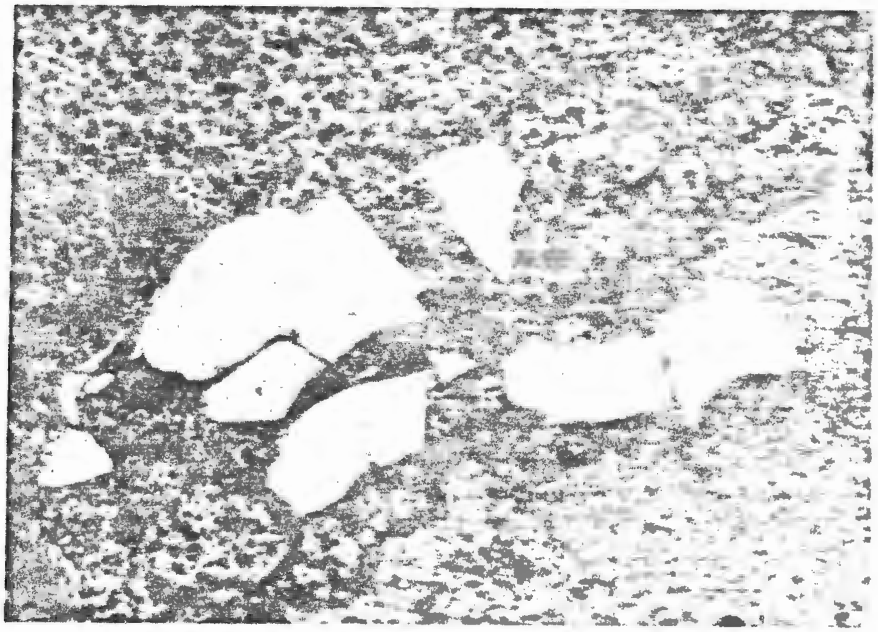

Plate 3
Angular arsenopyrite fragments located within fracture zone in gold nugget. Dublin Gulch. (250 x)

Thompson, and of Crook[8] in finding silver, copper and iron chemically combined with gold in each specimen. Native gold is known to contain silver in amounts ranging from 2 to 450 parts per thousand.[9] Copper, silver, and gold are face-centred cubic structures but copper is generally present in gold in amounts less than 50 parts per thousand because the atomic diameter differs from that of gold by 12.5%. In all samples, silver was classed as a strong constituent, copper as medium and iron from medium to faint. None of these elements seem to be more concentrated in one area than another.

Tin was found, at least as very weak traces, in all localities sampled. At Dublin Gulch, where lode cassiterite is known, tin was determined as a faint constituent of placer gold. A striking occurrence of tin, however, was found on Monte Cristo Hill, approximately seven miles up Bonanza Creek. The sample consisted of coarse flakes, a number of which were half gold and half a soft, grey, malleable, metallic substance. Here, both the uncontaminated flakes and the grey mineral showed distinct

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8 W. S. Crook, Preliminary Spectrographic and Metallographic Study of Native Gold. A.I.M.E. - Metals Technology Feb. 1939.

9 A. B. Edwards, Textures of the Ore Minerals. Australasian Institute of Mining and Metallurgy. 1960. pp. 47-50.

tin lines of medium or greater strength. The grey metal was isolated from the pure gold and spectrographed (see Table 1). It was composed chiefly of gold with admixed amounts of copper, iron, mercury, arsenic and antimony in approximately the same proportions as the placer gold with which it is associated. However, the grey mineral showed a slightly above normal trace of lead and anomalously high amounts of tin.

A flake containing both gold and the grey metal in contact was mounted and polished. The grey mineral proved to be harder than gold, was greyish white in colour, isotropic, and showed without etching an eutectic texture of two or more phases (see Plate 4). The boundary between the gold and the white mineral appeared diffuse, irregular, free of inclusions, and could not be clarified under high magnification. A narrow homogeneous band of white metal separated the gold from the eutectic textured tin-rich mixture. In light of the boundary characteristics, the association between the two minerals was not believed to be a mechanical one.

Determinations of microhardness were made on both gold and the grey mineral using a Wilson "Tukon Tester". The gold was found to have a Diamond Pyramid Hardness (D.P.H.) of 44 and the grey mineral, 125. Common lead-tin alloys are known to have a D.P.H. of less than 20, while a

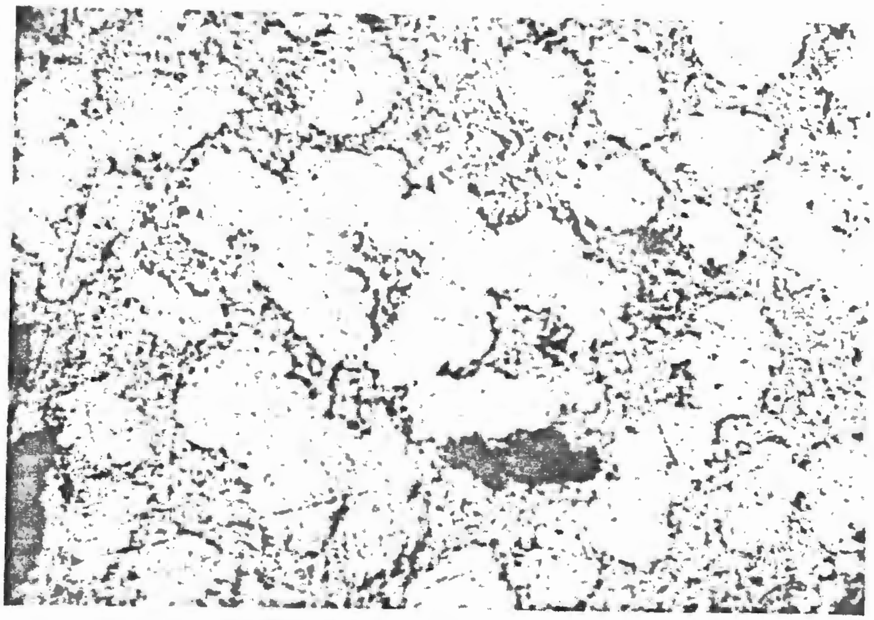

Plate 4
Eutectic intergrowth in unidentified Au-Sn-Pb compound.
(Unetched) Monte Cristo Hill, Bonanza Creek. (650 x)

copper-lead-tin alloy of composition Cu - 80%, Sn - 10%, Pb - 10%, has a value of 65.[10]

Dr. J. R. Lund of the Metallurgy Department, University of British Columbia, was of the opinion that a gold-rich eutectic mixture with chemically combined impurities such as tin and copper could have a D.P.H. of 125. He further suggested that the white metallic substance might be a complex gold alloy of at least binary or ternary degree.

Hansen [11] has shown , by X-ray analysis of synthetic alloys in the gold-tin system,the existence of the three intermediate phases AuSn, $AuSn_2$ and $AuSn_4$. The gold-tin eutectic crystallizes at 280°C as Au - 70%, Sn - 30%. In the gold-lead system, Hansen found two intermediate phases of composition Au_2Pb and $AuPb_2$. Unless annealled, Au_2Pb decomposes into Au and $AuPb_2$. The gold-tin lead eutectic crystallizes at 215°C as Au - 15%, Pb - 85%.

Though no definite conclusions were reached, a comparison of the X-ray powder photographs made of the grey

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[10] T. Lyman, Metals Handbook. American Society for Metals, Cleveland, Ohio. 1948.

[11] M. Hansen, Der Aufbau der Zweistofflegierungen (Constitution of the Binary Alloys). Edwards Bros. Inc., Michigan. 1936.

mineral showed at least partial correlation with that of AuSn. Further work must be done to determine the nature and composition of this gold-tin mixture. When completed, the author plans to add the results and discussion as Appendix I.

Mercury was also consistently alloyed with gold in every locality. Bonanza Creek in particular showed relatively strong mercury traces. The Hunker Creek system was, on the whole, poorer in mercury than the Mayo Area, while both were much weaker than Bonanza. All samples were known to be free of mercury contamination.

Lead was always present but randomly distributed throughout the samples. It was always classed as faint component except at Monte Cristo Hill. Here, both in the previously described half grey - half gold flakes and in the clean gold, lead was a significant constituent.

The Mayo area was consistently richer in arsenic than the Klondike as can be seen from Table 1. Gold from Dublin Gulch, where gold-arsenopyrite quartz veins were found in place, showed a significant amount of arsenic.

Antimony was notably concentrated in specimens from the Mayo region while the Klondike area, except for Discovery Hill, was poor in that element. The courses of Duncan Creek and Thunder Gulch drain the Keno Hill -

Galena Hill area where argentian tetrahedrite is the chief ore mineral. Both creeks showed good traces of antimony and in addition, the lead-antimony-iron sulphosalt, jamesonite, was identified as inclusions in gold from Thunder Gulch.

Bismuth was found only in gold specimens from the Mayo area,where placer concentrates, as stated previously, have yielded galenobismutite, bismuth and bismuth tellurides. The Dublin Gulch - Haggart Creek system showed significant amounts while Highet Creek gold contained traces of bismuth.

Sphalerite, is a widespread mineral of the Galena Hill ores and is present in the vein systems near Haggart Creek. No lode deposits are known in the Klondike area however. Such a distribution is very clearly supported by the similar distribution of zinc as a trace element, the Mayo samples showing significantly stronger zinc lines than those of the Dawson region.

Manganese is poorly distributed and lacking in many samples, although Hunker Creek gold showed faint traces in all specimens. If gold had, as those favoring a chemical rather than a mechanical origin for placers state, precipitated from solution in the stream gravels in the presence of manganese, a much higher content of the trace element would be expected.

TABLE I. MINOR ELEMENTS IN PLACER GOLD

DETERMINED SEMI-QUANTITATIVELY
BY SPECTROGRAPHIC ANALYSIS.

S-STRONG M-MEDIUM F-FAINT

LOCALITY	Ag	Cu	Fe	Sn	Hg	Pb	As	Sb	Bi	Zn	Mn
BONANZA CREEK											
1. VICTORIA GULCH	S	M	F+	F	F+	F+	—	F=	—	F+	F
2. ADAMS HILL	S	M	F	F	M−	F+	—	F	—	—	—
3a. MONTE CRISTO UNCONTAMINATED	S	M	F	M−	M−	M−	F=	F−	—	—	—
3b. MONTE CRISTO GREY MINERAL	S	M−	F+	S−	F	M+	F−	F−	—	—	—
HUNKER CREEK											
4. PREIDO HILL	S	M	F+	F	F+	F+	F=	F−	—	—	F−
5. GOLD BOTTOM	S	M	F+	F=	F	F	F+	F−	—	—	F
6. DAGO HILL	S	F+	F+	F	F	F	F−	F=	—	—	F
7. HUNKER CREEK	S	M−	F+	F+	F	F	F	—	—	F	F
8a. DISCOVERY HILL YELLOW	S	F	F	F−	F−	F−	—	F+	—	—	—
8b. DISCOVERY HILL WHITE-YELLOW	S	M−	F+	F	F+	F	—	F+	—	F=	—
MAYO AREA											
9. DUBLIN GULCH	S	M	M	F	F	F+	M−	—	M	F++	F
10. HAGGART CREEK	S	M	F+	F	F+	F	F	F	F	F−	—
11. THUNDER GULCH	S	M+	F+	F−	F	F−	F	F	—	F−	—
12. DUNCAN CREEK	S	M	M	F	F+	F+	F	F	—	F	F
13. HIGHET CREEK	S	M+	F+	F	F−	F	F	F−	F	F−	F

A number of elements were not detected in any of the spectrographic analyses. Generally these were believed unfavorable for forming alloys with gold or were absent from the area completely. Examples are platinum, palladium, cobalt, nickel, molybdenum and tungsten.

STUDY OF MICROSTRUCTURES

In an attempt to add to the present knowledge of the composition and origin of alluvial gold, sixteen polished sections were prepared using samples varying from coarse flakes to nuggets. The specimens were mounted in cold setting plastic, etched to bring out significant microstructures, and interpretations made of any textures developed.

Preparation of Specimens

In order to mount the specimens without heat or pressure which might cause recrystallization of the gold, "Koldmount", a lucite plastic, was employed. The samples were placed in silicon rubber molds into which liquid "Koldmount" was poured. The substance solidified to a hard, fine-grained plastic which unlike dental cement will not chip upon grinding or provide pores for collection of abrasive. The mounted specimen was then ground on graded emery papers, finishing with No. 000. Grinding was completed with No. 600 abrasive on a Buehler Microcloth lap and by using the compounds alumina, tin oxide and magnesium oxide respectively, a high polish was finally attained. Only very light pressure could be applied in order to avoid distortion of surface features.

In the etching which followed, both time of immersion and correct concentration of reagent varied from specimen to specimen. For gold of purity greater than about 900 fine (i.e. deep yellow in colour), concentrated aqua regia and immersion time from one to ten seconds was satisfactory. With an increase in silver content (i.e. specimens are whitish yellow) the concentration had to be reduced to as little as 1:2, aqua regia to water.

Crystal Structures

An examination of the crystal structure of gold was made by use of two techniques: (1) etching of the polished surface of nuggets and flakes with immersion from 2 to 15 seconds to bring out crystal boundaries (see Plate 5). (2) deep etching for fifteen minutes or more to show the component microcrystals contained within the larger crystal boundaries (see Plate 6). Photographs were taken using a Reichert Wien Metallograph, made available by the Metallurgy Department.

The first and most common type of microstructure revealed by short etching time was an aggregation of anhedral, rounded crystals, differing greatly in size from one to another and for the most part untwinned (see Plate 5). Fisher[12] found this structure was similar to that developed by melting gold and silver together and allowing them to freeze as an alloy. Further studies of sections were indicative of the fact that the gold had undergone no recrystallization since deposition in veins. Rose and Newman[13] showed that heating native gold at 80°C for 100 hours or at 200°C for a few seconds caused growth of new crystals and widespread rectilinear twinning. Rectilinear twin bands, generally close-spaced and parallel to the direction of crystal elongation were found by Fisher to form typically by recrystallization. Since such twinning was rare or absent in sections examined, recrystallization of gold must not have occurred.

With continued etching, the smaller crystals were found to darken more quickly than the larger ones. Such an observation can be explained in light of a conclusion

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[12] M. S. Fisher, The Origin and Composition of Alluvial Gold, with Special Reference to the Morobe Goldfield, New Guinea. Trans. of Inst. of Min. and Met. - 1935, vol. 44, pp. 337-380.

[13] Rose and Newman, op. cit., 1937, p. 15.

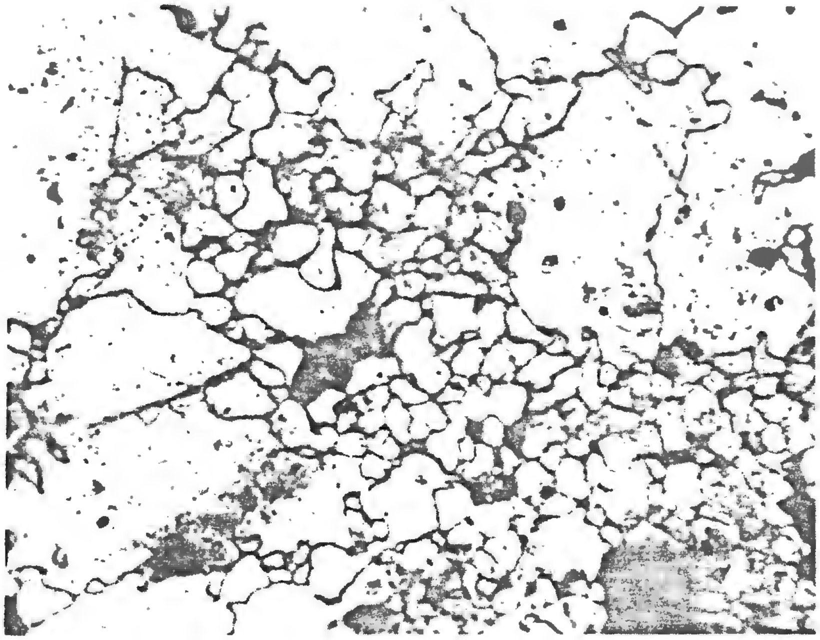

Plate 5
Aggregation of anhedral, subrounded gold crystals differing greatly in size and shown after etching with concentrated aqua regia for 6 seconds. Highet Creek. (200 x)

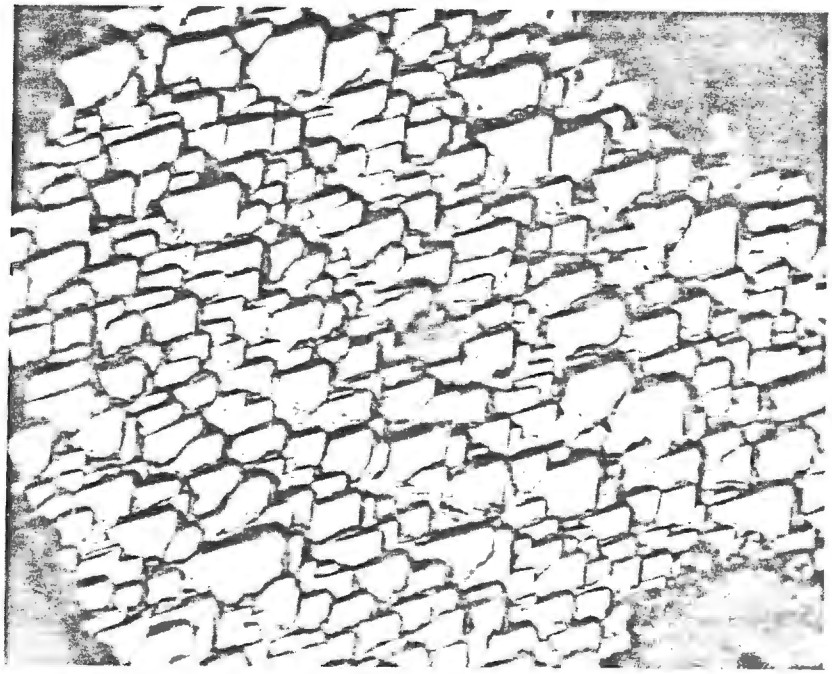

Plate 6
Strongly oriented microcrystals of gold in the shape of elongated octahedrons. Area shown is similar to that within grain boundaries evident in plate 5 after deep etching. Victoria Gulch. (1100 x)

made previously, that susceptibility to etching is increased with the silver content. The gold-silver equilibrium diagram (see Figure 4) demonstrates that under non-equilibrium conditions (i.e. rapid cooling), the first crystals to be produced are richer in gold than the smaller silver-rich and acid-susceptible crystals produced near the completion of solidification.

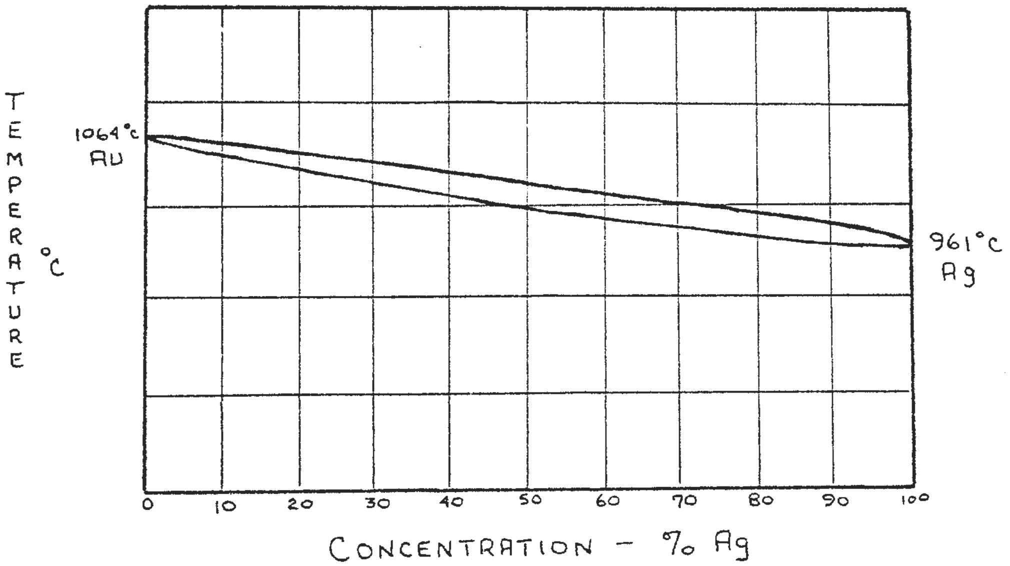

Figure 4. The Gold-Silver Equilibrium Diagram (After Hansen, Aufbau der Zweistofflegierungen)

A second type of crystal pattern was the polygonal type, (see Plates 7 and 8) shown by Bannister[14] to occur when crystallization proceeds radially from centres. Where interference from two centres occurs, a straight line is formed, while with interference from three centres, three lines are formed at about 120 degrees to one another. One may observe in Plates 7 and 8, that a thin dark band has developed almost continuously around the polygons. The residual silver rich solution, trapped between the grain boundaries was believed responsible for the formation of this marginal segregation.

As explained above, prolonged etching revealed aggregates of microcrystal groups, each group differing from an adjacent one by orientation or form. The most common form was that of an aggregation of strongly oriented crystals, resembling octahedrons elongated parallel to the anistropic fabric (see Plate 6). Such an anistropic texture suggests that the gold was precipitated and grew under conditions of directed stress, possibly at considerable depth in the earth. However in other grains, the microcrystals varied in texture from unoriented to mammillary. The mammillary surface showed a distinct concentration of fibrous and diamond shaped inclusions, (see Plate 9).

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[14] Bannister, Journal of the Institute of Metallurgy. 1929, vol. 42. p. 141.

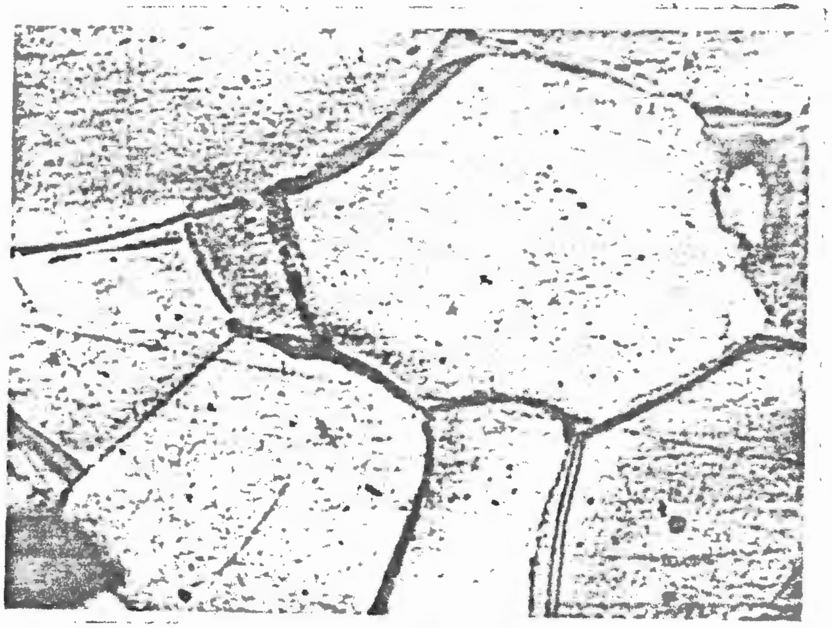

Plate 7
Polygonal crystal boundaries in gold nugget etched for 10 seconds with aqua regia. Dark borders are composed of residual silver-rich gold. Discovery Hill, Hunker Creek. (275 x)

Plate 8
Polygonal crystal showing boundaries caused by simultaneous growth from three centres. Note dark, silver-rich segregation along grain boundaries. Discovery Hill, Hunker Creek. (850 x)

Plate 9
Mammillary microstructure and concentration of acid resistant inclusions shown after prolonged etching with aqua regia. Duncan Creek. (1700 x)

The euhedral nature of the inclusions and their relative resistance to etching, caused the writer to believe they were formed early in the mineralizing fluid. The mammillary texture must have crystallized early as well, as no other area shows a similar concentration of inclusions. It was therefore suggested as being a cross-section of close-spaced dendrite arms.

Zoning

By etching the gold for times of 5 to 15 seconds, compositional zoning was revealed both in individual grains comprising the flakes and in some nuggets as a whole. Examples were found in most sections after careful polishing. Etching was repeated several times in order to achieve a surface undistorted by strain. The zoning shown in shades of grey (see Plates 10 and 11) is actually brightly coloured in red, green, yellow and blue, the different hues produced depending on the thickness of silver chloride film produced on etching. Zonal structure graded from a series of sharply defined light and dark bands (Plate 10) to a vaguely defined concentric pattern (Plate 11), both developed by differing amounts of silver alloyed with the gold from one band to the next. The light bands are silver-poor and etch slowly while the dark bands are silver-rich. Fisher[15] has produced a similar zoned structure using electrodeposition in a cyanide solution and at intervals changing the anode to one of differing composition. In light of this evidence, Fisher believed zoning in gold was caused by periodic fluctuations in the composition of mineralizing fluids during crystal growth. In the case of Plate 10, oscillating composition is distinctly evident while in Plate 11 the fluid may have changed composition gradually, producing vague zones. In two of the samples, the entire nugget showed a vague zonation with a white, silver-poor band located near and

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15 Fisher, op. cit., 1935, p. 348.

parallel to the outer margin (see Plate 15).

Plate 10
Sharply outlined oscillatory zoning of gold caused by fluctuations in composition of mineralizing fluid. Dark areas are silver-rich. Specimen shown after 15 second etch. Highet Creek. (125 x)

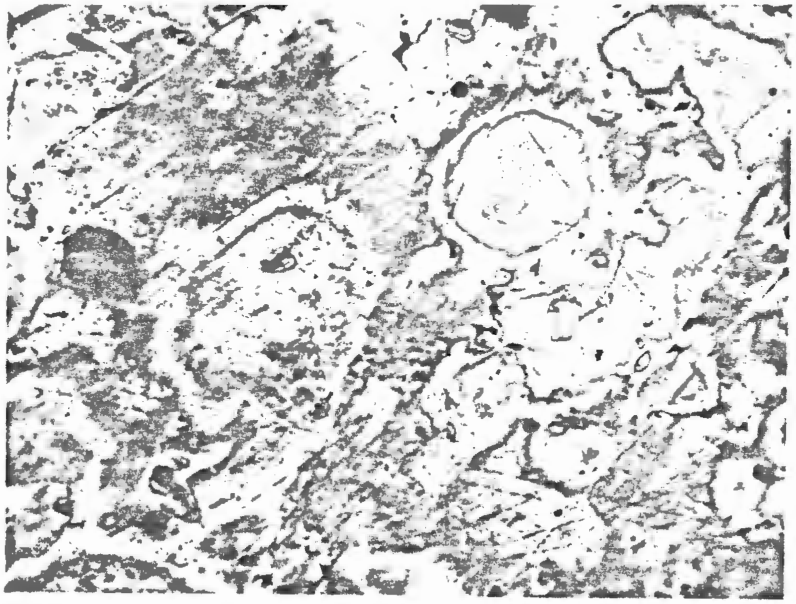

Plate 11
Vague concentric zoning, showing a gradual change in composition from the centre to the margin of the grains. Revealed after a 10 second etch with aqua regia. Highet Creek. (200 x)

Twinning

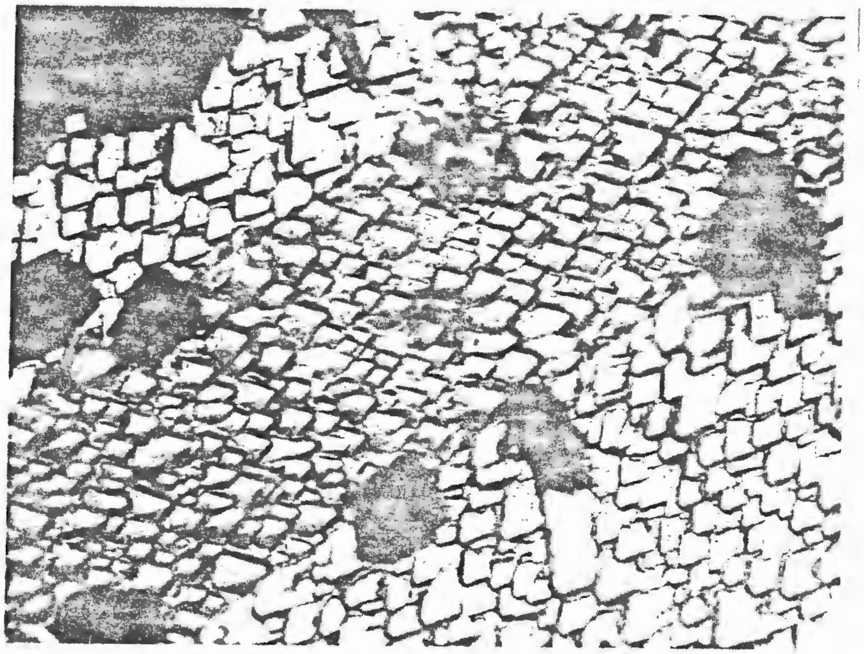

Plate 12
Simple twinning shown by strongly oriented microcrystals after prolonged etching. Growth was believed to have occurred under stress. Victoria Gulch, Bonanza Creek. (700 x)

Gold is a face-centred cubic and twins on the 111 plane either by gliding due to strain or growth twinning, contemporaneous with precipitation from solution. Recrystallization, as discussed above, is produced by heating or straining of the substance so that it may be raised to a higher energy state.[16] Twinning was, however,

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[16] L. G. Berry and B. Mason, Mineralogy. W. Freeman and Co. 1959. p. 139.

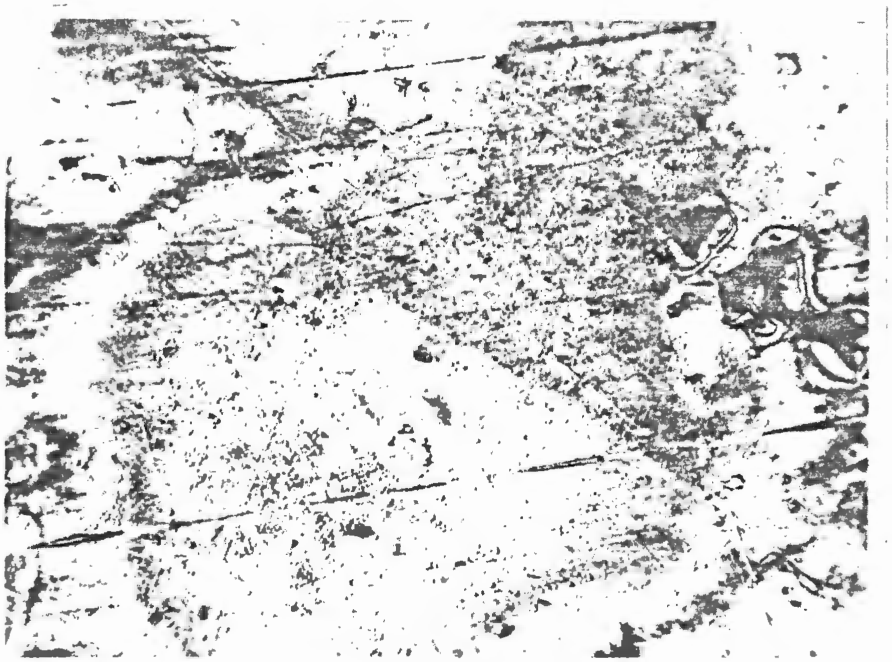

Plate 13
Simple contemporaneous twin brought out by brief etching with aqua regia. Highet Creek. (700 x)

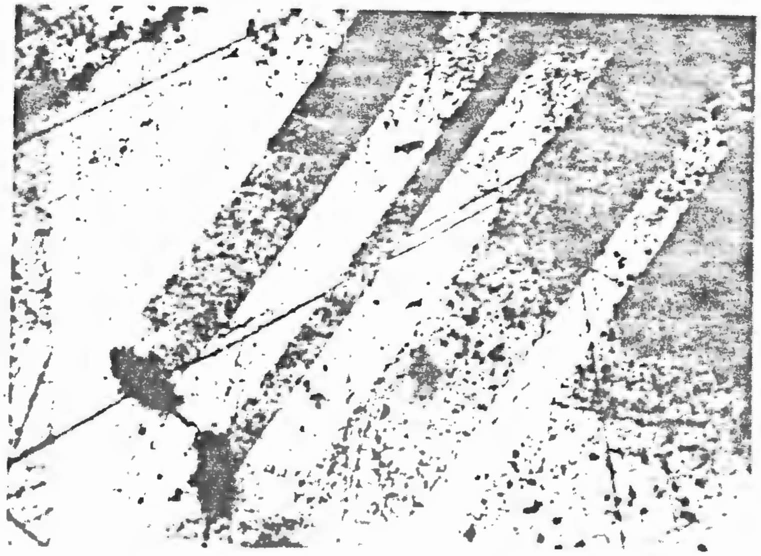

Plate 14
Polysynthetic twinning shown after brief acid etching. Discovery Hill, Hunker Creek. (150 x)

rare and rather than recrystallization, contemporaneous growth twinning of two types was observed: (1) Simple twins (see Plates 12 and 13); (2) Polysynthetic twinning (see Plate 14).

The microcrystals comprising the twinned area in Plate 12 show a very strongly directed fabric and appear to be the result of growth under stress. The other examples may or may not have developed in a high stress environment.

Dendrites

Only in the dendritic specimen from Discovery Hill were microscopic aborescent growths revealed. Prolonged etching followed by light repolishing was employed to bring out these structures. The dendrites were of two types: (a) a moss-like variety (see Plates 15 and 16) (b) a trellis-like type (Plate 16, lower right). Since little or no solid diffusion occurs in a gold-silver solid solution, the dendrites could not have formed after cooling was complete. Rather they must have developed as delicate fibres in the mineralizing fluid under conditions of very slow cooling. Finally, the dendrites were enclosed by later crystallization of anhedral gold crystals. Close examination of the dendrites (see Plate 16) revealed them to have a stalk of unetched silver-poor gold grading into darker, silver-rich leaves. Such a structure is predicted by the gold-silver equilibrium diagram (see Figure 4).

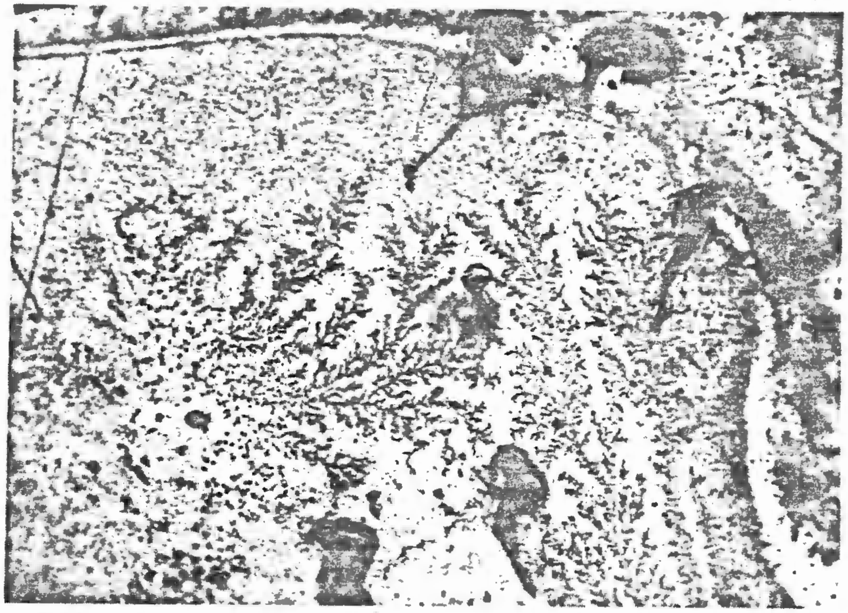

Plate 15
Moss-like dendrites revealed after prolonged etching. Note gold rich white band positioned parallel to outer margin of nugget. Discovery Hill. (200 x)

Plate 16
Combination of moss - and trellis - like dendrites. Note white, unetched stalks composed of finer gold than the darker leaves. Discovery Hill, Hunker Creek. (200 x)

Redeposited Surface Gold

It is generally stated, although not always rightly, that alluvial gold increases in fineness with increasing distance from the source. The proponents of a chemical origin for gold, by deposition from stream water, apparently attributed this observation to an increase in the ratio of precipitated gold to the original tiny nucleus of vein gold. Others explain the phenomena as a result of diffusion of silver out of the nugget and into solution, leaving a pure residue of gold. As Fisher mentions, however, such diffusion would leave a spongy deposit of gold on the nugget surface. No such deposit has been seen, but rather a thin film of gold whose true thickness is about .01 mm. has been found coating the nuggets, bordering cavities, and penetrating into the nuggets as discontinuous blebs (see Plates 17 and 18). The purity of this gold frosting was shown by its resistance to etching even after prolonged immersion in aqua regia.

An origin for this coating was presented by Fisher[17] as the result of redeposition of gold by a corrosion process similar to the dezincification of alpha

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[17] Fisher, op. cit., 1935, p. 363.

brass. Silver atoms, more soluble than gold, are dissolved from the nugget surface, dragging the adjacent gold atoms into solution. The gold becomes ionized, immediately reacts with the parent nugget and redeposits as a frosting of almost pure gold (i.e. close to 1000 fine) on the surface. Such enrichment is significant enough in the case of dust and flakes to account for the increase of fineness, observed in alluvial gold, with increasing distance down stream. This mechanism will have little effect on the average fineness of nuggets, however, since the surface coating is inconsequential when compared to the total nugget weight.

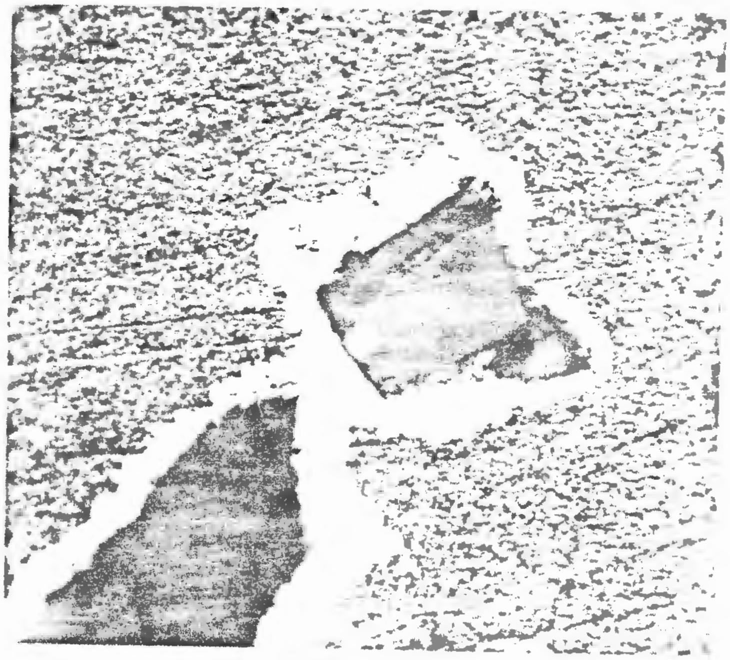

Plate 17
Redeposited surface gold of high purity, shown unetched by acid immersion around irregular nugget border. Hunker Creek. (250 x)

Plate 18
Frosting of redeposited gold bordering cavities in nugget.
Discovery Hill, Hunker Creek. (700 x)

COMPARISON WITH OTHER WORKERS

The minor elements found in gold from investigated localities were compared with those of Warren and Thompson[18] who analyzed placers from the same area but worked with fewer samples.

In the Mayo area, close agreement was achieved with previous work done, both with respect to presence and amounts of trace elements in placer gold. In the Dawson

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[18] Warren and Thompson, op. cit., 1944. Table 1, p. 461.

region, on the other hand, few similarities were found in the two sets of results. Warren and Thompson reported placers free of antimony, tin, arsenic, lead, mercury, bismuth, manganese and zinc. The present author, however, found at least traces of all these elements with the exception of bismuth, zinc and manganese on Bonanza Creek and all but zinc and bismuth on Hunker Creek. Possible explanations for this discrepancy might be found in inhomogeneity of placer gold, the analysis of too few samples or inherent errors in the spectrographic method.

CONCLUSIONS

As a result of spectrographic analysis of alluvial gold from the Klondike and Mayo regions, and semi-quantitative tabulation of the elements found, the author was able to suggest the presence of certain metallogenic zones in the area. These might be considered favorable areas for prospecting for lode deposits of the characteristic elements.

The delimiting of metallogenic zones met with most favorable results when the elements zinc, bismuth, antimony and arsenic were considered. The other metals, tin, lead, mercury, copper, iron and silver followed no definite distribution in the gold samples and could not be used as zonal indicators. Mercury may have originated, at least in part, as refuse from previous placer operations. All other elements were believed to be original constituents of the parent gold veins.

Zinc was considered to be the most favorable "path-finder" element of the study, being found in the Mayo region as consistent trace amounts with alluvial gold, while generally absent from the Klondike. This distribution was believed to be a consequence of the proximity of tetrahedrite - sphalerite - silver deposits on Keno and Galena Hills as well as in smaller showings throughout the Mayo region. No similar deposits are known to exist in the Dawson area.

Antimony, present in lode deposits of Galena Hill as tetrahedrite and in vein systems near Haggart Creek as jamesonite, was present in greater amounts in placer gold from Mayo than from the Klondike. Anomalous traces at Discovery Hill on Hunker Creek, however, may be significant.

Arsenic, another good zonal indicator, was very weak or absent in Klondike placers, while consistently present in faint to moderate amounts in the Mayo district. Arsenopyrite - gold - quartz veins are known both at Dublin Gulch and Keno Hill but not further west in the Hunker - Bonanza area.

Bismuth, reported in placers of Dublin Gulch and Highet Creek in the form of galenobismutite, native bismuth and bismuth telluride,[19] was present as trace amounts in alluvial gold from these creeks only. Although no lode deposits of bismuth-bearing minerals are known in the area, the author believes that they may be found.

Tin was considered to be a poor zonal indicator, being distributed randomly as a trace element in gold through both the Dawson and Mayo regions. Furthermore it occurs only in faint traces at Dublin Gulch where cassiterite is found in place.

The remaining elements, mercury, copper, silver, iron, manganese and lead, traces of which were either alloyed or in solid solution with the gold from most localities, could not be used to indicate metallogenic zones. As has been stated, however, trace amounts of zinc, bismuth, antimony and arsenic were distributed in significant patterns and could, in many cases, be directly correlated with the presence of known lode deposits.

On the basis of evidence which has been presented, the author suggests that small geographic areas, such as the Mayo or Dawson regions, show a characteristic assemblage

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[19] Aho, op. cit., 1949. pp. 7-24.

of minor elements in alluvial gold, indicative of the proximity of lode deposits bearing these elements. It was also suggested that placer gold provides a good "pathfinder" element for use during the exploration stage of a geological program because of several properties:
(1) It is easily recognized by prospectors, (2) it is found in small quantities in most B. C. and Yukon streams, (3) it carries with it a diagnostic assemblage of minor elements. By integrating the spectrographic analysis of placer gold samples with other preliminary geochemical methods such as soil and water sampling, tentative metallogenic zones could be delimited and therefore, certain areas chosen for intensive study.

The origin of alluvial gold, about which the author tried to take an unbiased view, was proven to his satisfaction to be mechanical (i.e. accumulated in streams by weathering of gold-quartz veins) rather than chemical (i.e. precipitation from solution in stream gravels).
The most convincing line of evidence was gained by a study of the textures produced upon etching polished sections of gold with aqua regia. The microstructures were no different from those present in lode gold.[20] All zoning could be interpreted by mechanisms operative during deposition from

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[20] Fisher, <u>op. cit</u>., 1935. p. 378.

hydrothermal solutions. Textures which might be expected from colloidal deposition were not observed.

The presence of inclusions in several nuggets, made possible a rough estimation of temperature of deposition of the gold veins from which the placers were derived. Euhedral and fractured rhombs of arsenopyrite in two samples indicated formation above 500°C. Jamesonite blebs, on the other hand, found in Thunder Gulch placer gold, pointed to a temperature between 250°C and 500°C.[21] Furthermore, the rarity of twinning gave evidence that recrystallization had not occurred since original emplacement. This evidence suggests that the gold-quartz veins from which the placers originated were in the mesothermal to hypothermal range. The deposits were emplaced in a moderate stress field as pointed out by strongly directed microcrystal growth, but cooled slowly under almost equilibrium conditions as shown by euhedral inclusions and dendrites.

Further discussion of the gold-tin-lead eutectic mixture found at Monte Cristo Gulch on Bonanza Creek will be confined to Appendix I,to be added at a later time.

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[21] Edwards, op. cit., p. 160.

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